Aalto University
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Analysis and Forming of Energy Efficiency and GreenIT Metrics Framework for Sonera Helsinki Data Center HDC

Thesis submitted for examination for the degree of Master of Science in Technology.

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Abstract of master's thesis

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Abstract

The two objectives of this thesis were to investigate and evaluate the most suitable set of energy efficiency metrics for Sonera Helsinki Data Center (HDC), and to analyze which energy efficient technologies could be implemented and in what order to gain most impact. Sustainable IT is a complex matter, and it has two components. First and the more complex matter is the energy efficiency and energy-proportionality of the IT environment. The second is the use of renewable energy sources. Both of these need to be addressed.

This thesis is a theoretical study, and it focuses on energy efficiency. The use of off-site renewables is outside of the scope of this thesis. The main aim of this thesis is to improve energy efficiency through effective metric framework. In the final metric framework, metrics that target renewable energy usage in the data center are included as they are important from CO_2 emission reduction perspective. The selection of energy efficient solutions in this thesis are examples from most important data center technology categories, and do not try to cover the whole array of different solutions to improve energy efficiency in a data center.

The ontological goal is to present main energy efficiency metrics available in scientific discourse, and also present examples of energy efficient solutions in most energy consuming technology domains inside the data center. Even though some of the concepts are quite abstract, realism is taken into account in every analysis. The epistemology in this thesis is based on scientific articles that include empirical validation and scientific peer review. This forms the origin of the used knowledge and the nature of this knowledge.

The findings from this thesis are considered valid and reliable based on the epistemology of scientific articles, and by using the actual planning documents of Sonera HDC. The reasoning in this thesis is done in abstracto, but there are many empirical results that qualify the results also as ´in concreto´. Findings are significant for Sonera HDC but they are also applicable for any general data center project or company seeking energy efficiency in their data centers.

Keywords Energy efficiency, data center, metric, GreenIT, renewable energy

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Abstract of master's thesis

Tekijä Matti Pärssinen		
Työn nimi VihreäIT metriikoiden analysointi sekä mittaus viitekehyksen luonti Sonera Helsinki Datakeskus (HDC) projektille.		
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Tiivistelmä

Lopputyöllä on kaksi päätavoitetta. Ensimmäinen tavoite on löytää sopivin mittausviitekehys energiatehokkuuden osoittamiseksi Sonera Helsinki Datakeskukselle (HDC). Toisena tavoitteena on analysoida, mitä energiatehokkaita ratkaisuja tulisi implementoida ja missä järjestyksessä, saavuttaakseen mahdollisimman ison vaikutuksen. Vihreä IT on monimutkainen asia ja samalla siihen liittyy kaksi eri komponenttia. Ensimmäisenä komponenttina, ja merkityksellisempänä sekä monimutkaisempana, on energiatehokkuus ja energian kulutuksen mukautuvuus suhteessa työkuormaan. Toinen komponentti vihreän IT:n osalta on uusiutuvien energialähteiden käyttäminen. Molemmat komponentit on huomioitava.

Lopputyö on teoreettinen tutkimus. Lopputyön ontologinen tavoite on esittää keskeisimmät energiatehokkuusmittarit, jotka ovat saatavilla tieteellisessä keskustelussa, ja esittää myös esimerkkejä energiatehokkaista ratkaisuista teknologia-alueisiin, jotka kuluttavat eniten energiaa data keskuksissa. Vaikka osa esitetyistä ratkaisuista on melko abstraktissa todellisuudessa, realismi on pyritty ottamaan huomioon arvioita tehdessä. Epistemologisesti tämä lopputyö perustuu tieteellisiin artikkeleihin, joissa on tehty empiiristä validointia ja tiedeyhteisön vertaisarviointia tiedon totuusarvosta. Kirjoittaja pyrkii välttämään oman arvomaailman ja subjektiivisen näkemyksen tuomista analyysiin pyrkimällä enemmänkin arvioimaan ratkaisuja perustuen päätavoitteeseen, joka on sekä lisätä energiatehokkuutta että vähentää CO_2 -päästöjä datakeskuksessa.

Lopputyön löydökset todetaan valideiksi ja luotettaviksi, koska ne perustuvat tieteellisten artikkeleiden epistemologiaan ja siihen, että arvioinnin pohjana on käytetty todellisia Sonera HDC -projektin suunnitteludokumentteja. Päätelmät ja analyysit ovat abstrahoituja, mutta perustuvat empiirisiin tuloksiin, jotka koskevat käytännön tekemistä sekä valintoja. Löydökset ovat merkittäviä Sonera HDC -projektin kannalta, ja myös muille datakeskuksille, jotka haluavat toimia kestävän kehityksen pohjalta.

Avainsanat Energiatehokkuus, datakeskus, mittarit, VihreäIT, uusiutuva energia

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This thesis is part of a large data center project called Sonera Helsinki Data Center (HDC). The focus of this thesis is on energy efficiency. This trend is becoming increasingly relevant and it is one of the main targets for the new data center project. Writing this thesis has been an interesting journey into the world of data centers and sustainability.

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Helsinki, April 18th, 2016

Matti Pärssinen

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SYMBOLS AND ABRIVIATIONS

IaaS	Infrastructure as a Service
PaaS	Platform as a Service
SaaS	Software as a Service
AC	Alternating Current
ALUR	Average Link Utilization Ratio
ARP	Address Resolution Protocol
ASDC	Average Server Degree Connectivity
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ATS	Automatic transfer switches are connected to primary and secondary power sources.
AWLB	Adaptive Workload Balancing Algorithm
BER	Bit-Error-Rate
BOR	Bandwidth Oversubscription Ratio
CAPEX	CAPital EXpenditure
CDCEE	Cloud Data Center Energy Efficiency
CDF	Computational Fluid Dynamics
CDN	Content delivery network
CEEDA	Certified Energy Efficient Datacenter Award
CNEE	Communication Network Energy Efficiency
CoC	Code of Conduct
COP	Coefficiency of performance
CPU	Central Processing Unit
CRAC	Computer Room Air Conditioner
CUE	Carbon Usage Effectiveness
DAL	Database Access Latency
DC	Direct Curent
DCE	Data Center Efficiency
DCell	Digital Load Cell Converter
DCeP	Data Center energy Productivity
DCiE	Data center infrastructure energy
DENS	Data center Energy efficient Network-aware Scheduling
DHCP	Dynamic Host Control Protocol
DNS	Dynamic Name Server
DNS	Dynamic Network Shutdown
DRUPS	Diesel Rotary Uninterruptible Power Supply
DSC	Dynamic Smart Cooling
DVFS	Dynamic Voltage and Frequency Scaling
DWPE	Data Center Workload Power Efficiency
DVS	Dynamic Voltage Scaling
EAR	Energy-Aware Routing
ECMP	Equal-Cost Multipath
ECP	Anomaly Elastic Computing Platform
EER	Energy Efficient Routing
EPC	Energy Proportionality Coefficient
ESD	Energy Storage Devices
ETR	External Traffic Ratio
ExP	Express Path

FBFLY	Flattened ButterFLY
FICORA	FInnish COmmunications Regulatory Authority
FTP	File Transfer Protocol
FTTCab	Fiber To The Cabinet
FTTH	Fiber To The Home
FVER	Fixed to Variable Energy Ratio
HDFS	Hadoop Distributed File System
HPC	High performance computing
HPG	Highest Potential Growth
HPR	High Performance Routing
HVAC	Heating Ventilation Air Conditioner
ICMP	Internet Control Message Protocol
ICT	Information and Communication Technology
IP	Internet Protocol
IRR	Internal Rate of Return
ISCL	Inter-Server Communication Latency
ISER	Inter-Server Error Rate
ISHD	Inter-Server Hop Distance
ISO	International Standards Organization
ITE	IT Efficiency
ITR	Internal Traffic Ratio
ITU	IT Utilization
KATAKRI	Authorities' auditing tool for ensuring compliance with the national security auditing criteria
KPI	Key Performance Indicator
KVM	Kernel-based Virtual Machine
LAN	Local Area Network
LEED	Leadership in Energy and Environmental Design
LLC	Limited Lookahead Control
MEP	Mechanical, Electrical and Plumbing
MMTE	Management and Monitoring Traffic Energy
MMTR	Management and Monitoring Traffic Ratio
NAS	Network-attached storage
NEBS	Network Equipment-Building System
NIC	Network Interface Card
NPUE	Network Power Usage Effectiveness
NTP	Network Time Protocol
OPEX	OPerating EXpence
OSPF	Open Shortest Path First
PDE	Power Density Efficiency
PDU	Power Distribution Units
PON	Passive Optical Network
PPW	Performance per Watt
PUE	Power Usage Effectiveness
QoS	Quality of Service
RAID	Redundant Array of Independent Disks
RAM	Random Access Memory
RC	Random Choice
RCI	Rack Cooling Index
REC	Renewable Energy Credit

REF	Renewable Energy Factor
RES	Renewable Energy Sources
RHI	Return Heat Indexes
RIP	Routing Information Protocol
ROI	Return On Investment
RPUE	Revised Power Usage Effectiveness
RTI	Return Temperature Index
SAN	Storage Area Network
SHI	Supply Heat Indexes
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
sPUE	System Power Usage Effectiveness
SQL	Structured Query Language
SWOT	Strength, Weakness, Opportunity, Threat
TCA	Total Cost of Acquisition
TCI	Thermal Correlation Index
TCO	Total Cost of Ownership
ToR	Top-of-Rack
UDER	Uplink/Downlink Error Rate
UDHD	Uplink/Downlink Hop Distance
UDLC	Uplink/Downlink Communication Latency
UPS	Uninterruptable Power Supply
VAHTI	Valtionhallinnon tietoturvallisuuden johtoryhmä' or the Government Information Security Management Board
WAN	Wide Area Network
VL2	Virtual Layer 2 network architecture
VLAN	Virtual Local Area Network
VM	Virtual Machine
WPE	Workload Power Efficiency
VPM	Virtual Power Management
WUE	Water Usage Effectiveness

1 INTRODUCTION

Data centers form the core of Internet services and more widely the cyber-universe. They sit at the heart of the ICT ecosystem and have become essential to the functioning of business, service, academic and governmental organizations [24]. Global warming and climate inconsistencies have caused the cost of energy to become a major challenge for the sustainability of e-businesses [13]. With rapid increase in the capacity and size of data centers, there is a continuous increase in the energy consumption [13].

Energy consumption has been addressed with varying intensity. Car industry has changed a lot in the past decades mainly because legislation has changed the rules of the business. It is not only a sustainability issue for car manufacturers to provide greener cars, it is enforced by legislation. [64] Customers are also demanding environmentally sustainable cars. Governments support greener cars by reducing taxing. [64] Another more disrupting example is the transformation in the lighting industry, where legislation was changed so that classic light bulbs are no longer available and it is forbidden to sell them anymore. Change is rapid when regulations step in. [62] The third type of transformation can be seen in the airline industry where reduction of fuel consumption in airplanes has become a competitive advantage as the flight ticket price erosion has taken margins lower. Cost savings have been targeted to lower fuel consumption of airplanes together with the airplane manufacturers. Fuel consumption has become a requirement for new airplanes. [63] Also many airline alliances are formed in order to maximize the utilization rate on each plane. Both of these actions are also environmentally sustainable ways of doing business.

In the data center industry similar regulation decisions or changes in customer demands have not happened. There is no strict regulation on how data centers should be built in a sustainable way and no incentives to do so. Similarly there is little consciousness on how the services are actually produced and how energy efficient the existing solutions are. According to Gartner 2013 study, data centers typically account for up to 44 % of overall IT spending. The same study reveals data center energy usage accounts for 12% of the overall data center spending distribution. As competition increases and profit margins go down, efficiency and cost reduction must be sought from energy efficiency as well.

The challenge in GreenIT is that electrical power usage is not a typical design criterion for data centers, nor is it effectively managed as an expense. This is true despite the fact [3] that the electrical power costs over the lifetime of a data center may exceed the costs of the electrical power systems including the Uninterruptable Power System (UPS) and the cost of the IT equipment together. [4] Fujitsu ICT Sustainability: The Global Benchmark 2011 study states that ICT sustainability is not a high priority for most ICT departments. CIOs are interested in sustainability, but they are balancing many competing priorities. ICT sustainability is a “nice to have” rather than a “must have”. The same study states that the single most important reason ICT managers and leaders do not prioritize sustainability or feel they have a compelling reason to do so, is the lack of visibility to power consumption. More than half of the respondents have no understanding of how much power ICT consumes. Only one in seven include the cost of ICT power consumption in their ICT budgets. From Fujitsu report it is surprising that the lowest awareness index score comes from the energy efficiency metrics. Few organizations are effective in measuring the effectiveness of ICT sustainability, and monitoring improvements in it. The classic saying about not being able to manage something that cannot be measured is relevant and metrics should be a key component of ICT sustainability. [60]

TeliaSonera is investing in a new Helsinki Data Center (HDC). It is intended to become operational in 2017. The following goals are set for the HDC: it must have the longest data center life cycle and it must be the most energy efficient data center in Finland. The underground spaces will have a higher safety and security level and they are constructed in accordance to VAHTI, KATAKRI and FICORA regulations. The data center will be designed for a maximum of 30 MW IT-load and for 15 000 square meters of white space. The data center will be located in Pitäjänmäki, in Helsinki, Finland. [46]

The main research questions and sub questions are:

1. What is the most suitable set of energy efficiency metrics for Sonera Helsinki data center (HDC)?
    a. What metrics are available?
    b. What are the most suitable metrics for HDC?
    c. How well do the most suitable metrics cover the data center energy efficiency?
2. In order to gain the most impact, which energy efficient technologies should be implemented and in which order?
    a. What kind of energy efficiency improving solutions exist within different domains of technology?
    b. What are the most relevant solutions for Sonera HDC?
    c. In which order should they be implemented?

The primary goal of this thesis is to find a holistic set of relevant metrics for large, GreenIT emphasizing data centers, from the available energy efficiency metrics. The secondary goal is to provide a suggestion on which energy efficient solutions should be implemented and in which order.

The ontological goal of this thesis is to present the main energy efficiency metrics available in scientific discourse and also to present examples of energy efficient solutions within in the most energy consuming [4] technology domains inside the data center. Another goal is also to create relations between the validated metrics and relating energy efficient solutions. The epistemology in this thesis is based on scientific articles that include empirical validation and scientific peer review. These articles form the origin of the used knowledge and the nature of this knowledge. The writer attempts to put his own values aside and only consider the research questions and the goal of reducing both carbon emissions and use of energy in the data center.

This thesis is a theoretical study and it focuses on energy efficiency. The use of off-site renewables is outside of the scope of this thesis. The main aim of this thesis is to improve energy efficiency through effective metric framework, thus not so much to select available renewable energy sources from grid electricity markets. In the final metric framework, metrics targeting renewable energy usage in the data center are included as they are important from CO_2 emission reduction perspective. The selection of energy efficient solutions in this thesis are examples from the most important data center technology categories and do not try to cover the whole array of different solutions to improve energy efficiency in a data center.

This thesis will contribute a set of metrics to the data center providers that ensures energy efficiency is visible to decisions making, once implemented. The evaluation of the metrics is done by investigating four different orthodox dimensions in relation to each of the metrics. The aim is to ensure energy efficiency is not only "nice to know information" but one of the main influencing factors in decision making and technology selection during the years to come. Since environmental issues are gaining global visibility, it can be anticipated that the GreenIT is becoming a differentiating factor for customers selecting their outsourcing partners for data center services in the near future.

The second contribution of this thesis is the evaluated energy efficient solutions from the point of view of the Sonera HDC. They are structured to a phased plan for implementing. The way the evaluations are constructed is valuable as it takes into consideration four different rational dimensions before forming a final conclusion. The methodology is also valuable for future technology evaluations. All solutions are evaluated from cost perspective as well. The division between CAPEX and OPEX driven solutions is relevant and it also indirectly shows in which phase of the data center lifecycle the energy efficient solution is most convenient to implement. CAPEX driven solutions are advisable to be implemented already when designing a new data center. OPEX driven solutions can be implemented also to existing data centers with moderately low investments.

The findings in this thesis are considered valid and reliable based on the epistemology of scientific articles and by using the actual physical facility planning documents of Sonera HDC. The reasoning in this thesis is done in abstracto, but there are many empirical results that qualify the results also as ´in concreto´. The findings are significant for Sonera HDC but they are also applicable for any general data center project or company seeking energy efficiency in their data centers.

Chapter two answers to four main questions, which clarify the energy efficiency ecosystem in data center context to the reader. Sonera HDC project is introduced and the requirements for the data center are presented in Chapter two. Chapter three introduces five different energy efficiency solution domains one by one, answering the first sub-question of the second main question. In Chapter four, findings from scientific articles regarding energy efficiency metrics are introduced. All potential metrics are gathered into one table containing the name of the metric, how it is calculated and what is its main purpose. Chapter four also analyses these metrics. Metrics are first categorized to different domains and then evaluated individually against four different dimensions, ending up with a list of recommended metrics, prioritized by their importance. As a result a general metric framework that holistically covers the whole energy efficiency domain is introduced. Metric framework answers the first main research question and remaining sub-question. Chapter five focuses on analyzing different energy efficient solutions and answering the second main question and the remaining sub-questions. Chapter six concludes the paper and presents a spider web metric framework and a phased recommendation plan to implement various energy efficient solutions based on their significance, complexity and how they are perceived by customers and data center providers.

2 DEFINITIONS OF KEY CONCEPTS AND INTRODUTION TO SONERA HDC PROJECT

The first of the three parts of the previous literature and research of this thesis consists of the answers to the first four main questions that clarify the grounds for the reader to understand the further analysis. In addition the case of the Sonera Helsinki Data Center (HDC) is presented. The structure of this chapter is described in a Figure 1.

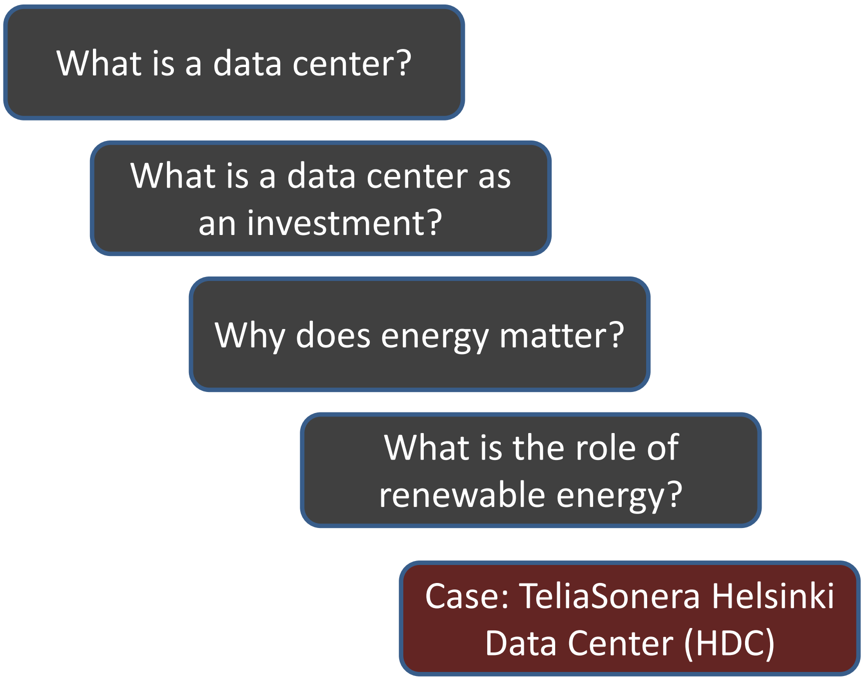


Figure 1. Main questions for setting the grounds.

2.1 What is a Data Center?

Data centers form the center of the cyber-universe [24]. Nowadays users access services based on their requirements without a regard to where the services are hosted. This model has been referred to as utility computing, or recently as cloud computing. The later term means the infrastructure as a "cloud" from which businesses and users can access applications as services from anywhere in the world on demand. Cloud computing can be classified as a new paradigm for the dynamic provisioning of computing services supported by state-of-the art data centers that usually employ Virtual Machine (VM) technologies for consolidation and environment isolation purposes. [12]

Cloud computing delivers an infrastructure, platform and applications as services that are made available to consumers in a pay-as-you-go model. In industry these services are referred to as Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and software as a service (SaaS) respectively. [5] Data centers are the heart of cloud computing [13]. Figure 2 presents the high-level components that form the data center. The energy efficiency solution and metrics that are covered in this thesis are marked with gray color. The services and applications are not in the scope of this thesis.

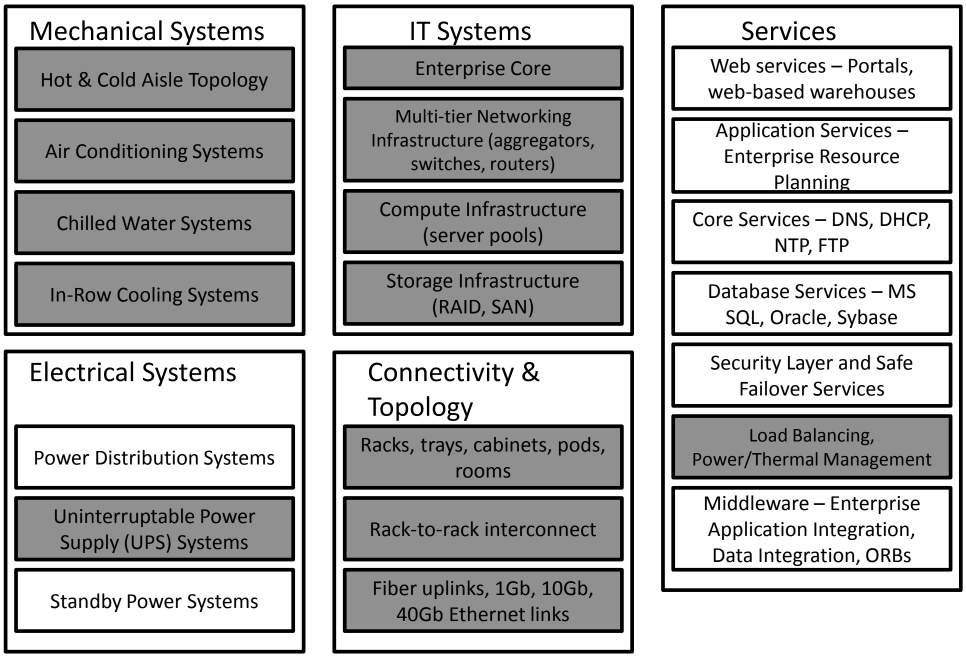


Figure 2. A high-level view of the key cyber-physical components comprising a data center. [15]

2.2 What is a Data Center as an Investment?

Datacenter is a large capital investment or capital expenditure (CAPEX). This means spending money now in the hopes of getting it back later through future cash flows. The process of evaluating potential investment usually starts from generating ideas based on opportunities or by identifying solutions to problems. All relevant information related to the possible investment should be investigated. It is necessary to consider possible alternatives in order to see best possible potential profit; this means that financial consequences of each alternative should be evaluated carefully. Monetary consideration is only one dimension; there could also be non-financial aspects in each alternative that affects the investment decision. Eventually there is the actual decision point whether to proceed or not. If investment decision is accepted, it should include a plan for implementation and the plan should also be implemented. The implementation should be done in a controlled fashion and the actual results should be compared to the initial plan for future learning and for corrective decisions during the actual project. [43]

When considering particularly a data center investment and Total Cost of Ownership (TCO) of a data center, operating costs is as essential factor as the actual investment. Usually the basic concept of TCO is understood as the sum of initial capital expenditures (CAPEX) added to ongoing and long-term operational expenditures (OPEX). TCO is a critical metric when designing a new data center facility or selecting equipment for it. With the explosion of data center size — identifying and weighing the value of TCO variables when specifying, building and operating a data center, may be more elusive. A simple miscalculation can cost data center providers millions of euros each year. TCO is an estimation of the total costs just as Net Present Value (NPV) is an estimation of the present values of future cash flows.

Energy is an important TCO variable, as data centers consume it in significant amounts. Servers and data equipment account for 55% of the energy used by a data center, followed by 30% utilized by the cooling equipment to keep the facility operational. [45] According to Gartner 2013 Data Center Cost Portfolio study done with Cisco Systems the overall spending distribution in data center is divided into people (29%), energy and facilities (12%), networking (10%), software (22%), servers (11%), storage 7%) and the rest (9%). Electrical power distribution losses, including uninterruptible power supply (UPS) losses, amount to a significant 12% of the total energy consumption. Only 3% is consumed by lighting.

OPEX includes expenses such as electricity, staff, consultant or hired workforce, maintenance contracts, facility management and so on. It is not trivial to decide whether to invest in a data center or to outsource the data center as there are many strategic options available and also many decision points along the way. [45]

One does not have to spend much time around cloud computing before running into arguments regarding cloud economics and encountering the phrase "CAPEX versus OPEX." This phrase refers to the fact that building your own data center requires CAPEX, while using an external cloud service that offers pay-as-you-go service falls into ongoing OPEX. This creates the contrast of "CAPEX versus OPEX". [45]

There have been many discussions comparing the cost of a 24/7 use of a PaaS or IaaS provider instance against the cost of hosting a server within a company's own data center. Usually the comparison is made between the average selling price of a 1U server, divided by 36, which is the number of months in the typical expected service lifetime of a piece of equipment and per month price for renting a server from PaaS or IaaS provider. The idea is to show that it is cheaper in the former case. Therefore, one can conclude cloud computing is bound to be more expensive than self-owned. Typically this means that it is inappropriate for typical corporate applications requiring round-the-clock availability. A further argument is given that since cloud providers seek to make a profit; they are ipso facto more expensive than internal data centers. [45]

This discussion is a logical fallacy. There is a misunderstanding of the real key issues for most companies, and this is misdirecting the conversation away from where it should be directed. The relevant question is; what proportion of the total portfolio of corporate applications is appropriate for external cloud hosting, and what decision criterion should be used to make that assessment – noting that economics is not the sole criterion. [45]

Comparing the monthly cost of a PaaS or IaaS server against a putatively similar piece of hardware in a data center is misleading. It overlooks the direct costs that accompany running a server: security, power, floor space, storage, and IT operations to manage those resources. It also ignores the indirect costs of running a server: network and storage infrastructure and IT operations to manage the general infrastructure. Lastly the overhead costs of owning a server: procurement and accounting personnel, not to mention a critical resource in short supply: IT management and its attention. [45]

When these costs are added to the internal server, it significantly raises the monthly overall cost to host a server in own data center. In the recent UC Berkeley Cloud

Computing Paper, the RAD Lab estimates cloud providers to have lower costs by 75-80% vis-à-vis internal data centers. Some of this advantage is related to the purchasing power through volume, some through more efficient management practices, but also because these cloud providers are focused on data center business and managed as profitable enterprises with a strong attention to cost. [45]

The typical cost discussion, internal data center versus cloud provider costs, is over-simplified and fails to assign a true cost structure to the internal data center side of the comparison. It is also known that some IT organizations do not have a clear understanding of their true costs to begin with. These kinds of cost comparisons ignore the utilization of the internal server: if it is running at 20% utilization, the effective cost of a given level of computing is actually five times higher than typically assumed in these cost comparisons. [45]

Even if the cash outflow is roughly the same, the cloud alternative is still more attractive. This is because a payment on a capital good like a server is one of a series - each of which the enterprise is committed to, no matter if the server is being used or not. Once a company purchases a capital good, it is stuck with it. Even if the company is no longer using it, the finance company still expects its monthly payment. [45]

By contrast, in cloud service there is an option value in flexibility, for which a premium is paid. Even if the cloud alternative is more expensive over a given period, there is no implied commitment beyond it. Furthermore, there is an imputed value to the scalability offered by the cloud alternative. The fact that customer can easily grow capacity in a short period is in itself valuable, and, naturally, carries an option value. Therefore, it can be concluded that given the option values associated with cloud computing, companies might be willing to pay more than the cost of an equivalent amount of internal server capability. [45]

Finances are one aspect on the investment decision. Cloud services have challenges that are related to other aspects of the service. Security and privacy are not so easy to control when using cloud services. Especially when using public cloud services it is not so clear how security and privacy issues are handled when the service provider is serving many customers at the same time. It is also difficult to assess the costs involved because of the pay-as-you-go nature of the service. Budgeting and the assessment of the cost are variable. Service level agreements of the cloud service are not sufficient to guarantee the availability and scalability.

Another challenge in Cloud services is that services should be integrated to on premise IT without any lock-in period. In reality any integration creates a natural lock-in. It is not so easy to switch between service providers, which were the ultimate goal from customer perspective. Cloud providers still lack the 24/7 service, this might result in outages. It is important to monitor the service with third party tools, which cost money also. IT is vital to have plans on how to supervise usage, SLAs, performance, robustness, and business dependency on these services.

One challenge with Cloud services is that as businesses save money on hardware, they have to spend more money to the bandwidth. This can be low for some smaller application but it can be high for the data-intensive applications. These challenges need to be addressed and considered, they are not blocking the use of Cloud computing but need to be taken into consideration along with the financial aspects.

Companies are limited by the public markets in the amount of capital expenditure they are able to make. Because capital investment is limited, companies usually want to direct their investment toward revenue-generating activities. This is why many companies prefer to lease real estate rather than purchase. Companies do not want to tie up precious capital in dead assets. [45] Rightly or wrongly, IT is managed with an eye to minimize its cost, which is why IT reports to the Chief Financial Officer in many companies. Given these factors, making comparisons between the costs of running an internal server versus the cost of a cloud-based on is off-target. Unless the cloud costs are significantly higher, there are many attractive aspects to cloud economics that would suggest viewing it as very desirable option. A better strategy would be to identify decision criteria for determining whether a given application should be hosted internally or could be moved to a cloud environment. With defined criteria, a portfolio analysis can be undertaken to establish a set of recommendations and an action plan. [45]

2.3 Why Does the Energy Matter?

Energy consumption is declining in Europe´s data centers due to consolidations and the use of virtualization and other energy efficient technologies. An example of such technological advance is the cooling system. [8] In the Table 1, BroadGroup 2014 illustrates key trends in Western Europe data centers:

Table 1. Key trends in Western Europe data centers. [8]

Western Europe	2013	2014	2015	2016	2017	2018	2019	2020
Net data centre space (thousands of m2)	10256	10221	10105	10055	9875	9555	9365	9155
Average power density (kW/m2)	1,1	1,1	1,2	1,2	1,3	1,3	1,2	1,3
Total power usage (GW)	11,3	11,2	12,1	12	12,8	12,4	11,3	10,9

According to the BroadGroup study the annual electricity consumption is 80TWh in western European data centers. It is about 3% of the total European electricity consumption. A datacenter dynamics study in 2011 states that the total power consumption of global data centers is around 31GW, meaning Western Europe represents about one third of the global consumption. [8]

There is a great need to change energy consumption as it is costly – or is it? According to Dinkar Sitaram, et al, [20] energy prices vary greatly between different countries. For example, from Statista portal the global electricity prices by select countries in 2015 the price of electricity in US dollar cents per one kWh, is 15,7 in Italy, compared to 6,42 in Finland. It is almost two and a half times more expensive to use electricity in Italy.

Data centers also produce high levels of CO_2 emissions. There are many ways to reduce global CO_2 emissions with innovative services from data centers, such as online taxation, video conferencing and online billing, which can enable a green economy. [29] The ultimate goal is to deploy IT environments by enabling power efficiency, aiming at small ratios of required W/Gbps and W/user [29].

The United States Environmental Protection Agency (US EPA) reported the energy consumption of data centers in 2006 nearly doubled from year 2000 and it is continuously increasing globally. Energy related operational costs will continue to double every five years between 2005 and 2025 [13]. Trends show there is a rapid increase in IT infrastructures, accelerated by the demand of computational power. There are many computer intensive businesses and scientific applications that create this demand. It is important to note that server management, maintenance, electricity and cooling costs have exceeded the server equipment costs. [28] [30] [37] [40] In order to get a full picture of this growth rate, according to Fredric T. Chong, et al, one must look at the exponentially growing, massive global data, with 1 000x growth within the next 13 years. [35] This is a problem. According to the same research, in order to meet this demand, technology scaling will provide no more than 25x improved computational efficiency during the 13-year period, leaving at least a 40x gap between computation growth and data growth. The actual gap cannot be predicted, but it is likely to be far worse, as transistor energy efficiency has begun to improve more slowly than density. [35] Below is a presentation of the energy consumption in different ICT technology areas according to ITU from Oct. 2008.

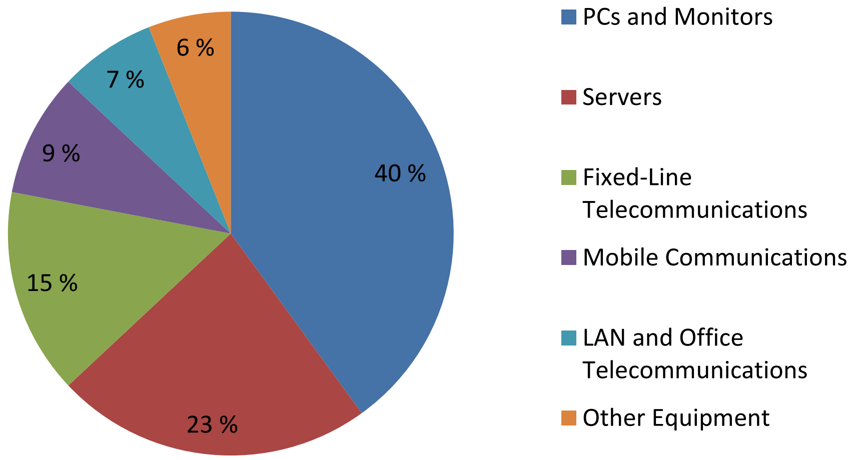


Figure 3. Energy consumption in ICT sectors. [29]

According to Jinkyon Cho, et al, in 2014 there were about 23 000 data centers in the world and the market is expected to grow to about USD 343,4 billion. According to the same study one large internet data center consumes 10-20MW of electricity. Data centers are over forty times more energy intensive compared to normal office buildings. [31] Power related costs are growing faster than computer related costs [23]. Even though there have been many improvements in energy efficiency of the hardware, unfortunately the overall consumption continues to grow due to ever increasing requirements for computing resources. [33] Energy efficiency has never been a significant goal in the IT industry. Since the 1980s, the only target for IT has been to deliver more and faster; this has traditionally been achieved by packing more into a smaller space, and running processors at a higher frequency. This consumes more power, which generates more heat and CO_2 emissions, so a costly cooling system is required. [3] Below is a figure of typical data center energy consumption distribution.

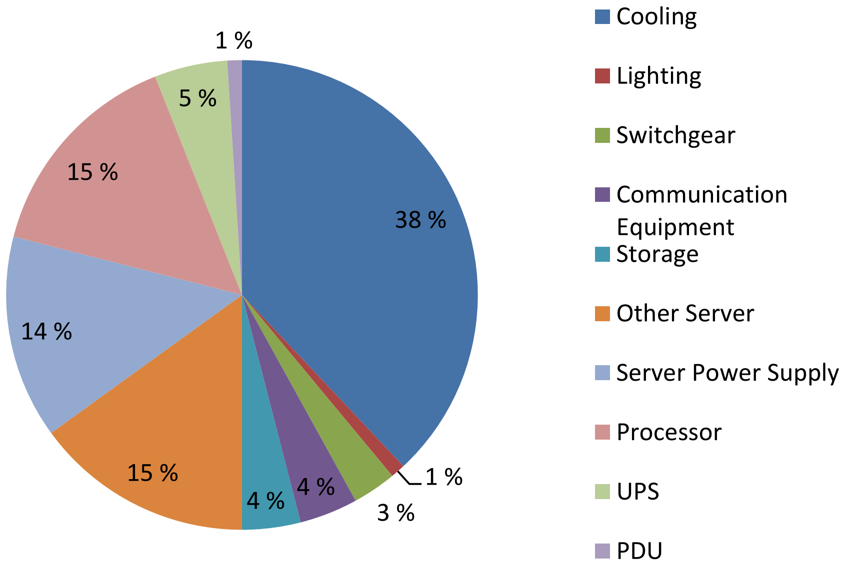


Figure 4. Analysis of typical data center energy consumption. [31]

According to a Greenpeace report "How clean is your cloud", both Yahoo (using 56,4 % clean energy) and Google (using 39,4% clean energy) are active in supporting policies to drive renewable energy investments and in powering clouds with green energy [34]. But the same report in contrast shows that many large IT companies, such as Amazon, Apple and Microsoft, rapidly expand their cloud business without adequate attention to the electricity source, and they rely heavily on brown energy to power their clouds [34]. The biggest problem according to Greenpeace report is that there are numerous small and medium sized data centers that consume the majority of energy, yet are much less energy efficient [34]. It should be noted that high energy consumption not only results in large electricity cost, but also incurs high carbon emission [34]. To get actual figures, according to Greenpeace, in US, generating 1kWh of electricity emits about 500g of CO_2 on average. IT carbon footprints in 2014 cover 2% of the global greenhouse gas emissions. [34]

Reports from data center operators indicate that servers run between 10% and 50% of their maximum utilization levels. Servers process a continuous stream of task requests which operators try to distribute evenly across the data center to avoid high loads and to meet Service Level Agreement (SLA) targets for latency. [23] According to a 2008 Gartner report, 50% of data centers will soon have insufficient power and cooling capacity to meet the demands of high-density equipment [24].

To overcome the aforementioned scenarios, there has been increasing attention towards implementing GreenIT solutions. The main objective of GreenIT is to increase energy efficiency and to reduce CO_2 emissions. [13] The GreenIT phenomenon has increased the interest of information system researchers, business practitioners, and politicians towards energy efficiency. In addition the demand for developing methods to monitor and measure the energy efficiency and use of renewable energy sources is emerging.

[10] [28] [40] GreenIT solutions provide environmentally friendly techniques and methods towards implementing more effective and efficient organizational and national strategies, as well as policies to attain sustainable business worldwide [10] [7]. Basically there are two ways to make the data centers greener; one way is to improve energy efficiency and the other is to use a clean energy supply. [13] Technology is approaching the stage of creation and outsourcing of sustainable IT businesses based on principles of green economics. [10] In summary, GreenIT can be presented with the following equation:

GreenIT = Renewable Energy + Energy Efficiency [34] (1)

In the next part, renewable energy is presented briefly as it is something any organization in the data center market can freely use and it is a "simple" sustainability and value issue. This thesis concentrates more on the energy efficiency part of the GreenIT, thus it is more relevant from research question perspective.

2.4 What is the Role of Renewable Energy?

Data centers use onsite and offsite renewable energy (transported through a grid) from wind turbines, solar panels or wave energy in order to become less dependent on black energy from the grid, which is more expensive and less clean [25]. Use of renewable energy is also a popular research topic [34]. Modern data centers with green energy vision only use renewable energy. Power grids have transformed themselves into smart grids all around the world by utilizing integrated ICT solutions. [14] In addition, data center management should be revised to utilize off-grid renewables. Smart grid and smart meters allow new pricing schemes compared to old flat tariffs. Smart grid also allows feeding to the grid when a customer is producing off-grid renewables that it can sell to the utility grid. In some countries consumers can also feed and sell excess renewables to the grid. [25] Smart grid can offer new pricing strategies such as Time-of-Use (ToU), which is based on more utilities charged for peak hour usage. These real-time tariffs directly impact electricity pricing [14].

There are also challenges with using renewable energy sources. By looking at energy efficiency alone one may not take full advantage of renewables. Energy efficient capacity management may be optimized towards a target where servers are switched off for long periods of time in order to save energy and reduce idle capacity. This is a challenge as sometimes renewables are intermittently unavailable. A data center provider misses opportunities to use onsite renewable energy when servers are switched off for long duration. [25] Renewables are available only when the wind blows or the sun shines. It could mean that during low wind and cloudy afternoon renewables can produce only enough energy for statistically light early morning workloads in the data centers [25]. As a consequence, policies that schedule workloads energy efficiently and consolidation heuristics of virtual machines must adapt to uncontrollable changes in the availability and abundance of renewable energy sources or the data center provider must have a portfolio of different energy sources that it can utilize [25].

The following four factors are potential scenarios for power challenges in the data center. Firstly, power is available to the data center facility, but power distribution infrastructure is constrained. Secondly, power is available to the facility, but standby or backup power is insufficient for growth. Thirdly, power is available in the area, but utility constraints prevent delivery to the data center. And fourthly, power costs are excessive in the region where the IT equipment and facilities are located. [10] There are four key challenges and requirements for renewable energy. Firstly, global users require 24/7 cloud services, therefore intermittent renewable energy represents a problem for data centers, which are consistent users of power. [34] Secondly, cloud capacity demand is dynamic, which requires dynamic power provisioning. Thus the power supply should be elastic. Dedicated renewable energy cannot be scheduled on demand. [34] Thirdly, high reliability services incur the problem of how to construct a reliable power supply in the presence of uncertain dedicated renewable energy. [34] Lastly, automatic management requires the power supply system to choose and supply power automatically among multiple power sources [34].

Today's most integrated smart grids can satisfy only up 19% of their workload from renewable sources. Wind and solar are the most used renewable sources. Wind currently provides 62% and solar 13% of the non-hydro renewable electricity worldwide. [34] It is known that solar or wind power output depends almost solely on the environmental conditions, such as solar irradiance or wind speed. [34] Their capacity factor, which is the ratio of the actual output over a period to its potential output if it operated at full nameplate capacity, can be much lower than that of grid energy, which is approximately 80%. Specifically, the capacity factor of wind energy is within 20-45%, while the capacity factor of solar energy ranges from 14-24%. [34]

Experiments with real power demand and renewable energy sources show that there are several advantages with using renewables. Firstly, renewable energy can lower both carbon emissions and energy costs for data centers. Secondly, on-site renewables can reduce costs by reducing peak power drawn from the grid. Thirdly, the most cost-efficient alternatives for CO_2 reduction vary with different carbon footprint targets. For a reduction target up to 30% the best option is to use onsite renewables. If the reduction target is higher, offsite renewables are required. A zero carbon footprint goal must resort to renewable energy products such as RECs (Renewable Energy Credit). [34]

Below is an illustration of an overall vision of data centers using renewable energy sources. The upper part of the Figure 5 illustrates on-site solutions for renewables, diesel generators for backup and different Energy Storage Devices (ESD). Examples of ESD are batteries, fuel cells and flywheels. Together these form an on-site energy solution.

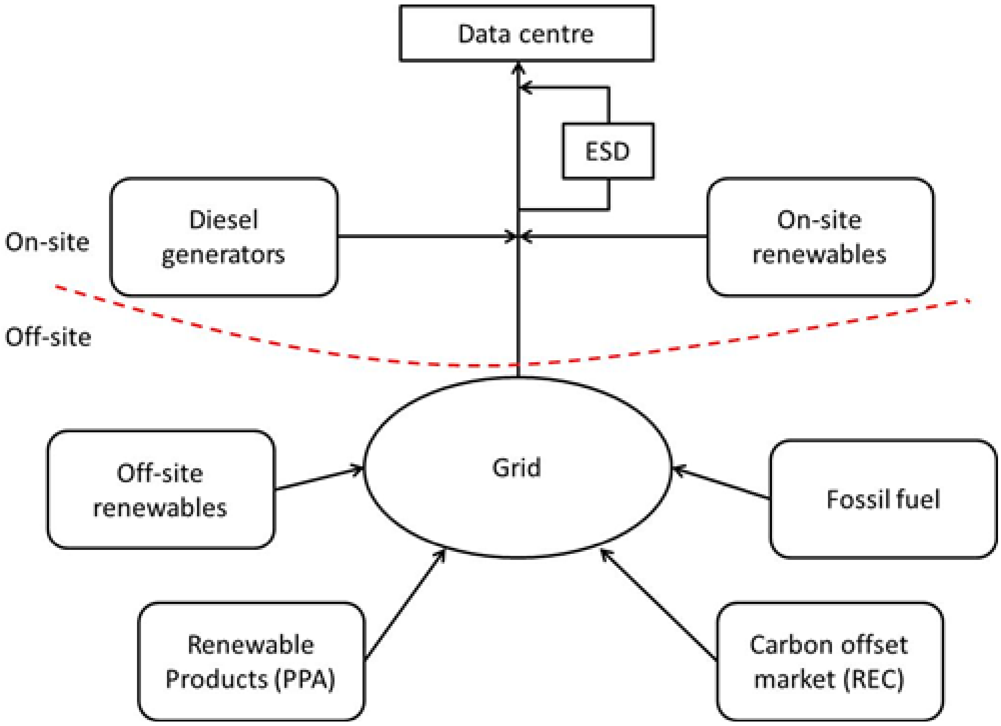


Figure 5. Overall vision of data center renewables. [34]

In the off-site part of the Figure 5 there are three kinds of implicit options to utilize renewable energy [34]. Firstly, there is the power purchase agreement (PPA), in which one purchases a portion of the green energy from a renewable energy source. Secondly, there are renewable energy credits (REC) which are tradable, non-tangible energy commodities. REC represents one MWh of electricity being generated from an eligible renewable energy source. Thirdly, there is the carbon offsetting, which represents the reduction of one ton of carbon dioxide. [34] This thesis concentrates on the on-site renewables, because it is a data center industry typical solution. Onsite renewables are resiliency factor as well as a sustainability factor. Selecting off-site renewables or purchasing energy derivatives from renewable electricity market is influential but does not offer competitive advantage. In addition, using the carbon offset market does not rationally qualify as a solution specified in the GreenIT philosophy with overall carbon emission reduction as a target.

2.5 Case: Sonera Helsinki Data Center (HDC)

TeliaSonera is currently the second largest telecommunication company and mobile network operator in Finland. TeliaSonera is investing in a new Helsinki Data Center (HDC). It is intended to become operational in 2017. HDC is primarily meant to facilitate TeliaSonera´s business demands. TeliaSonera has set the following goals for the HDC: it must have the longest data center life cycle and it must be the most energy efficient data center in Finland. The shell and the core of the building must be designed for a 30-year lifespan, allowing for a complete mechanical, electrical and plumbing (MEP) overhaul within this timeframe. Waste heat must be recovered for reusing it in the district heating system. TeliaSonera´s objective is to obtain the Leadership in

Energy and Environmental Design (LEED) Gold and Certified Energy Efficient Datacenter Award (CEEDA) certifications for the data center. [46]

The data center is meant for a mixed group of customers but mainly for enterprise, wholesale, retail and customers with special requirements. The data center will consist of above ground and below ground areas. The underground spaces will have a higher safety and security level and they are constructed in accordance to VAHTI, KATAKRI and FICORA regulations. The data center will be designed for a maximum of 30 MW IT-load and for 15 000 square meters of white space. The expected power density (kW/m2) will be 2 kW/m2 at data center level, whereas specific rooms can go up to 4 kW/m2. The actual IT-load will be determined by the number of racks and the power per rack. The white space is not entirely available for racks, as cooling equipment, partition walls and internal corridors are included in it. The actual ratio between gross and net white space in practice varies between 70% and 80%. Industry average power density figures are around 2 kW/m2/rack and 4 kW/m2/rack. Table 2 shows that the IT-load is strongly dependent on the number of racks and the power per rack. [46]

Table 2. IT-load dependency on number of racks and the power per rack [46].

	Min	Max
Gross White Space	15 000	15 000
Gross - Net Ratio	80 %	60 %
Net White Space	12 000	10 500
Racks	6 000	5 250
kW/m2 Net White Space	2,5 kW	2 kW
kw/Cabinet	5 kW	4 kW
IT-Load	30 MW	21 MW

Based on the currently available information on racks and power density, 24 MW IT-load seems a more realistic figure for the HDC design purposes. The day one install base is intended to be a 6 MW IT-load, and expected power growth per year is 2 MW. The data center will be located in Pitäjänmäki, in Helsinki, Finland. [46]

The following parts describe the applicable standards and other requirements for the HDC and the building site. These standards cover the areas of safety, operational resilience, quality and sustainability. Individual standards are addressed in the subsequent paragraphs. All of these requirements affect energy efficiency. VAHTI, KATAKRI and FICORA have multiple requirements for security and redundancy. As a rule of thumb, the more redundant, the less energy efficient the data center is.

2.5.1 FICORA

FICORA is the Finnish Communications Regulatory Authority. It provides the regulation on resilience of communications networks and services. The regulation applies to the priority rating of the elements, redundancy, reserve routes, power supplies and physical protection. The regulation also applies to the resilience of the cooling systems. Regulation applies to operators and service providers. [46]

The applicable standard is FICORA 54B / 2014 M 17.12.2014 issued December 17th 2014. Rooms housing TeliaSonera operator equipment in the basement are subject to this regulation. These rooms have a rating one, which is the highest level. Equipment are serving common communication services to the public and therefore are subject to this highest level of security and resiliency [46]

According to TeliaSonera the following conclusions are drawn from FICORA authorities and prevail above the standard. The equipment has to operate even in the case of a building collapse. Short term power backup must be provided by means of batteries which need to last for three hours. Long term power backup can be provided by an external mobile generator which has to be placed outside the collapse zone of the building. A collapse zone is defined as the area around the perimeter of a structure that could contain debris if the building collapsed. This area is often defined by establishing a perimeter at a distance from the building that is equal to 1,5 times the height of the structure. Although not stated in the guideline, backup cooling needs to be provided as well. Both, external or internal cooling solutions are possible. It is reasonable to have three hours local cooling after which city water can be used. It is also possible to connect an external chiller to the building. [46]

S1 class structural strength is required when the rooms with critical operator equipment are below ground. According to the regulation the S1 class concrete with steel casing must hold 100 kPa (1 bar) stresses. This holds for the ceiling and the walls. The structural requirements also apply to the doors. As they are heavy to operate, they are normally left open. Additional doors will be installed for everyday use. Redundancy of electrical and mechanical infrastructure shall be N+1. N+1 redundancy is a form of resilience that ensures system availability in the event of component failure. Components (N) have at least one independent backup component (+1). The level of resilience is referred to as active or passive or standby as backup components do not actively participate within the system during normal operation. Redundancy is not required after a building collapse. There are no requirements regarding ventilation, pressure or smoke extraction. No back up ventilation will be provided. Fuel storage for one week or other arrangements that guarantee one week fuel supply is required. Grid-independent (under floor) water leakage detection system and dewatering system is required. The system has to work after a building collapse. [46]

2.5.2 VAHTI

Vahti is the Finnish 'Valtionhallinnon tietoturvallisuuden johtoryhmä' or the Government Information Security Management Board. The guideline describes reliability of operations, continuity, quality, risk management and preparedness, as well as promotes information security as an integral part of operations, management and administration. [46]

The applicable standard is Vahti 2/2013, issued May 17th 2013.

The entire basement with an exception of the FICORA rooms is subjected to these requirements. The minimum requirement is the Vahti II or 'enhanced level' and wherever reasonably conceivable the Vahti III or 'high level' requirements will be implemented. Although Vahti provides guidelines on resilience of cooling and power systems related to component or grid failure, it does not stipulate requirements for these solutions in the case of a building collapse. Therefore the guideline cares more for preserving information stored in the IT-rooms than operational continuity (in case of a building collapse). IT-room means the room where IT equipment resides. Hence, redundant cooling and power systems will not be installed as they are not specifically required. [46]

2.5.3 VAHTI and FICORA Comparison and Conclusions

Since the VAHTI and FICORA rooms are all in the basement it is relevant to pursue a generic solution for the entire basement. The basement will be subject to VAHTI regulations, including continuous operation of the ventilation equipment after a building collapse (required per VAHTI but not per FICORA regulations). FICORA regulations prevail above VAHTI regulations for equipment that are regulated according to FICORA legislation. This means that continuous operation of equipment has to be guaranteed for FICORA equipment only. For VAHTI-III equipment a shutdown is allowed although damage shall not occur. [46]

The entire basement will be constructed according S1 requirements. In practice this does not differ much from the VAHTI requirement of collapse proof structures. VAHTI-III and FICORA do require leakage detection and a dewatering system, although it is not explicitly stated the systems have to be active after a building collapse. The design includes these requirements due to the increased risk of leakages after a collapse. [46]

2.5.4 CSA Requirements

Built-in IT equipment facilities in cellars must be able to withstand loads caused by the building collapsing on top of it, with no damage being caused to the equipment. The ceiling and each peripheral wall must be assumed to be fully and independently load-bearing. Doors must be able to withstand these heavy loads as well. Doors, locks, apparatus, ducts, pipes and brackets together with other corrosion-prone parts and accessories must be protected from corrosion as appropriate. [46]

2.5.5 Mechanical, Electrical and Plumbing (MEP) Requirements

The basement area must be equipped with a drainage system which operates independently from the external electricity supply (i.e. connected to a backup generator). Piping below the raised floor is allowed since a drainage system will be put in place. Temperature of the IT-room should be between 20 and 26 degrees Celsius. Relative humidity range is 32-60%, with the set point at 50%. The IT-room must be held at overpressure after a building collapse and the ventilation equipment must be located in a separate fire compartment. Air intake and exhaust must be outside of the building collapse zone. Fresh air in the IT equipment facility must, in the first instance, be taken from outside the area of the structures that could collapse. The height of the air intake point above the horizontal surface should be at least 80 cm. Air must enter the air intake opening from below. [46]

Ventilation ducts must be provided with automatically operating fire dampers. Ventilation equipment must be fitted with gas and particle filters. Bypassing the chemical filters during normal operation when a gas detection system is used, is allowed. The detectors' sensitivity and reaction time must be such that the filters can be switched on based on the information from the detectors. Gas filtering is normally not required. It is sufficient to reserve space where the filtering can be put in at a later stage. An example of such situation is when the political escalation requires so. During filtration, the air current must be at least 0.9 dm3/s per actual square meter of the facility. It must be possible to use a ventilation system in an IT equipment facility to maintain excess pressure when the supply of air from outside is impossible. Nuclear or biological filtering is not considered. [46]

Sound insulation between rooms belonging to different security zones is required. Cooling and air conditioning equipment must be in a separate fire compartment. This holds for the generating equipment only. CRACs can be located in the same fire compartment as the IT equipment. Electrical equipment should be put in a separate fire compartment; however, it is allowed to put UPS devices and power distribution panels in the same room. The UPS has to operate as a direct filter between the electricity network and IT equipment. A DRUPS complies with this requirement. [46]

2.5.6 KATAKRI

KATAKRI is the authorities' auditing tool for ensuring compliance with the national security auditing criteria. It can be used in assessing an organization's ability to protect classified information. KATAKRI is also used as a tool in conducting a facility security clearance (FSC). [46]

The applicable standard is KATAKRI version 2015 issued March 26th 2015.

The regulation focuses on (national) security (protective requirements) rather than operational resilience (redundancy). Rooms in the basement may be subject to this regulation. These rooms will have protection level III (enhanced level or 'confidential') or level II (high level or 'secret'). [46]

Katakri defines structural requirements for design items such as walls, floors and ceilings. They must be concrete, steel, brick or strong wood. Doors must fulfil the SFS EN 1627 class standard and at the security zone border lock FK class three and safety lock FK class four. Within security zone lock FK class three is required. Windows under four meter height must fulfil at least SFS-EN 356 / P6B standard for level III. For level II, windows under four meter height and no skylight windows are not allowed. Soundproofing must prevent sound from carrying on to neighboring rooms, for example through cable ducts or air conditioning channels. Smoke ventilation channels must have intrusion detection and for level II they must also be protected by steel bars. Critical equipment must be UPS protected (HVAC). [46]

2.5.7 LEED

A gold level certification of LEED for Data Center Version 4 rating system is set as a preliminary target for the project. LEED Version 4 is the newest version of the globally recognized green building rating system, operated and the certification awarded by US Green Building Council. LEED for Data Center Version 4 certification is tailored to meet the data center specific requirements. LEED certification evaluates sustainability aspects of the building design and construction. It emphasizes energy performance but also responsible material choices, ecological construction work and the users' wellbeing. The compliance for LEED certification is verified by an independent third party USGBC. As the certification requirements are globally equal, certified buildings are internationally comparable. [46]

The gold level certification requires the project building to meet the minimum requirements and to acquire at least 60 points. LEED provides a set of requirements that provide points whenever a requirement is met. A preliminary study has been carried out in Sonera HDC against the design principles and 47 points were found achievable with minor investments. The amount of points still lacks the energy performance credits which are valuated when the first energy simulations of the whole building are done. The HDC project has a good opportunity to achieve high points from energy performance, as regulations in Finland are stricter than the American ASHRAE standards on which the criteria are based. LEED requires some additions to the HDC project which are normally not integrated in a data center design. These relate to site lay-out, material use, energy and water monitoring and efficiency. Although not complete, the ones which have a major impact on further design development are listed in the following chapters. [46]

Energy and Water Use Performance

Very high energy efficiency targets have been set for the HDC project. The energy consumption profile of data centers differs significantly from a conventional office or a commercial building as electricity consumption of IT system is remarkably high. The operation of data center generates a great amount of heat, hence the possibilities to provide the waste heat to a district heating grid must be examined. Early stage energy simulations will be carried out in order to find the most cost and energy efficient solutions for cooling systems. Renewable energy will also be generated at the site with photovoltaic solar panels which are installed to the available roof area. [46]

Enhanced metering and commissioning strategies are implemented to ensure energy performance of the project. Commissioning will cover all mechanical, electrical, plumbing, and renewable energy systems as well as the building envelope. Commissioning authority or team will review the design documents and contractor submittals, verify the system testing at commissioning stage, verify seasonal testing, develop an on-going commissioning plan and review building operation within ten months of completion. [46]

Indoor potable water use is limited with water efficient fixtures. With metering lavatory faucets and waterless urinals, over 40% water savings are pursued. Also an advanced water metering strategy is implemented. In case cooling is carried out with wet cooling towers, water efficiency and water use measurability will be set as an equipment requirement. Water usage for major components like sanitary blocks and cooling towers need to be sub-metered. A one-time potable water analysis needs to be conducted to determine the optimal number of water cycles for the cooling towers. Building level energy metering needs to be put in place and this data has to be shared with the USGBC during the first five years of operation. Sub-level metering has to be put in place for equipment that represents 10% or more of the total annual consumption. Though this data does not have to be shared with the USGBC the data does need to be remotely accessible. [46]

Refrigerants which have an ozone depletion potential (ODP) of 0 and a global warming potential (GWP) of less than 50 have to be used. If this is not feasible the environmental impact of the refrigerant has to be calculated. [46]

2.5.8 Certified Energy Efficient Datacenter Award (CEEDA)

CEEDA (Certified Energy Efficient Datacenter Award) is a certification scheme introduced by Datacenter Dynamics in 2014. It is aimed to improve performance and energy efficiency of data centers with the aid of a two year long benchmark and assessment cycle. There are assessment schemes for design and operation stages and for colocation facilities and enterprise facilities. Bronze, Silver and Gold certificates can be obtained. The certification scheme is rather new and the CEEDA prerequisites are still mostly unknown. CEEDA consultants have confirmed that a gold level is very achievable for this facility although the requirements and certification process remains vague at this stage. [46]

2.6 Challenges of Energy Efficiency in the Data Center

According to Energy Star November 2012 study "Understanding and Designing Energy-Efficiency Programs for Data Centers", there are many challenges in implementing energy efficiency solutions, to data center. Lack of knowledge and risk aversion is one challenge. IT managers demand high reliability for power and cooling systems. As a result, they may be doubtful towards projects that could affect reliability. They may also have misperceptions about the tradeoff between energy efficiency and performance. Vendors sometimes have a disincentive to encourage energy efficient measures. As an example, server virtualization and consolidation may reduce future sales of servers. Energy efficient equipment and related services cost more to purchase. This barrier is often experienced when the IT manager purchasing the equipment is not responsible for paying data center OPEX, which includes the electricity bill. [61]

In addition to these, energy efficiency program administrators face challenges in ensuring the investment in data center energy efficiency generates energy savings beyond what would occur naturally in this marketplace. Financial barriers related to the cost of energy efficient solutions and services are often incorporated with split incentives, created when the decision maker responsible for authorizing an energy efficiency project does not receive direct benefits from the project. In data centers, the most common split incentive is between the IT manager and the facility manager. The split incentive can occur because in some instances the IT manager, responsible for selecting and deploying IT equipment in a data center, typically makes financial decisions based on available CAPEX budget, and is not responsible for power usage or its associated costs. On the other hand the facility manager, responsible for power delivery, cooling systems, and related utility bills, primarily manages the operating budget and often cannot influence how the CAPEX budget is spent. [61]

Generally, in organizations where this kind of a situation is present, the IT manager seeks to stretch the CAPEX budget as much as possible, often by buying less energy efficient, lower cost IT equipment. This eventually leads to a cooling system or power delivery capacity shortfall, which must be rectified by the facility manager. The facility manager must overcome the capacity shortfall with limited CAPEX funding, as well as absorb the ongoing OPEX increases. [61]

Understanding market conditions and program implementation challenges is important for effective program planning and for developing a reasonable forecast of energy savings. Major challenges for data center program administrators are technical complexity, long lead times, and product production cycles associated with data centers, as well as the risk of free-ridership. All elements of data center operations are technically complex, because they use special purpose equipment with the goal of ensuring reliability. Generally, identifying energy-efficiency opportunities and accurately characterizing savings is best suited for engineers and technical experts who specialize in data center facilities and IT equipment. Program managers should evaluate whether their traditional technical services team has sufficient data center expertise to support the evaluation of cooling, power delivery, and conditioning systems and if so, whether using their staff in this capacity is effective. [61]

2.7 Summary of the Chapter

This chapter defines a data center and presents key components of data center architecture. It is important to understand the relation between different technologies that form the data center as a complete system. In addition it is important to understand data center as an investment and how the dilemma between the TCO of building an own data center relates to the TCO of utilizing PaaS or IaaS service models. This is by no means a trivial question and forming a rational decision includes the evaluation of many different attributes.

Energy efficiency is becoming a major factor when considering data center profitability. It is one of the major contributors to data center OPEX and the TCO of a data center. On top of this, carbon emission reduction is a target for the whole industry as such. Data centers are growing in size and in energy consumption intensity, a trend that needs to be addressed with sustainable solutions and metrics. Renewable energy sources have a significant role, but alone are not enough to address the whole challenge of ever increasing energy consumption. Data centers need a 24/7 resilient supply of power, which is not the nature of wind-, solar or other renewable energy production, as they vary as a function of time and circumstances.

The last part of this chapter presents the requirements and targets set for the TeliaSonera Helsinki Data Center. There are many security and data center facility requirements that need to be addressed but also many sustainability and energy efficiency certifications that the HDC is aiming for. Finally challenges when implementing energy efficiency solutions are presented in this chapter. These challenges include split incentives in solution vendor side and also in the IT management side. Energy efficiency programs include technical complexity, long lead times, and product production cycles associated with data centers.

In Chapter 3 GreenIT solution space is clarified. This is done in a structured literature review way.

3 LITERATURE AND RESEARCH ON GREEN IT DATA CENTER SOLUTIONS

The aim of this chapter is to clarify the GreenIT solution space by dividing it into five different parts which are presented in a hierarchical structure presented in Figure 6. The analysis starts from the largest energy consuming unit, the data center as a whole. Findings related to cooling and air conditioning of a data center are then presented. This is one of the most energy hungry domains in the data center and includes many alternative solutions to reduce their energy consumption. In the third part, energy efficient technologies for telecommunication networks with special focus on data center networks are introduced. There will not be mobile network specific solutions in this thesis even though they are very important from energy efficiency and energy consumption perspective. The fourth part focuses on energy efficient solutions for virtualization technology, as it is one of the main fundamental solutions to the increasing energy demand. The final part of this chapter investigates solutions for the smallest unit in the overall system, the processors. Although they are small and consume relatively little energy compared to bigger systems, they are massive in quantity. Processors are everywhere.

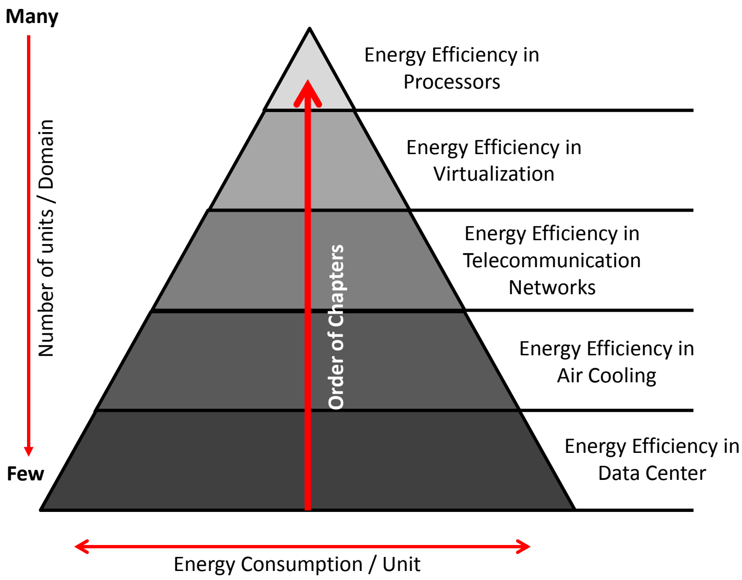


Figure 6. Previous literature and research structure on energy efficient solutions.

3.1 Energy Efficiency in Data Centers

In the European Code of Conduct (CoC), it was decided to ask participating companies to monitor their energy consumption and to implement a set of established best practices. For the purposes of the CoC, the term "data center" includes all buildings, facilities and rooms which contain enterprise servers, server communication equipment, cooling equipment and power equipment, and provide some form of data service. [8] A study by Nader Nada and Abusfian Elgelany point out that with a rapid increase in the capacity and size of data centers, there is also a continuous increase in the demand for more energy [13]. According to Paolo Bertoldi, et al, making data centers more energy efficient is a multidimensional challenge requiring a concerted effort to optimize power distribution, cooling infrastructure, IT equipment and IT output [8].

In Figure 7, the critical points where energy is lost or wasted are presented. The system receives energy and after processing it provides completed tasks. Energy is mainly wasted during idle times and on redundancy assurance. Energy is lost when it is not consumed by any of the subsystems or it is working as an overhead for supporting the system.

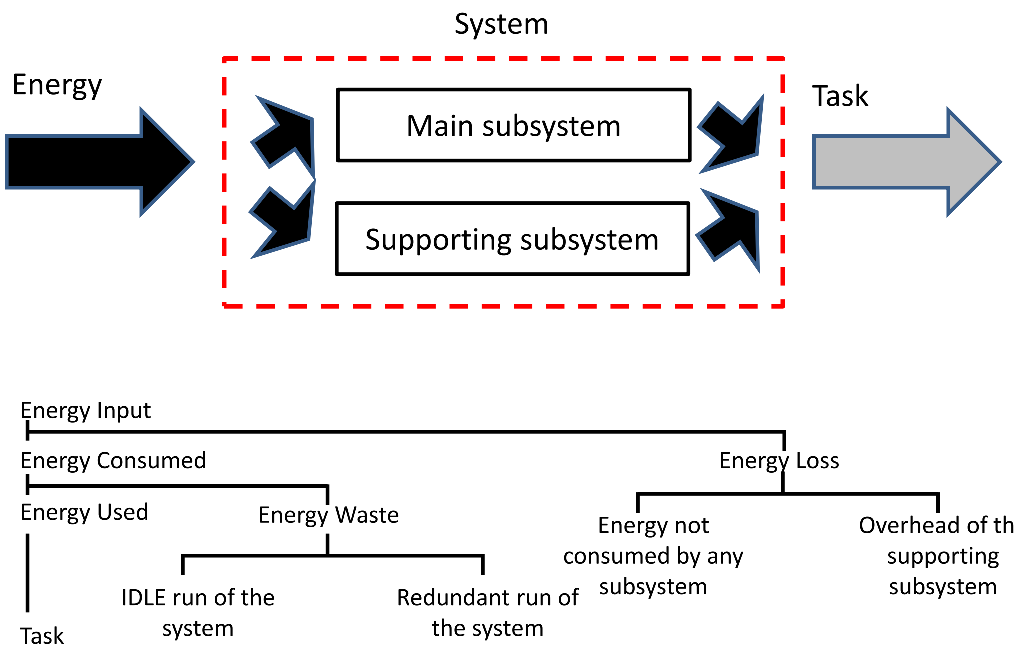


Figure 7. Critical points within a system where energy is lost or wasted. [19]

Data center energy costs and environmental impacts are dynamic challenges to cloud computing [13]. The ability to have a variable cost instead of a fixed cost or asset will provide a growth platform for innovation and experimentation on different business models [41]. Electrical power usage is not a common design or decision criterion for data centers, nor is it effectively managed as an expense. This is true despite the fact that the electrical power costs over the lifecycle of a data center may exceed the costs of the electrical power system including the UPS, and also may exceed the cost of the IT equipment. [4]

A typical data center configuration is usually a facility with several rows of server racks. Each row comprises of several racks (cabinets), each rack contains several chassis, and each chassis contains multiple blade servers. Modern data center is designed in a hot aisle/cold aisle style. [24] A power transfer system safely manages energy sources by isolating the electricity from different sources and by ensuring that the data center gets enough power [25]. Automatic transfer switches (ATS) are connected to primary and secondary power sources. If primary source falls below a preset threshold the ATS disconnects from the primary source and connects to a secondary energy source. When the primary source is functioning again, it switches back to it. UPS ensures continuous power delivery to the actual computing equipment. [25]

Computing and storage capacities of data centers are continually increasing, made possible by advances in the underlying manufacturing process and design technologies available. An unwanted side effect of such capacity increase has been the rapid rise in energy consumption and power density of data centers. [24] This means that by reducing energy consumption one can reduce the power capacity related costs as well as the energy costs [3]. The key point here is that there are two kinds of energy consumption reductions: those reductions that avoid energy consumption, but do not reduce power capacity requirements, and those that also allow the reduction of installed power capacity. Energy use reduction without reducing installed power capacity is "temporary consumption avoidance", and those that allow the reduction of installed power capacity is "structural consumption avoidance". [3] Economies of operating a data center are comprised by four main factors that contribute to the TCO. They are the following: [15]

- *Resiliency:* Meaning that the cost is derived from the level of redundant infrastructure built into a data center [15].
- *Downtime:* Meaning that the cost of downtime is drastically different among different types of businesses and facility design considerations should reflect this [15].
- *Financial considerations:* Financial factors include aspects of site selection, cost segregation, capital recovery factor, staffing costs, and internal rate of return (IRR) [15].
- *Vertical scalability:* This means cloud computing type of elasticity capabilities incorporated into data center infrastructure and available floor space. A good example is the increasing power and cooling densities without disrupting the data center operation [15].

An energy efficient data center is one where the inlet air to all the systems is maintained at a specified temperature, typically 25 °C, and the exhaust hot air at 40 °C. The exhaust hot air is prevented from mixing with incoming cold air and is driven back to the air conditioning units. [27] The air conditioning resources are also set, by virtue of vent tile openings, and other variable settings, to deliver proper mass flow for a given geometric distribution of heat loads [27]. An energy efficient smart data center operates through a pervasive sensing layer - a network of hundreds of temperature sensors at the inlet and outlet of the servers in the racks [27]. A data center management system, based on high level thermo-fluids policies, enables the automated dynamic provisioning of air conditioning resources and distribution of the compute workloads for power management. Thus, the "smart" data center manages energy as a critical resource and maintains the data center in a provisioned state completely in balance with the heat loads. [27]

Figure 8 illustrates the Green Cloud architectural elements. On the bottom layer there are the physical machines with power on or power off capability. On top of the physical infrastructure resides the virtual machine layer. It is responsible for maintaining the virtual machines operational. The green service allocator includes the “brains” for generating energy efficient decisions, consolidating and scheduling VMs to different physical servers and taking care of the accounting for the services. It is also the interface towards the customers.

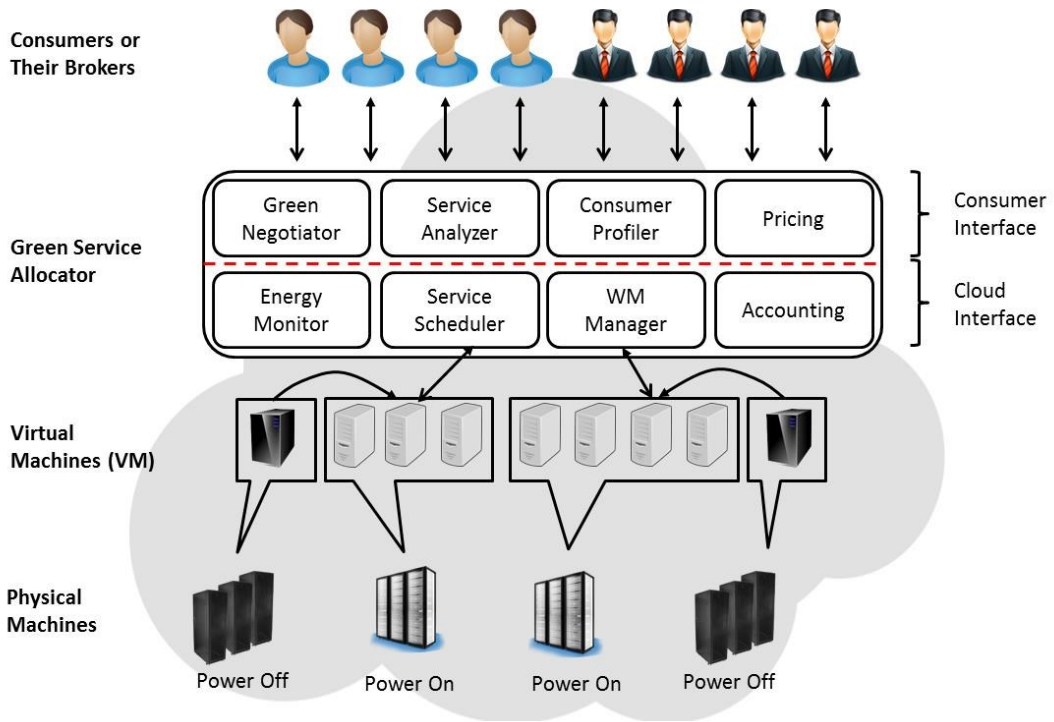


Figure 8. Green Cloud architectural elements. [12]

The modern data center management system determines the admission policy of the tasks at different times and affects the energy consumption of a data center. It also sets the revenue of the data center in the case of hosting data centers and determines the performance levels for the served tasks. A management system affects the reliability of the data center and determines the life time of devices used in the data center. [15]

Large-scale data center practices provide few key benefits. Firstly, server, networking, and administration costs for a cloud provider are five to seven times lower than those for an average private provider. Secondly, the actual cost of power consumed by the servers plus the cost of cooling the servers is 34% of the total cost of ownership of a data center, where as amortized server costs during a 10-year lifetime of a data center form 54% of the total cost. [15] Thirdly, switching off a server is not as economically prudent as using the server with full capacity at all times. This can be exploited by using a spot pricing model. [15]

An energy proportional data center means that a global power manager controls the operational status of servers to supply sufficient computing capacity to handle the current demand, cutting energy usage by hibernating redundant servers. A reduction in computing capacity can impact service quality. [32] There are two ways to reduce the cost of energy consumed in data centers. The first method is to use efficient placement algorithms to reduce the energy consumption. These algorithms could operate inside a single data center (for example, deriving more efficient routing algorithms to reduce the power consumption in data center network switches) or across data centers. Examples of such algorithms are Data center Energy efficient Network-aware Scheduling (DENS), VMPlanner and VM Consolidation algorithms, presented by Buyya, et al. [20]

DENS methodology minimizes the total energy consumption of a data center by selecting best-fit computing resources for the execution of a job, based on the load level of the servers and communication potential of the data center components. The DENS methodology is meant for a three-tier data center architecture. The three tiers are namely the core network, the aggregation network and the access network. [20] The second method is to move the applications to data centers located in areas where cost of energy is relatively low. [20] While current algorithms can bring substantial savings in energy consumption, they do not take availability into consideration. For example, if a workload fits into a single server, current algorithms will result in consolidation of all applications into a single physical server, compromising availability. [20] Energy efficient data center algorithms mainly fall into two classes. VMPlanner is a combination of VM placement and network routing algorithm. Virtual Machine (VM) placement algorithms attempt to consolidate VMs onto the fewest number of servers. Efficient network routing algorithms attempt to do energy efficient routing by consolidating the network traffic onto the smallest number of links. [20]

Figure 9 presents the Green Cloud architecture. There are four main blocks in this architecture. To the right, there is the managed environment, which includes applications, VMs, physical machines and real time power meter. It is controlled by the migration manager, which is responsible for scheduling and on/off powering control. The monitoring services block illustrates utilization workloads, on/off status and power consumption. Everything is managed through one user interface. The idea of a Green Cloud is to utilize simulations efficiently.

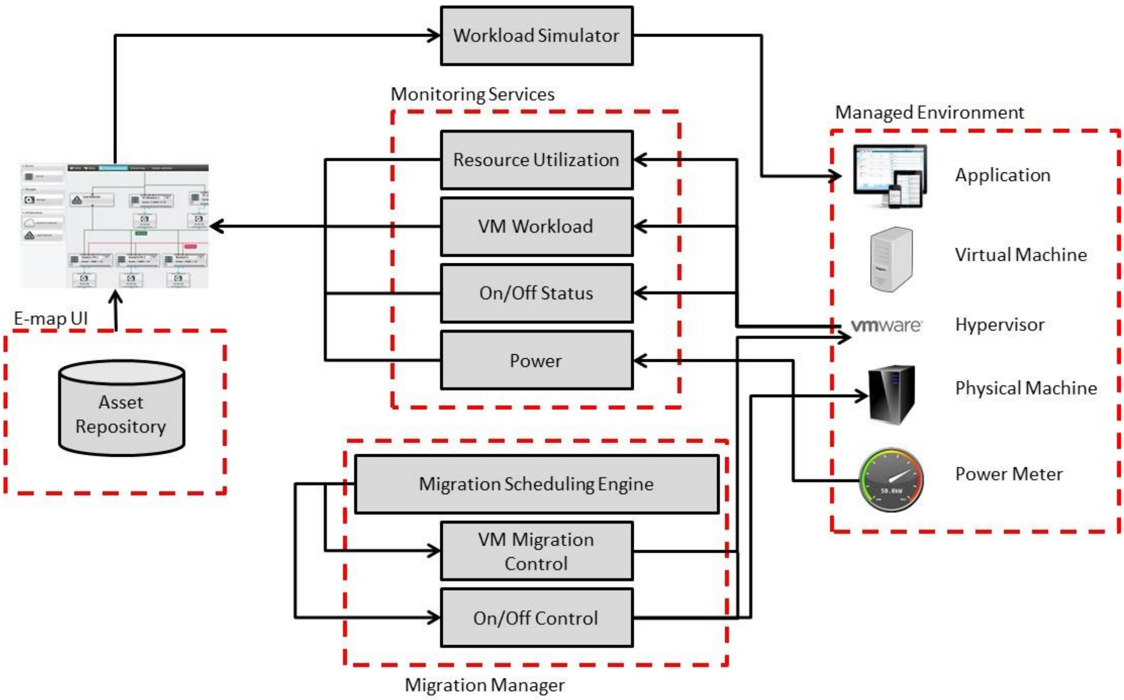


Figure 9. Green Cloud architecture. [22]

There are also a number of different techniques currently employed in non-energy-proportional data centers to reduce the energy cost and power density [24]. One of them is load balancing, which is used to distribute the total workload of the data center between different servers evenly, in order to balance the per server workload and achieve uniform power density. [24] Server consolidation is also used to assign incoming tasks to the minimum number of active servers in the data center and shutting down unused servers [24]. It is important to note that a watt saved in typical data center power consumption saves at least a watt in cooling, this is naturally dependent on the PUE value of the data center [29].

Cloud service providers typically own geographically distributed data centers. This means that they can distribute workloads among geo-dispersed data centers to benefit from the location diversity of different types of available renewable energies [34]. Cloud data centers support wide range of IT workloads. One type of workload includes delay-sensitive non-flexible applications, such as web browsing. Another type of workload includes delay tolerant flexible applications, such as scientific computational jobs. Workload flexibility can tackle the challenges in integrating intermitted renewable energy. This is achieved by delaying flexible workloads to periods when renewable sources are abundant without exceeding their execution deadlines. [34] Data centers are usually equipped with uninterrupted power supplies (UPS) in case of power outages. Since UPS systems are usually over-provisioned, UPS can store energy during periods of high renewable generation and supply power when renewable energy is insufficient. [34]

Existing research ideas for improving data center energy efficiency include for example the following topics: Zhiming Wand, et al, proposed a mechanism to support maximizing resource utilization by using active and idle energy consumption by finish time minimization. The mechanism reduces power consumption by allowing spare servers to be in an idle state. [13] Rajkumar Buyya, et al, proposed a novel mechanism with three stages. Firstly, there should be architectural principles for energy efficient management of clouds. Secondly, there should be energy efficient resource allocation policies and scheduling algorithms which consider QoS and the device´s power usage characteristics. Thirdly, a novel software technology is required for energy efficient management of clouds. Automation and control systems are a necessity. [13]

Anton Beloglazov, et al, developed a unique mechanism which supports dynamic consolidation of VMs based on adaptive utilization thresholds that take into account Service Level Agreements (SLA). [13] Nguyen Quang Hung, et al, proposed a server selection policy and four algorithms solving a lease scheduling problem. Lease scheduling problem addresses a challenge which is to allocate and schedule computing resources in a way that providers achieve high resource utilization and users meet their applications' performance requirements with minimum expenditure. This approach reduces energy consumption by 7,42% compared to the existing greedy mapping algorithm. [13] Uddin, et al, introduced a framework to improve the performance and energy efficiency of data centers. They developed a classification mechanism for data center components depending on different resource pools and parameters, such as energy consumption, resource utilization and workload. The framework highlights the importance of implementing green metrics to data centers in terms of energy utilization and carbon dioxide (CO_2) emissions. [13] S. Kontogiannis, et al, developed a mechanism called Adaptive Workload Balancing Algorithm (AWLB) for cloud data center based web systems. The AWLB ensures optimal workload distribution based on the discovered application requirements and measured resource parameters. The AWLB algorithm also supports protocol specification for signaling among network switches and data center nodes, and utilizes other protocols such as SNMP and ICMP for its balancing process. [13]

Current emphasis to reduce data center construction and operating costs is directing focus to seek for alternatives to conventional ways of doing things. The so-called modular data center first appeared in 2007 as Project Blackbox. [18] A modular data center is defined as more of an approach to data center design that incorporates contained units, many times in the form of prefabricated modules. Modular data center can reduce the construction and operational costs. [18] Dividing the tops of the racks increases the pressure loss of the server fans. The pressure loss and server fan power are proportional to the square and cube of the air volume inside rack, respectively. Project Blackbox also proposed an outside air fans and louvers on top of the racks instead of the partition. [18]

The input power in the data center is divided into an in-series path and an in-parallel path to feed the switchgear and the cooling systems. [29] At the switchgear, UPS and Power Distribution Units (PDU) power losses in the form of thermal heat occur due to AC/DC/AC conversions. A typical UPS present an efficiency of 80%. The useful work of a data center is associated to a percentage of power; typically less than 30% is delivered to IT equipment. [29] Current systems operate at high fixed power dissipation levels while busy or idle. The typical range of power between these two states is maximum at busy to approximately 60% of that maximum at idle. Systems with multiple power states substantially lower power dissipation when idle or when executing low performance workloads are needed. [27]

3.2 Energy Efficiency in Air Cooling

Energy has to be managed as a resource in a data center. There is a need for a global management system that dynamically deploys cooling resources in a data center based on dynamic heat load distribution, and deploys the heat loads or compute workloads based on the most energy efficient cooling configuration in the room. [27] The basic idea in a data center is to deliver cold air under an elevated floor. [38] Heated air forms hot isles behind the racks, which get absorbed by air conditioning intakes. Air enters the rack from the front and exits from the back. [38] According to Anton Beloglazov and Rajkumar Buyya, an insufficient or malfunctioning cooling system can lead to overheating of the resources, reducing system reliability and device lifetime. [33]

From the thermodynamic perspective, heat dissipation and energy efficiency can be optimized for an isolated system. Data centers are not closed systems. This is the reason why it is difficult to optimize. As a consequence, the mixing of cooling streams and heat sources at different temperatures complicates heat transferring and fluid mechanics. A reason for overprovisioning is commonly to apply closed system methods to an open system design. This usually leads to oversizing the cooling capacity and it affects the control of cooling resources. Airflows are in dynamic interconnection in an open system. [27] Another common reason for over-sizing is the demand for more and faster computing resources, as well as higher uptimes. This risk avoidance is increasingly forcing data center consultants and facility engineers to overprovision the cooling resources when designing new data centers. [11] Another reason is that cooling resources are overprovisioned to cover for a worst case scenario. [26] In data centers, air conditioners are the largest consumers of power for cooling purposes. Thermal distribution implicitly correlates with energy costs of a data center and it is essential to optimize [38] [28].

There are two main systems for data center air conditioning; the Heating Ventilation Air Conditioner (HVAC) and Computer Room Air Conditioner (CRAC), both are needed. In computing and especially in enterprise data centers, HVAC systems control the ambient environment (temperature, humidity, air flow and air filtering) and must be planned for and operated along with other data center components such as computing hardware, cabling, data storage, fire protection, physical security systems and power. Cooling is performed by the CRAC unit. Hot air transfers its heat to a cold substance, typically cold water or air, while passing through a pipe in the CRAC unit. When cold enough, the air enters a room via CRAC fans. The heated substance is directed to a chiller for cooling. [24] The efficiency of the cooling process depends on different factors. These factors include for example the substance used in the chiller and the speed of air exiting the CRAC unit. Coefficiency of performance (COP), which is a term used to measure the efficiency of a CRAC unit, is designed as the ratio of the amount of heat that is removed by the CRAC unit (Q) to the total amount of energy, that is consumed in the CRAC unit to chill the air (E). [24]

$$COP = \frac{Q}{E} \quad (2)$$

In order to reach significant increase in energy efficiency, successful and effective thermal management strategies must be implemented. This in turn reduces the total operational cost of a data center. [28] Local variations in heat flow and server heat generation impact the efficiency of cooling in different places within the data center [26]. To overcome these challenges a Dynamic Smart Cooling (DSC) is introduced. It is a set of real-time control systems, which can directly manipulate the distribution of cooling resources throughout the data center according to the needs of the computer equipment. DSC uses a network of temperature sensors at the air inlet and exhaust of equipment racks. Data from the sensors is fed to a controller where it is evaluated. The controller can independently manipulate the supply air temperature and airflow rate of each CRAC in the data center. [26] In order to accomplish this efficiently, the impact of each CRAC in the data center must be evaluated with respect to each sensor. The result of such an evaluation will define the regions of influence of each CRAC unit. This information is used to determine which CRACs to manipulate when a given sensor location requires more or less cool air. DSC systems have been shown to operate much more efficiently than traditional control systems which contain sparse temperature sensing, usually only at the inlet of each CRAC, and rudimentary operating algorithms that do not consider local conditions. [26]

3.3 Energy Efficiency in Telecommunication Networks

Telecommunications sector as a whole accounts for approximately 4% of the global electricity consumption. Capacity issues and delivery of complex real time services are some of the main concerns that yield high power consumption patterns in networks. Telecommunication networks constitute a major sector of ICT, and they undergo a tremendous growth. [29]

On average, there are 14 hops between a cloud provider and end user on the Internet. In practice, it means there are 13 routers involved in forwarding the user traffic, each consuming from tens of watts to kilowatts. [3] Neglecting the core network operation, fixed line networks suffer energy losses due to cable transmissions, switching and routing, broadband access and data centers. Mobile networks consume much energy especially for base station operations [29]. The losses are due to cooling processes of electronic equipment, over sizing of non-critical components and inefficient data manipulation and workload management [29]. Main functionality of a network can be summarized as the process of regeneration, transportation, storage, routing, switching and processing of data. [29]

The main factors which create energy efficiency in the networks are presented in Figure 10. All of these aspects are covered in this thesis.

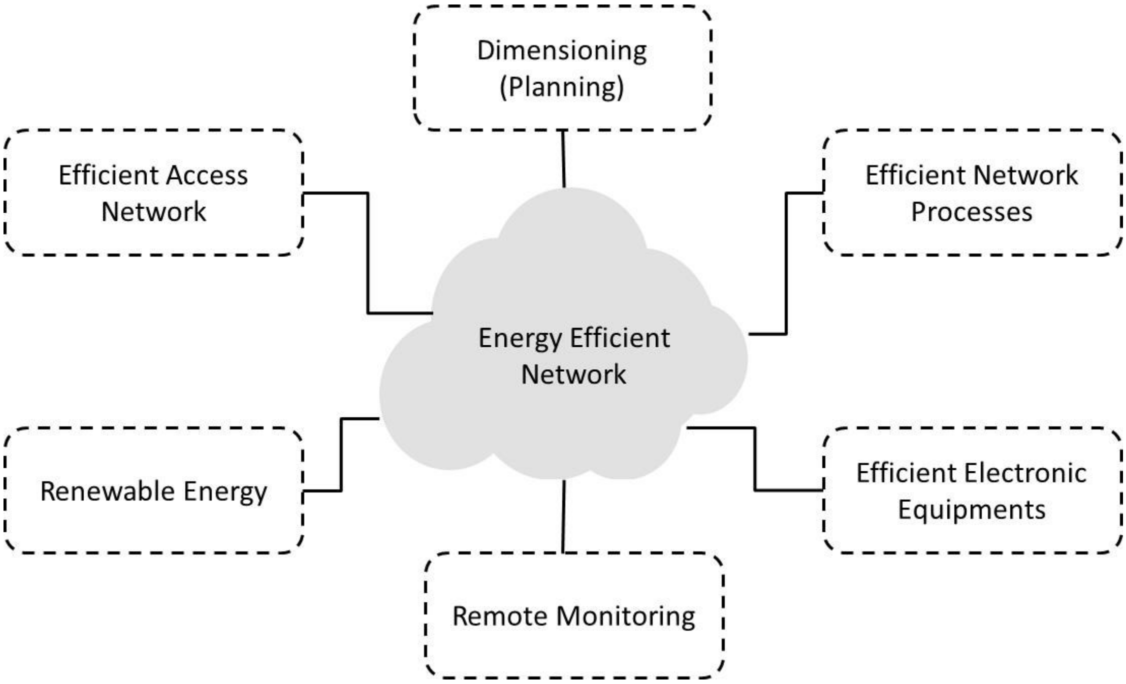


Figure 10. Main factors of energy efficient networks. [29]

As far as the overall network performance is concerned, energy consumption is higher at the access part of the network, and in the operation of the data centers, which provides computation, storage, applications and data transfer in a network. [29] In Figure 11 is a topology of a typical data center network. [4] It is a three layer network that includes edge, aggregation and core devices. All devices are secured with two alternative links for redundancy purposes.

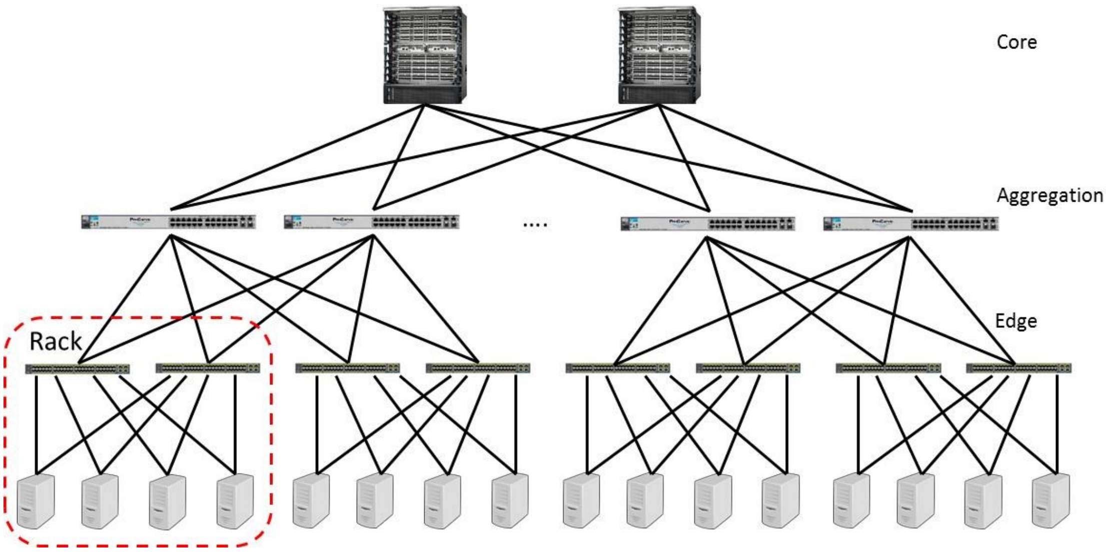


Figure 11. A typical data center network. [4]

Managing a network to operate in a green manner is a complex task. Optimizing energy consumption in one part can increase power consumption and degrade performance in other parts of the network. It is a systemic challenge. Total network optimization is better than the sum of optimizations of individual parts. [29] There are six key steps in network energy efficiency. These steps are: efficiency optimization, efficiency to network dimensioning, efficiency at access network, efficient electronic equipment, use of renewable energy sources (RES) and remote monitoring of the network for better management of the equipment, as presented in Figure 10. [29] Energy efficiency architecture should focus on intelligent and efficient access techniques and efficient operation and data manipulation by data centers. The largest amount of energy is consumed by routing and switching, the regeneration and processing of data. On the other hand, backbone and aggregation networks present lower energy demands. [29] Optical fibers are considered as the best fitted solution for energy saving, at the same time providing high data rates. [29] General strategies identified for improving energy efficiency are; sleeping mode / switching off, traffic consolidation, virtual machine consolidation, optical devices, energy-aware routes, traffic patterns, traffic locality, energy-aware devices, heat minimization, traffic minimization and green energy. [21] Figure 12 presents some key solutions for energy efficient networks. There are plenty of technologies to every part of the network, the list is not inclusive.

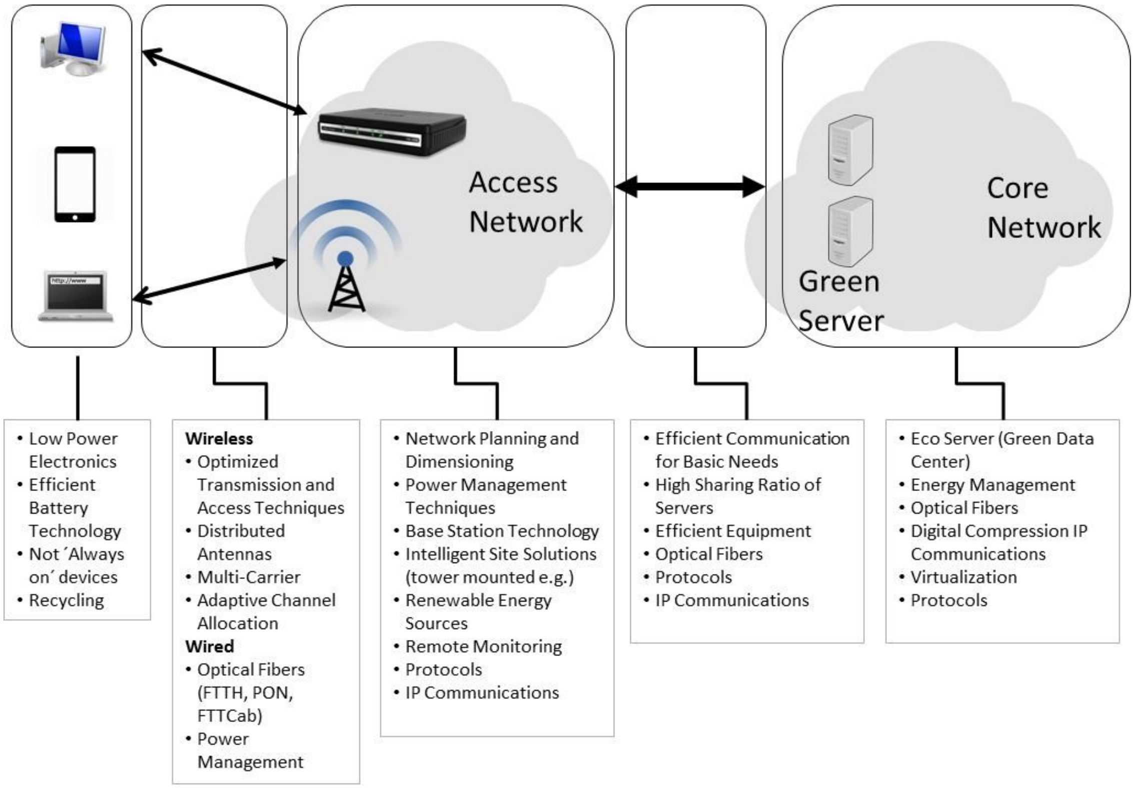


Figure 12. Energy efficient solutions of telecommunication networks. [29]

Energy proportional data center networks are being studied heavily. [16] As servers themselves become more energy proportional, the data center network can become a significant fraction (up to 50%) of the consumed cluster power. There has been a demonstrated power reduction of 85%, which approaches the ideal energy-proportionality of the network. [16] There is a significant power advantage to having independent control of each unidirectional channel comprising a network link, since many traffic patterns show very asymmetric use. System designers should work to optimize the high-speed channel designs to be more energy efficient by choosing optimal data rate and equalization technology. [16] Unfortunately todays network elements are not energy-proportional: fixed overheads such as fans, switch chips, and transceivers waste power at low loads [4]. Maximum efficiency comes from a combination of improved components and improved component management [4].

Shang, et al, proposed a power-aware interconnection interworking that utilized Dynamic Voltage Scaling (DVS) links. DVS technology was later combined with Dynamic Network Shutdown (DNS) to further optimize energy consumption. [3] The design for these power-aware networks when on/off links are employed is challenging. There are issues with connectivity, adaptive routing, and potential network deadlocks. [3] Because a network always remains connected, such challenges are not faced when using DVS links [3]. A proactive approach is necessary for on/off procedures [3].

There are three different energy efficient topologies available. Firstly there is the flattened butterfly (FBFLY), which takes advantage of recent high port count switches to create a scalable, yet low-diameter network. This is accomplished by making a deliberate tradeoff of fewer links at the expense of increased routing complexity to load balance the available links. [16] FBFLY uses less hardware than comparison topologies with equivalent size and performance. As the number of switch chips dominates the power consumption of a network, power levels can be further reduced by adding plesiochronous links. [16] There is significant advantage to having independent control of each unidirectional channel comprising a network link, since these channels typically see asymmetric use, and ideally, high-speed channels typically evolve to be more energy-proportional themselves. For example, a link operating at 2,5 Gb/s should consume proportionally less power than a link operating at 40 Gb/s. [16] Figure 13 shows an 8-ary 2-flat FBFLY topology. Each square in the figure represents a switch, and each of the eight switches interconnects with the other seven switches. In addition, each switch links with eight host nodes. A k-ary-n-flat flattened butterfly is constructed from a k-ary-(n-1) flattened butterfly and a k-ary-2 flattened butterfly. For instance, an 8-ary 3-flat FBFLY can be constructed by copying the 8-ary 2-flat Eight times, then interconnecting each switch in one group with the corresponding seven switches, one in each of the other seven groups. [42] Flattened 8-ary 2-flat topology is proposed as a cornerstone for energy-proportional communication in large scale clusters with 10 000 servers or more [16].

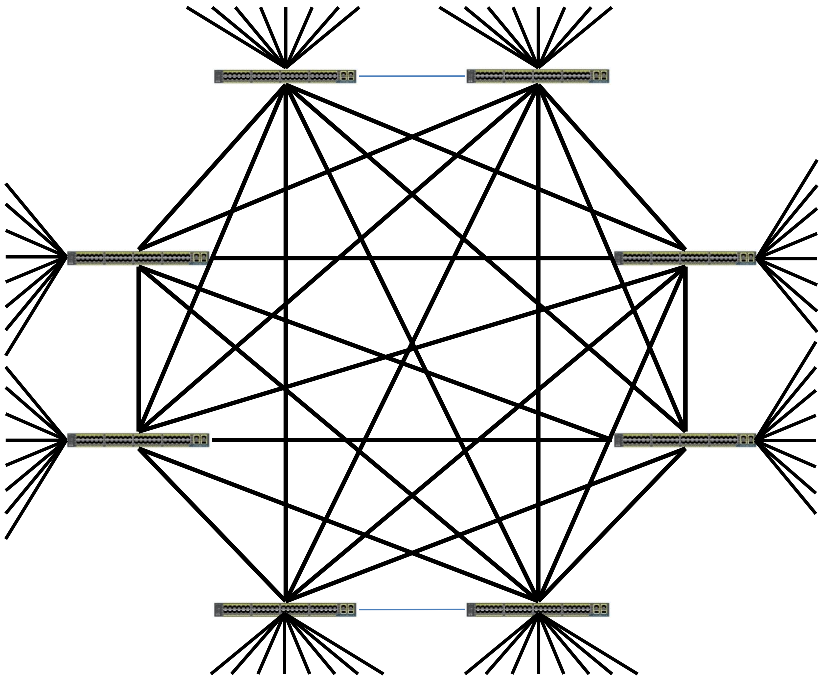


Figure 13. 8-ary 2-flat flatted butterfly (FBFLY) topology. [42]

As a second energy efficient topology there is the elastic tree [4]. It includes a network wide power manager, which dynamically adjusts the set of active network elements, links and switches to satisfy dynamic data center traffic loads. [4] Monitoring and management platform continuously evaluates the data center traffic conditions, and chooses the set of network elements, which must stay active to meet performance and fault tolerance goals; then it powers down as many unneeded links and switches as possible. [4] The Strategy is clear: turn off the links and switches which one does not need right now, in order to keep available only as much networking capacity as is required. [4] In elastic tree topology, three logical modules are needed - optimizer, routing, and power control [4]. Figure 14 presents the elastic tree main modules.

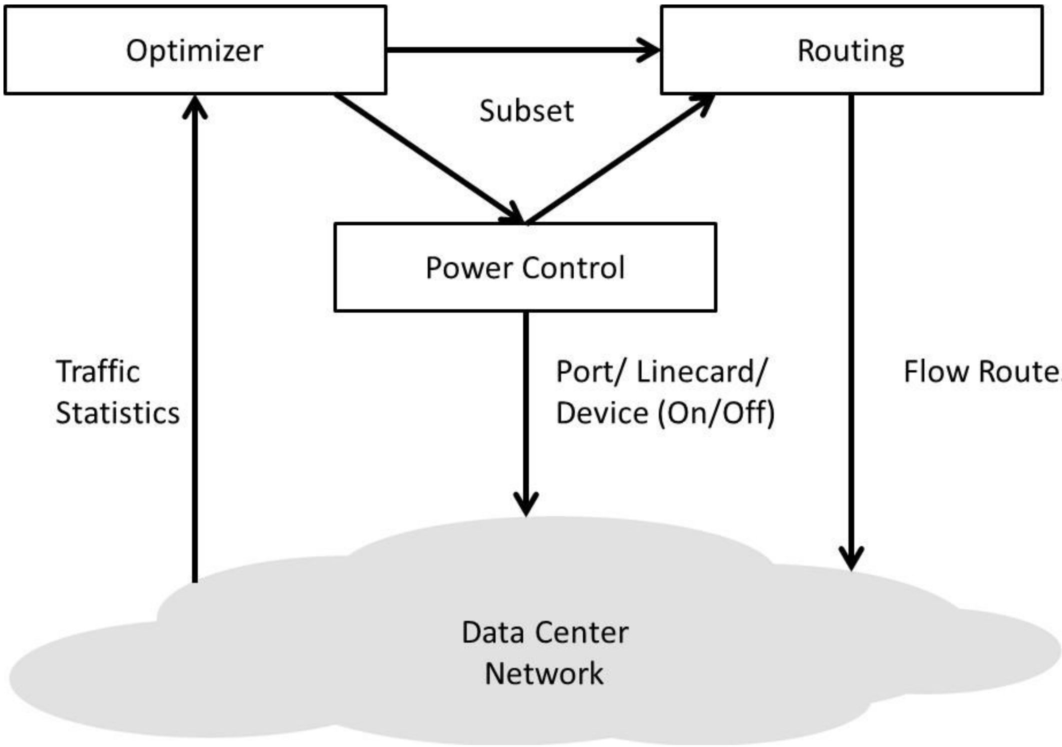


Figure 14. Elastic tree system diagram. [4]

The role of the optimizer is to find the minimum-power network subset which satisfies current traffic conditions. Its inputs are topology, traffic matrix, a power model for each switch, and the desired fault tolerance properties. Fault tolerance includes spare switches and spare capacity. The optimizer outputs a set of active components to both power control and routing modules. Power control module toggles the power states of ports, linecards, and entire switches, while routing chooses paths for all flows, then pushes routes into the network. [4] Figure 15 illustrates the elastic tree topology. It has a reduced active fault tolerance.

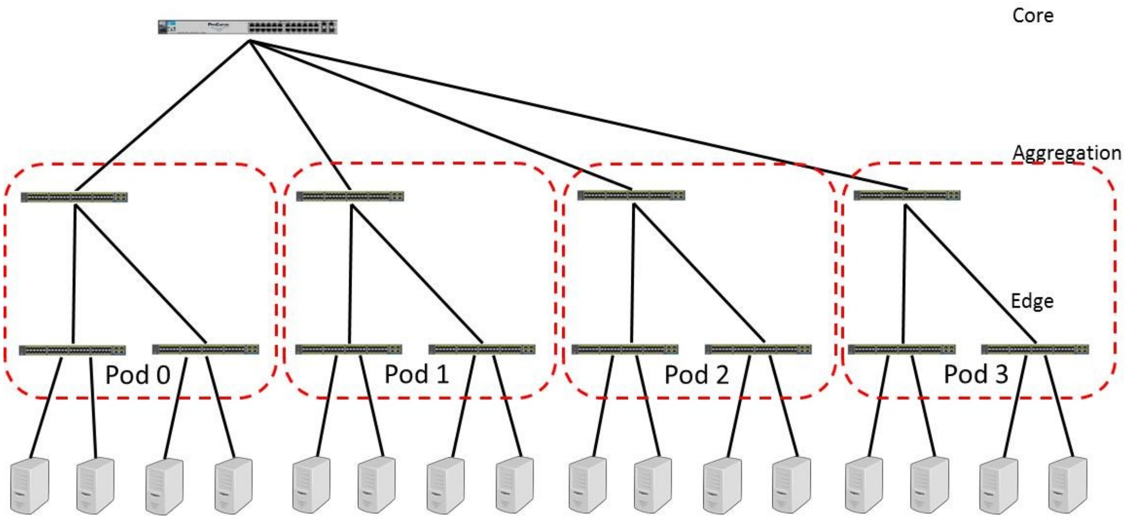


Figure 15. Elastic tree topology. [4]

As a third energy efficient topology there is the fat tree topology [4]. It is built from a large number of richly connected switches, and can support any communication pattern including full bisection bandwidth. Traffic from lower layers is spread across the core, using multi-path routing, valiant load balancing, or a number of other techniques. [4] The simplified idea is presented in the Figure 16.

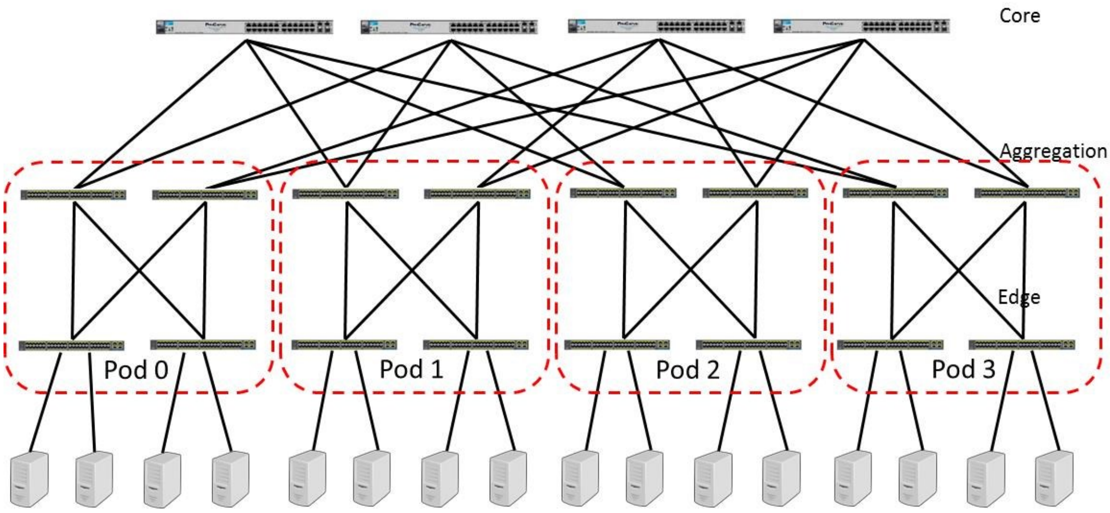


Figure 16. Fat tree topology. [4]

DENS technology in networking takes the potential communication needs of the components of the data center into consideration along with the load level in order to minimize the total energy consumption. This is done by selecting the best-fit computing resource for job execution. [3] Communication potential is defined as the amount of end-to-end bandwidth provided to individual servers or group of servers by the data center architecture. Load balancing becomes the key enabler for saving energy [3].

The performance of cloud computing applications, such as gaming, voice and video conferencing, online office, storage, backup, and social networking, depends largely on the availability and efficiency of high-performance communication resources. For better reliability and low latency service provisioning, data resources can be replicated closer to the physical infrastructure, where the cloud applications are running. A large number of different replication strategies for data centers have been proposed in the scientific research. [3]

3.4 Energy Efficiency in Virtualization

Virtualization has become the de-facto way of organizing computing in modern data centers. Main reasons for this development are: virtualization reduces hardware in use, it allows new business models like pay-as-you-go charging, it reduces costs, it improves resource utilization, [37] and it is easing server management. [2] [37] [39] Instead of incurring high upfront CAPEX in purchasing IT infrastructure and dealing with the maintenance and upgrades of both software and hardware, organizations can outsource their computational needs to Cloud service providers [2] [6]. The reason for extremely high energy consumption is not just in the amount of computing resources used, and the power in-efficiency of hardware, but rather the reason lies in the inefficient usage of these resources [2]. Data collected from over 5 000 production servers over a six-month period showed that on average, servers operate only at 10-50% of the full capacity most of the time, leading to expenses on over-provisioning, and thus extra Total Cost of Acquisition (TCA) [2]. On top of the previously described challenges, servers consume 70% of maximum full capacity power consumption even if idle [2] [37].

The most commonly used commercial virtualization platforms are VMware, Xen, KVM and Open VZ [37]. Similarly the most common open source platforms are Eucalyptus, OpenNebula, ECP (Anomaly Elastic Computing Platform), Virt and Nimbus. [37] Virtualization rests on top of blade servers, which are high performance and low cost [38]. Blade servers are compact in size [38].

Thus being a very promising technology from many perspectives, virtualization also presents some challenges. The main challenges according to Anton Beloglazov and Rajkumar Buyya are related to service level agreement issues, quality of service issues and energy saving features. [39]

One main energy efficient technology that virtualization introduces is live migration [39]. Live migration allows dynamic reallocation of virtual servers and uses a minimum amount of physical nodes and switches [2] [37] [39]. Efficient resource management in a cloud is not a trivial task, as modern service applications often experience highly variable workloads causing dynamic resource usage patterns. Therefore aggressive consolidation of VMs can lead to performance degradation when an application encounters an increasing demand resulting in increased resource usage. [2] Cloud providers have to deal with the energy/performance tradeoff [2]. Some key challenges that live migration technology is facing are for example placing of new VMs, bin-packing problems, challenges with variable bin size and variable bin costs. The bin-packing problem means that objects of different volumes must be packed into a finite number of bins or containers each of volume V in a way that minimizes the number of bins used. [39] One of the solutions to overcome these challenges is the best fit decreasing algorithm (BDF) and the modified BDF. [39] They are responsible for optimizing current VMs, selecting VMs that need to be migrated and for placing VMs based on Modified BDF. [39] Heuristics are the most essential components for selection and decision processes. Some of the most famous heuristics are dynamic utilization thresholds, single threshold (ST), and upper and lower utilization thresholds. The minimization of migrations (MM) heuristic migrates the least number of VMs to minimize migration overhead. Highest Potential Growth (HPG) heuristics migrate VMs that have the lowest usage of CPU relative to requested in order to minimize total potential increase of the utilization and SLA violation. Random choice (RC) heuristics chooses the necessary number of VMs randomly. [39] These together with memory compression technology are used to reduce the amount of data transmitted in the migration process. [37] All of these offer significant power savings to data centers.

Another main technology for energy efficiency is the Virtual Power Management (VPM). VPM provides states, channels, mechanisms, and rules to map soft power state to the actual changes of the underlying virtualized resource. [37] VPM is location independent [33].

Nathuji and Schwan have proposed architecture of an energy management system for virtualized data center, where resource management is divided into local and global policies [2]. Consolidation of VMs is handled by global policies that apply live migration to reallocate VMs [2]. Kusic, et al, has stated the problem of continuous consolidation as a sequential optimization and addressed it using Limited Lookahead Control LLC. Alternative to these is heuristic-based, allowing a seasonable performance even for large scale. [2] It is a novel technique for auto adjustment of the utilization thresholds based on a statistical analysis of the historical data collected during the lifetime of VMs. [2]

Other ways to effect energy efficiency include the Dynamic Voltage and Frequency Scaling (DVFS), terminal servers and thin clients [33]. Server energy consumption costs can be cut down significantly by utilizing low-power, high energy saving inactive power modes during idle periods of utilization [30]. However inactive power modes cannot be used in an ad hoc fashion as there are significant latencies associated with the power state transitions. Effective usage of inactive power modes mandates presence of significantly long periods of idleness in the system. [30] The rationale for leaving computers idle is often justified by service level agreements that require operators to deliver services within certain limits. These idle computers then remain waiting for a possible increase in user demand to handle the computing requirements of additional workload while maintaining the quality expected by the users. [30] As a result, a typical data center has a peak utilization of only 40% with long low-demand periods, some of which with utilization level as low as 5%. Figure 17 illustrates the VM based energy efficient architecture for cloud computing. There is the management module and monitoring module and the actual virtual/physical infrastructure.

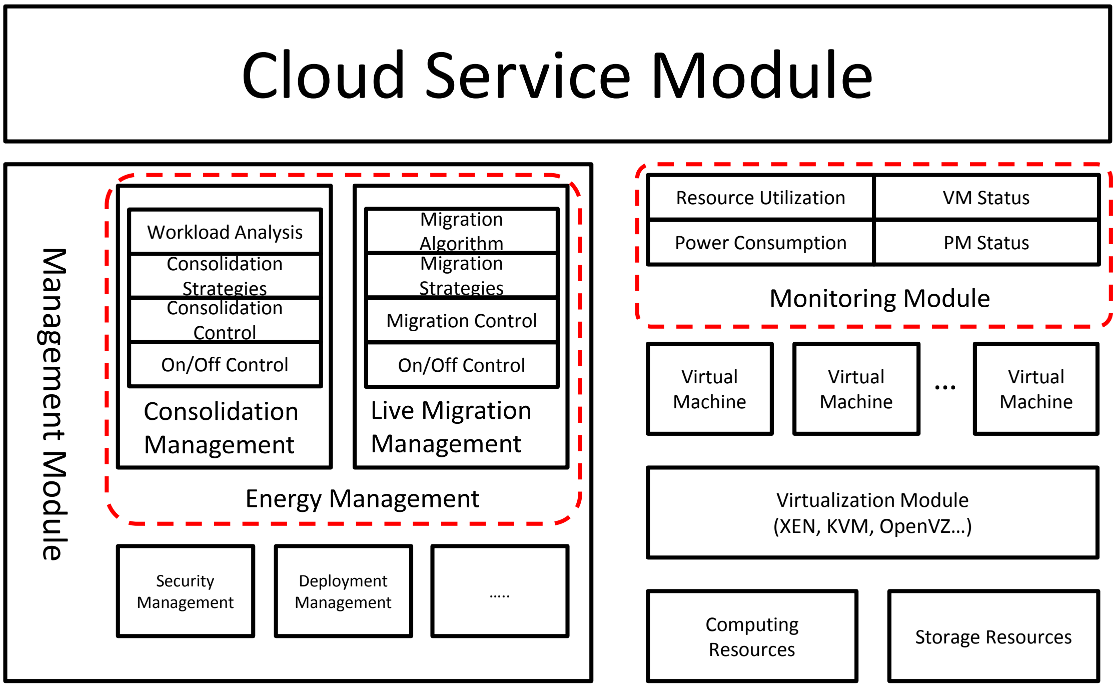


Figure 17. Virtual machine based energy efficient data center architecture for Cloud computing [37].

Energy-proportionality is a simple concept that can help to boost energy efficiency [32]. The idea is to dynamically manage capacity, so that excess resources and their energy consumption, can be temporally removed from the system, and restored later when needed. Server hardware is still far from the ideal vision of the energy-proportional computer and still draws considerable power when idle. [32]

A key challenge are the optimizations over multiple system resources - at each time frame VM are reallocated according to current CPU, RAM and network bandwidth [33]. Network optimizations, meaning optimization of virtual network topologies, created by intercommunicating VMs. Network communication between VMs should be observed and considered in reallocation decisions in order to reduce data transfer overhead, and network devices load. Thermal optimizations, meaning the current temperature of physical nodes, are considered in reallocation decisions. The aim of thermal optimization is to avoid hot spots by reducing workload of the overheated nodes, and thus decreasing error-proneness and cooling system load. [33]

Hybrid data center architecture has been studied a lot. It mixes low power systems and high performance ones. It recognizes different workload types. Workloads are divided to web services, where the data requested is usually a small object in a large dataset. The first request may lead to a database query but subsequent requests are cached in memory for fast retrieval, this technology is called memcached. [23] The second class is the data mining, which represents a large-scale data analysis workloads, which process a data set in a distributed fashion. This is done in order to populate the index used in search engines or for machine learning operations. [23] The third class is the computing intensive workloads, which represent CPU intensive applications such as image processing or video encoding [23]. Hybrid data center architecture shows that low power and high performance platforms exhibit different power performance based on the workload, and clearly a single solution cannot satisfy the wide range of applications seen in today's data centers [23]. Many components contribute to the overall power consumption and servers have a narrow dynamic range. The use of hybrid solution may help in designing a data center architecture that gives low latency, good performance/watt, and energy-proportionality in a wide range of workloads. [23] Hybrid data centers incur harder resource scheduling problems than traditional data centers. [23] Hardware and software architecture is one possible dimension useful for classifying and evaluating hardware and software designs in the extent to which the high performance and low power platform share common components. [23] Shared components have a direct impact on the complexity of the software architecture, on the degree of changes required in today's operating systems as well as on the overall cost, from factor and reliability of the hybrid platform. [23]

Hadoop Distributed File System (HDFS) is worth mentioning in this master's thesis. Given the massive bandwidth requirements, and the sheer amount of the data that needs to be processed, data-intensive compute clusters such as those running Hadoop have moved away from NAS/SAN model to completely clustered, commodity storage, which allows direct access path between the storage servers and the clients. [30] Hadoop data-intensive computing framework is built on a large scale, highly resilient HDFS managed cluster based storage. HDFS distributes data chunks and replicas across the servers for higher performance, load-balancing and resiliency. With data distributed across all servers, any server may be participating in the reading, writing, or computation of a data block at any time. [30] Energy-aware placement of data and focus on data-classification techniques to differentiate the data is needed. GreenHDFS is an energy-conserving, self-adaptive, hybrid, logical multi-zone variant of HDFS. GreenHDFS trades performance and power by logically separating the Hadoop cluster into Hot and Cold zones. Zone temperature is defined by its power consumption and the performance requirements. GreenHDFS uses classification policies to place data into a suitable temperature zones. Since computations exhibit high data locality in the Hadoop framework, the computations flow naturally to the data in the right temperature zone. [30] GreenHDFS techniques result in a number of servers in the cold zone with very low utilization and guaranteed periods of idleness. The CPU, memory and disks on these servers can then be transitioned to inactive power modes resulting in substantial energy savings. Zoning in GreenHDFS will not affect the hot zone´s performance adversely and the computational workload can be consolidated on the servers in the hot zone without exceeding the CPU utilization above the provisioning guidelines. [30]

GreenHDFS Definition of a hot zone: [30]

Data class: Consists of hot, popular data that is accessed very frequently. The popularity can be spatial or temporal.

Hardware class: Consists of high performance, high power, and hence higher cost CPUs.

Data Chunking Policy: Uses a chunk server placement policy that considers the problem of assigning n chunks f1, f2, f3, f4...fn among m servers, and aims to optimize the mean response time and the system throughput by minimizing the queuing delays on the server's disks in hot zone.

Power Policy: None.

Zone-Server Assignment: Majority (70% +) of the servers in the cluster are assigned to the hot zone up front.

GreenHDFS Definition of a Cold Zone: [30]

Data class: Consist of files with low spatial or temporal popularity with few to rare accesses. Tradeoff is performance for higher energy conservation in this zone.

Hardware class: Larger number of disks per server in these zones compared to hot zones.

Data chunking policy: None.

Power policy: Aggressive performance and SLA requirements are not critical for cold zone and employment of aggressive power management schemes, and policies for cold zone is required to transition servers to very low power consuming, inactive power mode.

File allocation policy: Tries to avoid powering-on a server and maximizes the use of the existing power-on servers in its server allocation decisions in interest of maximizing energy savings.

Data integrity policy: To ensure data integrity in the cold zone, disks in the cold zone are scrubbed from time to time. Files are moved from the hot zone to cold zone as their temperature changes over time.

3.5 Energy Efficiency in Processors

Traditionally power efficient designs attempt to find the right balance between two distinct, and often conflicting, requirements. First task is to deliver high performance at peak power, meaning maximization of computing capacity for a given power budget. [23] The second task is to scale power consumption with load, meaning energy-proportionality and very low power operations [23]. A fundamental challenge in finding a good balance between the two is that, when it comes to processor design, the mechanisms that satisfy the two requirements above are significantly different. [23] Byung-Gon Chung, et al, investigated that in a modern processor, less than 20% of the transistor count is dedicated to the actual cores. [23]

It is observed that dichotomy between low power and high performance system designs; choosing the most appropriate design for an energy efficient data center is far from straightforward [23]. This is because data center workloads are diverse, meaning that the workload dynamics, including job arrival patterns and completion times, may reverse the conclusion of static workload analysis. Processor is just one contributor to the overall power consumption. [23]

One of the techniques for energy-proportional processor design is Dynamic Voltage Frequency Scaling (DVFS) [6]. DVFS can be used to reduce the power consumption of the IT equipment. The energy consumption of a processor is approximately proportional to processor frequency, and to the square of the processor voltage. Decreasing the processor voltage and frequency will lower down the performance of the processor. However, if the execution performance is not so important, decreasing the processor voltage and frequency can reduce the power consumption of the processor. [6] Experimental results show that using the DVFS method is efficient in reducing the energy consumption and losing only light performance of the system. [6] In Figure 18 is the basic concept of DVFS technology.

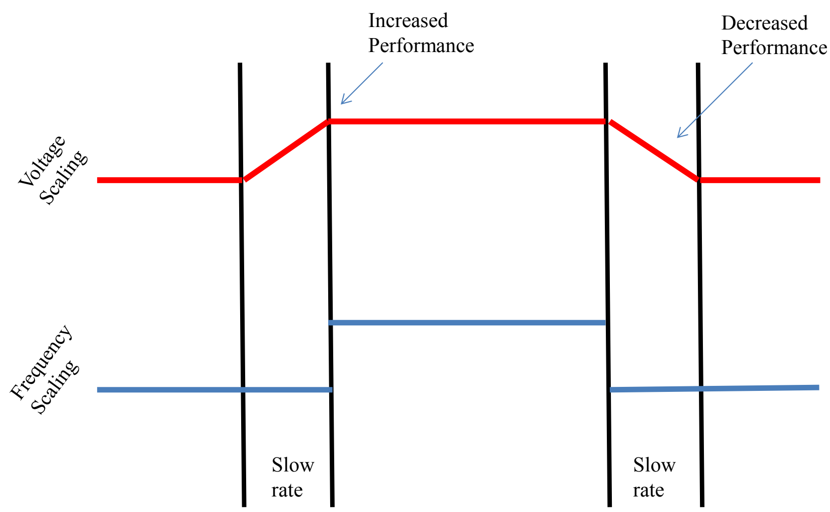


Figure 18. Dynamic Voltage Frequency Scaling (DVFS) concept.

3.6 Summary of the Chapter

Chapter three presents findings from over 45 scientific articles regarding energy efficiency in data centers. This is by no means a full picture of what is available in the market but it represents an overview of the types of solutions available. The purpose of this chapter is to take the reader to the world of energy efficiency, and to give a guiding map for further analysis and synthesis results in this thesis. There are many places in a data center where energy is either lost or wasted. It is essential to understand how green data center architectures are formed, and what kind of key elements they are built from.

Air cooling is one important area where new energy efficient solutions are being presented. Air cooling consumes a significant amount of energy, and it is a popular research topic. There are important solutions that need to be taken into account when investing into a new data center, but also when modernization is taking place. Especially dynamic systems with dynamic control possibilities are considered important.

Energy efficiency can also be sought in the telecommunication networks. There are many energy efficient architectures and routing algorithms. Energy-proportionality can be achieved in device level or overlay level. The main idea is to turn off excess devices or links, and bring them back online when the capacity is needed. Energy efficient solutions in virtualization are a collection of live migration tools and scheduling heuristics. Both of these can become competitive advantage for a cloud service provider. Virtualization is one of the main technologies used in modern data centers, and the idea is to increase utilization rate of the equipment. Virtualization is also used in networking as a norm.

The last part of Chapter three defines DVFS technology that adjusts processor frequency and voltage usage. Even though the individual net reduction of processor energy consumption is low, the amount of processors is enormous, and so the significance is high.

In Chapter four the literature and research findings on energy efficiency metrics are presented. Firstly the definition for valid energy efficiency metric is defined, and following with a conclusive table on the available relevant energy efficiency metrics in Appendix 1.The categorization and analysis on the energy efficiency metrics are also presented in this chapter, and each metric is evaluated independently. Evaluation is done through the selected and defined metric dimensions in order to normalize the metric importance in the overall picture. In the last part the selection of most suitable metrics is done.

4 SELECTING THE MOST IMPORTANT ENERGY EFFICIENCY METRICS

A major problem in the data center industry is the lack of a credible, appropriate, and industry-acceptable standard method to categorize installed hardware and software resources and workloads into measurable groups, so that available energy efficiency metrics can be applied to calculate power usage. Another major obstacle to improving power efficiency is the limitation of used and available metrics. [10] By using existing metrics it is not possible to distinguish the efficiency of the data center communication system from the efficiency of the computing servers, as both remain considered under the common umbrella of IT equipment [17].

In this chapter the definition of a good metric is presented, and also the key metrics in energy efficiency literature and research are gathered into one table, Appendix 1. This table forms the total set of relevant energy efficiency metrics from which a sub-set of metrics is selected to the actual framework based on analysis. Presentation of each individual metric is done after placing each metric into energy efficiency and technology domains that the metric measures. This is followed by the evaluation of importance of each metric. It is reader friendly to keep the theory and analysis of each metric together, and not to break them into separate parts. Figure 19 presents the process for investigating, selecting, and forming of the metric framework and related chapters.

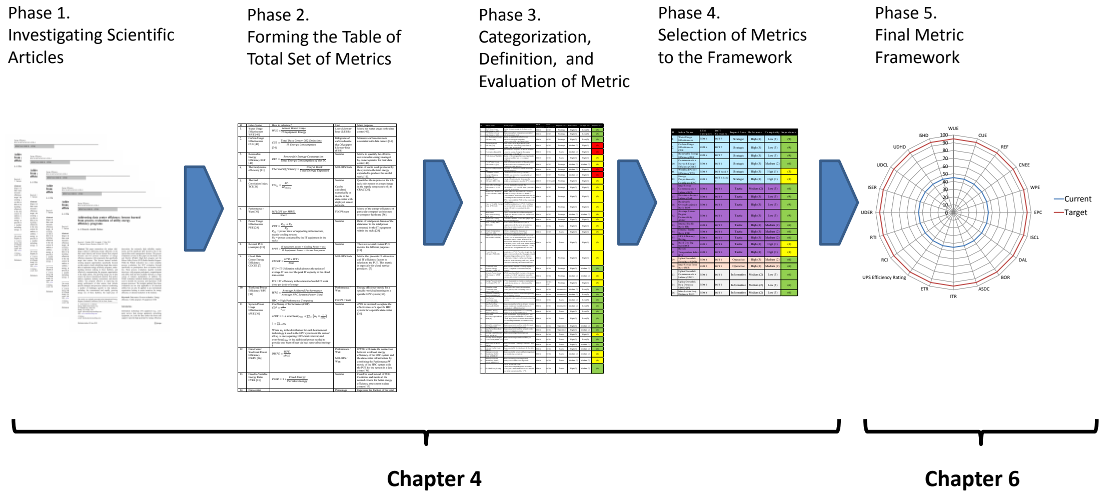


Figure 19. The process for forming the metric framework.

This chapter answers to the first main research question, and its sub questions.

4.1 Definition of a Good Metric

The Green Grid has specified the following characteristics of efficient data center metrics [10]. Firstly the metric name should be clear and intuitive. Secondly the metric should be capable of scaling according to the purpose for which it was initially created and should factor in technological, economic, and environmental changes. Thirdly the metric must be scientifically accurate and used precisely, and fourthly the metric must be granular enough to analyze individual aspects and provide data-driven decisions. [10] According to the common criteria, metrics should have the following properties defined as attributes for the selection to be an effective metric. First there must be definition of a metric, secondly there must be measurement capability, and thirdly, the purposed of metrics must be defined. [10] The metric must provide and contain the following attributes: it must clarify the definition of data center performance and energy. It must define the area to be measured in the data center. It must specify the base of energy values so that new values can be compared and benchmarks can be set. It must define the scope of the data center management according to the type of services it provides. It must provide solutions for energy efficiency improvement according to data center activities and infrastructure. It must clearly define the method of selecting IT equipment and total power as input to the data center. [10]

Measurement capability is essential for any good metric [10]. Proper regulation should be set on measurement methods to calculate the efficiency and to achieve the desired objectives. A mechanism should be used to estimate the nearest values in a situation where measuring is difficult to perform, and the results do not show the desired values. Measurement conditions such as service level agreements (SLA) should be followed while measuring values. The metric must be simple and cost-effective, that is, measurement costs should be low. [10] Aspects covering the usage of metrics are: The metric must consider data center diversity, and divide the data center into segments before metric application. It must follow security considerations and constraints already deployed. It must be easy to use and serve as motivation for both, businesses and users. It must have provision of numerical information. It should provide and effective way to evaluate cooperative efforts for energy efficiency improvement activities. [10]

There are plenty of different tools for presenting metrics. The spider web chart is selected for the purposes of this thesis as it collects several metrics into a single framework, which is relatively easy to present. [40] It can contain multiple KPIs, and it shows interrelationship between different KPIs. It provides self-evident visualization, and is very useful in overall energy efficiency monitoring. One can set the upper and lower bound, and do SWOT analysis based on the spider web chart results. [40] Other popular methods include; engineering/modelling method, performance benchmark method, performance indicators-based method and control chart method [40].

An important area of research in the field of data center metrics is the Computational Fluid Dynamics (CFD) [38]. The purpose is to evaluate the thermal performance of a data center given a specific configuration of a data center. Evaluation takes a long time to finish but fortunately a fast simulation can be used to speed up simulation. [38] Another area is the abstract heat flow model which creates an online prediction, and enables fast decision making. Integrating with thermal aware scheduler models to evaluate thermal performance of different policies, brings even more features, such as the capability to filter out some potential configurations, and verify them with CFD simulation. [38]

The first step in energy efficiency improvement is to effectively evaluate the energy consumption and data center environment by measuring the performance of a holistic efficiency metric. [28] Energy efficiency improvement of data centers is associated with significant challenges due to limited monitoring, efficiency measurement and evaluation, and even cooling system capabilities. Measuring the performance of a data center by using holistic metrics allows tracking improvements and changes, estimating the impact of the changes, and comparisons to other technologies and average industry performance. [28] To determine whether these metrics are effective or not, an assessment is needed for these metrics against their intended goals, and under a range of commonly used cases to determine the values of their effectiveness in terms of reporting, targets, education, analysis and decision support [13].

4.2 Collection of Energy Efficiency Metrics for Further Analysis

In Appendix 1, there is a collection of the relevant data center energy efficiency metrics. These form the total set of relevant metrics to this thesis purposes. It is a subset of all the available metrics. The metrics are indexed with an identity number that will be carried out throughout this thesis. In addition, the equation on how to calculate each metric, and the units of the actual outcome of the metric, is in the Appendix 1. In the last column, there is a short description of the main purpose of each metric. Selection of these metrics is based on the target of addressing the most energy consuming domains in a data center. Some of the metrics are important from the overall performance perspective which is a crucial element in a data center. Energy efficiency should not be implemented in such a way, that it reduces the availability or performance of the actual service which the data center is providing.

4.3 Energy Efficiency Metric Categorization

From 45 different scientific articles regarding GreenIT and energy efficiency and metrics, 37 different metrics were selected for further investigation (metrics are presented in Appendix 1). Energy efficiency is an ongoing iterative process, which must follow some kind of a systematic development framework like the Deming Cycle in order to be effective. This continual improvement process ensures that all relevant phases; Plan, Do, Check and Act are functioning systematically. Two main category groups were created to structure metrics to clear domains. Figure 20 illustrates the two categories that form the metric framework and their interrelationship.

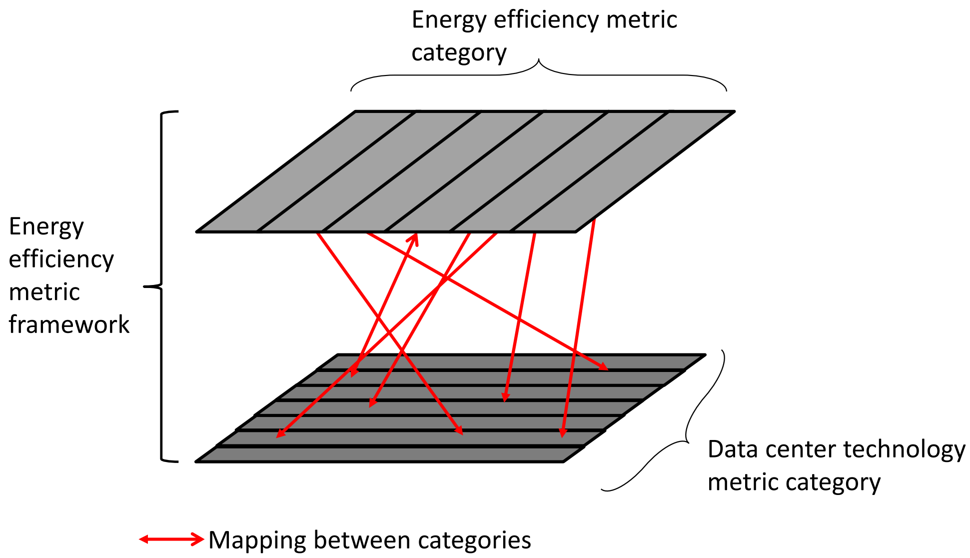


Figure 20. Metric framework.

The first category is the Energy Efficiency Metric (EEM). In this category there are six different energy efficiency domains. They are energy consumption of physical infrastructure (EEM 1), energy consumption of communication elements (EEM 2), energy consumption of computing elements (EEM 3), network energy consumption (EEM 4), general energy efficiency (EEM 5) and CO_2 and renewables use (EEM 6). These six domains create an overall coverage of energy efficiency metrics. The selection of these domains is grounded on the fact that these are the most energy consuming parts of the data center, according to Figure 4. Figure 21 presents the structural layout of the different energy efficiency domains in this category.

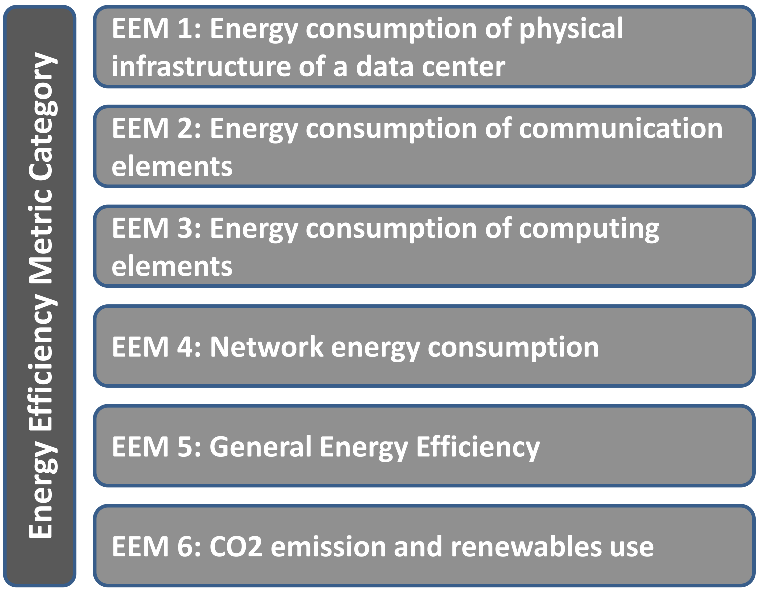


Figure 21. Energy efficiency metric category.

The second category is the data center technology (DCT). In this category there are included seven different technology domains based on the main solution areas of a data center. Together these seven domains form a holistic picture of a modern data center. The domains are; Servers (DCT 1), Network (DCT 2), Storage (DTC 3), Cooling (DTC 4), Air movement (DTC 5), Uninterruptable Power Supply UPS (DTC 6), and the last domain is “Applies to all equipment” (DTC 7). The last domain includes metrics, which touch all data center equipment in some direct or indirect way or the metric is an overlay metric, which does not try to separate different technologies from each other. Figure 22 presents a structural layout of the different domains in this category.

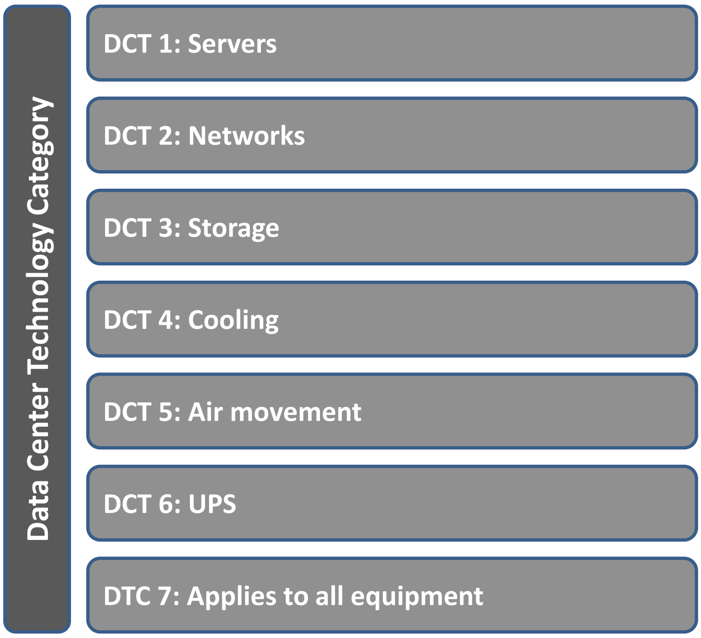


Figure 22. Data center technology category.

All 37 metrics fall into two categories as presented in Figure 23. From this figure it can be seen that all relevant domains inside the two categories are covered with energy efficiency metrics.

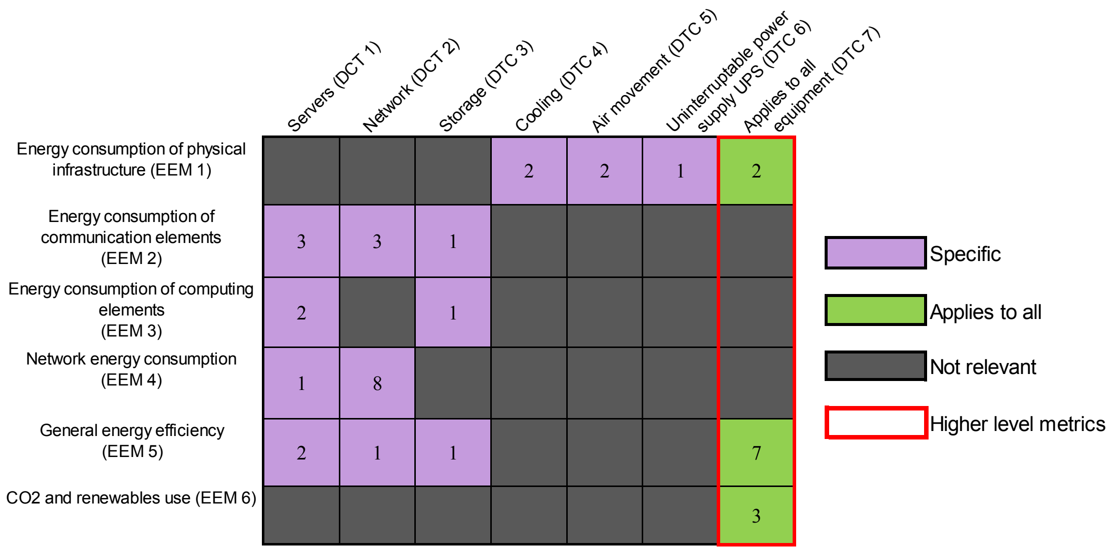


Figure 23. Energy efficiency metric coverage matrix.

Each of the energy efficiency domains is evaluated in the following parts in this chapter. After investigating common important factors for the metrics, the conclusion is that there are four different relevant dimensions for rating the metrics. First dimension is the area of impact. This dimension has four different levels. In the first level, a metric can provide informative input to different stakeholders. In the second level a metric can have strategic impact, and it has a corresponding target in the IT strategy. As a consequence a strategic metric covers a wide area of a data center and preferably the metric is also widely used and can be benchmarked. In the third level tactical metrics provide information for design phases and it covers some individual technology in a holistic way. A tactical metric is not perceived as being valuable enough by the industry to become strategically important to follow it. In the fourth level operative metrics are something that requires immediate attention.

The second dimension is relevance. It is divided into three classic levels; high, medium and low. Each of these levels receives a weight from three to one, three being the number for the most relevant. Relevance is evaluated from scientific articles, and the knowledge from TeliaSonera´s specialists. The evaluation has subjective features but it is strengthened by with fact based findings from articles. High relevance indicates that a metric is providing critical results, which can be trusted. In the case of low relevance, it indicates that the metric only covers a minor part or it only provides relative results which cannot be trusted. Dynamic sensor based metrics are also appreciated as they adapt to the changing conditions.

The third dimension is the complexity, which is used to evaluate how challenging it is to implement a metric and how difficult it is to interpret the results. In the fourth dimension metrics are cross checked in order to ensure that they take into account essential parts of a data center, from technology perspective. There shall not be any uncovered areas, which would lower the result reliability fed into the Deming Cycle for further development activities. Uncovered areas might lead to false assumptions in the overall analysis. In the conclusion part of this thesis the selected metrics form a holistic framework for a general large data center, and especially for the Sonera HDC project. Figure 24 illustrates the different dimensions, and presents how the importance is calculated as a function of these three dimensions.

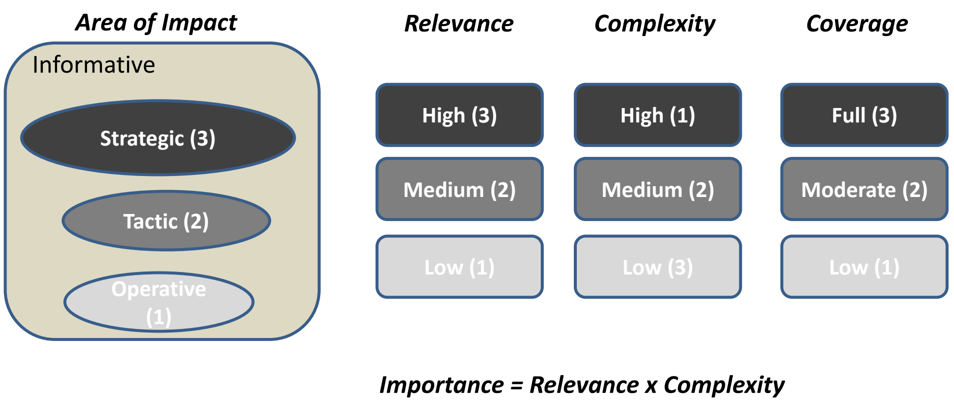


Figure 24. Metric dimensions and weighting.

4.4 Energy Efficiency Metric Category

Each of the domains in the energy efficiency metric category is presented separately in this part of the chapter. Metrics that are selected into a domain are evaluated individually below the summary table.

Table 3. Metrics for energy consumption of physical infrastructure (EEM 1).

EEM 1	Index Name	Main purposes	EEM Category	DCT Category
5.	TCI Thermal Correlation Index [26]	Quantifies the response at the i:th rack inlet sensor to a step change in the supply temperature of j:th CRAC.	EEM 1	DCT 4
14.	Data center infrastructure energy DCiE [28]	Expresses the fraction of the total power supplied to the data center and is delivered to the IT load.	EEM 1	DCT 7
16.	Rack Cooling Index (RCI) [28]	RCI evaluates how effectively the IT equipment inside the racks is maintained within the recommended rack intake temperature range.	EEM 1	DCT 4
17.	Return Temperature Index RTI [28]	RTI was proposed to measure air management effectiveness.	EEM 1	DCT 5
18.	Supply and return Heat Indexes SHI, RHI [28]	The level of separation of cold and hot air streams can be measured by the supply and return heat indices. SHI is defined as the ratio of sensible heat gained in the cold aisle to the heat gained at the rack. RHI is defined as the ratio of heat extracted by the cooling system to the heat gained at the rack exit.	EEM 1	DCT 5
19.	Power Density Efficiency PDE [28]	A variation of PUE. Provides insight into the improvements to both the IT equipment and the supporting cooling system. Enables evaluation of impact of physical changes inside the racks on energy efficiency, which is not possible using the common metrics.	EEM 1	DCT 7
37.	UPS Efficiency Rating	Shows how much of the original incoming utility power is used to power your critical load versus how much is lost in the operation of the UPS.	EEM 1	DCT 6

In Table 3 the relevant metrics are placed into the domain for the energy efficiency of a physical infrastructure of a data center. The physical infrastructure includes real estate, physical security systems and heating and venting and air conditioning (HVAC). There is some overlap between the air cooling domain and the physical infrastructure. Physical infrastructure domain is more focused on the overall physical infrastructure, not so much on an individual domain in a part of the data center. Metrics that belong to this domain are presented and evaluated next.

Thermal Correlation Index (TCI): Dynamic Smart Cooling system uses a network of temperature sensors at the air inlet and exhaust of equipment racks. Data from the sensors is fed to a controller where it is evaluated. The controller can then independently manipulate the supply air temperature, and the air flow rate of each individual CRAC in the data center. TCI is a static metric in a sense, and is based on the physical configuration or layout of the data center. Since it does not contain dynamic information, it can be thought of as the steady-state thermal gain at the sensor to a step change in thermal input at the CRAC. In essence, this metric quantifies the response at the i:th rack inlet sensor to a step change in the supply temperature of j:th CRAC. [26]

Impact: Tactical, Relevance: Medium, Complexity: High – TCI requires that the datacenter has Dynamic Smart Cooling system. The point that it does not support the dynamic nature of the physical configuration at the data center, is a setback against the relevance of this metric, and questions the actual metric output as a function of time, because of the configuration or layout changes in the data center. TCI is a tactical level *metric that ensures automatic adaptation to changing thermal conditions, and focuses on one of the most significant sources of energy consumption.*

***Data center infrastructure energy (DCiE*):** DCiE is a reciprocal of the PUE metric. It basically measures what percentage of facility power is delivered to the IT equipment. DCiE is a measurement of energy use at, or near, the facility utility meter. If the data center is in a mixed-use facility or office building, measurement should be taken only at the meter that is powering the data center. If the data center is not on a separate utility meter, one can estimate the amount of power being consumed by the non-data center portion of the building and remove it from the equation. Secondly one must measure the IT equipment load, which should be measured after power conversion, switching and conditioning is completed. According to The Green Grid, the most likely measurement point would be at the output of the computer room power distribution units (PDUs). This measurement should represent the total power delivered to the server racks in the data center. [28]

Impact: Strategic, Relevance: Medium, Complexity: Medium – DCiE has the same challenges as the PUE metric. It does not clearly ensure overall energy efficiency but is a relative metric. So as long as the numerator and denominator both increase relatively at a same pace, the actual net consumption increases thus it looks like the data center is energy efficient, when it is actually the opposite. DCiE is a strategic level metric mainly because it measures overall energy efficiency, and because it is one of the main benchmark metrics available in the market. Measuring DCiE is medium in complexity thus requires careful planning on what to include and leave out from the metric, similar to PUE.

Rack Cooling Index (RCI): RCI is a best practice performance metric for quantifying the conformance with thermal data center standards such as American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and Network Equipment-Building System (NEBS). RCI measures the degree to which an adequate environment is provided for in the racks. It evaluates how effectively the IT equipment inside the racks is maintained within the recommended rack intake temperature range. The RCI metric compresses the intake temperatures (measured or modeled) into two numbers: $RCI(HI) = 100\%$ means no intake temperatures are above the maximum recommended and $RCI(LO) = 100\%$ means no temperatures are below the minimum recommended. Both numbers equal to 100% signify absolute compliance meaning that all intake temperatures are within the recommended range. The recommended and allowable ranges for rack temperature are 18-25 °C and 15-32 °C. There are many applications of the RCI. Firstly it can be used to design equipment environments. The RCI combined with Computational Fluid Dynamics (CDF) modeling provides a standardized way of evaluating and reporting the effectiveness of cooling solutions. Secondly it can provide design specifications. Data center owners/operators can specify a certain level of thermal quality in a standardized way, for example$RCI > 90\%$. Thirdly it can assess equipment environments. Temporary or permanent monitoring of the environment is feasible by using intake temperature sensor arrays. Finally it can help product development. The RCI demonstrates the benefit of an energy efficient cooling solution. A product with an RCI near 100% could be marketed as such. [28]

Impact: Tactical, Relevance: High, Complexity: High – RCI is as such high relevance but it involves investing into a sensor network and dynamic analysis tools. CDF is *complex to implement thus this information together with the TCI would bring some dynamic elements for physical infrastructure management. RCI is also a good candidate to become a strategic level metric but it still lacks global adaptations.*

Return Temperature Index RTI: RTI is used to measure air management effectiveness. RTI evaluates the degree to which cooling air bypasses the rack equipment, as well as capturing the effect of air recirculation within the racks. Bypassed air does not contribute to rack cooling and lowers the temperature of the air returning to the air cooling system. Likewise, hot spots will be produced due to air recirculation, which in turn reduces efficiency and performance of the data center. Specifically, the RTI is a measure of net by-pass air (RTI < 100%) or net recirculation air (RTI > 100%) in the equipment room; both effects are detrimental to the thermal and energy performance. [28]

Impact: Tactical, Relevance: High, Complexity: High – Combined with RCI, RTI metric provides an opportunity to objectively establish the overall performance of the building's air-conditioning system. RTI can be obtained from the same system than RCI. Complexity to measure RTI is high and it requires a dynamic measurement system in order to function as a relevant metric. As with RCI, the RTI metric is a tactical level metric for design purposes.

Supply and Return Heat Indexes SHI, RHI: In order to improve data center thermal management effectiveness, physical separation of cold and hot air streams is imperative. Arranging IT equipment in separated cold and hot aisles using containment strategies prevents mixing of the air streams. The level of separation of cold and hot air streams can be measured by the supply and return heat indices. SHI is defined as the ratio of sensible heat gained in the cold aisle to the heat gained at the rack. RHI is defined as the ratio of heat extracted by the cooling system to the heat gained at the rack exit. Lower values of SHI and RHI suggest more effective separation of cold and hot aisles and less mixing of air streams. These two dimensionless indices not only provide a tool to understand convective heat transfer in the equipment room but also suggest means to improve energy efficiency. [28]

Impact: Tactic, Relevance: High, Complexity: High – Hot and cold aisle containment is one of the key solutions for isolating air streams. It is essential to know how effectively it is working in a dynamic way. Measuring is based on sensors and if RCI and RTI are implemented, it should not be too complicated to visualize heat levels in the aisles. SHI and RHI are tactical level metrics. After wide adaptation they will become strategic.

Power Density Efficiency PDE: PDE is a variation of PUE. It provides insight into the improvements of both the IT equipment and the supporting cooling system. PDE enables evaluation of the impact of the physical changes inside the racks on energy efficiency, which is not possible by using the common metrics. The PDE metric reflects the inefficiencies in the air flow thermal management due to higher rack to IT equipment volume ratio, which may lead to lower utilization of supplied cold air and a higher risk of re-circulation. Using volume power density in calculating PDE allows for comparison of data centers at different scales. Due to the limitations of existing metrics in holistically capturing data center energy efficiency, and thermal management effectiveness, the power density efficiency (PDE) metric is proposed. The PDE metric enables a more holistic assessment of data center energy efficiency, and supports the evaluation of the impact of design changes based on a single metric. [28]

Impact: Strategic, Relevance: High, Complexity: High – Due to the limitations of existing metrics in holistically capturing data center energy efficiency and thermal management effectiveness, the PDE metric is proposed. The PDE metric enables more holistic assessment of data center energy efficiency and supports the evaluation of the impact of design changes based on a single metric. Complexity is high because PDE requires wireless sensor network as many of the dynamic metrics do. PDE is a strategic level metric as it provides information regarding the energy efficiency of the whole data center.

UPS Efficiency Rating: During the initial process of matching a desired reliability to the actual requirements, the risk owner will often come up with a euro amount per minute or hour that unplanned downtime will cost the firm. This amount is then considered against the costs of designing and constructing a facility of sufficient reliability to minimize the risk of downtime. Typically the cost includes facility construction and equipment costs, design costs, and occasionally maintenance costs. One cost that is not always considered, however, is the cost of efficiency of the UPS system itself. Static UPS systems have efficiency ratings, which measure how much of the input electricity is actually available to the load after the overhead incurred by system electronics, power conversion and so forth. These efficiency ratings usually range from around 92% to 95%. Certain systems may be able to achieve efficiency ratings of up to 97% at or near full load. The issue of UPS efficiency can be broken down into two separate problems. Firstly different UPSs have different efficiencies. Secondly the same UPS has a different efficiency at a different load level. This fact, combined with the fact that not all manufacturers publish their data for different load levels, can make this a complicated issue; but it is an issue that needs attention during the design process. UPS Efficiency Rating metric shows how much of the original incoming utility power is used to power your critical load versus how much is lost in the operation of the UPS. [47]

Impact: Tactical, Relevance: High, Complexity: Medium – Designing an effective data center entails balancing many conflicting, and sometimes confusing design goals. In addition to system topology and other basic design requirements, the actual system components purchased, and their operating efficiencies can make a significant difference to the long-term cost of a data center. This is most apparent in the UPS itself, where higher efficiency and optimization of load to match rated levels can save millions of euros over the long term [47]. This is a dynamic metric that requires monitoring and measurement data from the UPS. The baseline graphs can be obtained quite easily from any modern UPS vendor. Matching actual data with the baseline is doable. This is a tactical level metric and would require strategic and operational metric to its side.

Table 4. Metrics for energy efficiency of communication elements (EEM 2).

EEM 2	Index Name	Main purposes	EEM Category	DCT Category
23.	Uplink/Downlink Communication Latency UDCL [17]	Communication latency between data center gateway and computing servers.	EEM 2	DCT 2
24.	Uplink/Downlink Hop Distance UDHD [17]	Hop distance between data center gateway and computing servers.	EEM 2	DCT 2
25.	Inter-Server Communication Latency ISCL [17]	Communication latency between computing servers	EEM 2	DCT 1
27.	Database Access Latency DAL [17]	Measures average latency of accessing database from computing server.	EEM 2	DCT 3
28.	Bandwidth Oversubscription Ratio BOR [17]	Ratio between the aggregate ingress and aggregate egress bandwidth of a network switch. Important to estimate the minimum non-blocking bandwidth available to every server.	EEM 2	DCT 2
30.	Inter-Server Error Rate ISER [17]	Measures error rate of the network paths between computing servers.	EEM 2	DCT 1
32.	Average Server Degree Connectivity ASDC [17]	Measures average number of links per server.	EEM 2	DCT 1

Table 4 presents the metrics that belong into the energy consumption of communication elements domain. These metrics are introduced and evaluated next.

Uplink/Downlink Communication Latency UDCL: Latency metrics are needed to ensure that energy efficiency activities do not compromise service usability. The most important latency-related metric is the UDCL. UDLC measures the time needed for an incoming request to the data center to reach a computing server (downlink) or the time it takes for a computing server result to leave the data center network (uplink), and be on the way to the end user. UDLC is added on top of the task execution time for every processed user request. As a rule of thumb, network topologies hosting computing servers closer to the data center gateway have smaller UDLC, and can provide faster response times. [17] A typical data center network is presented in Figure 25. From this figure it can be seen how UDCL is measured.

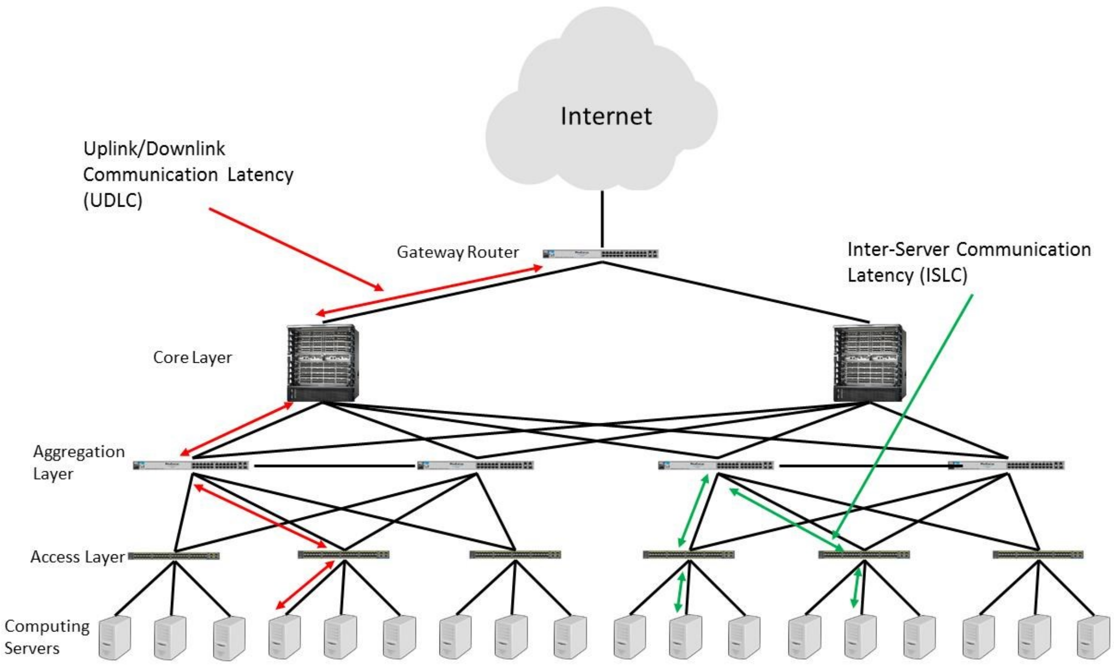


Figure 25. UDCL and ISCL description. [17]

Impact: Informative, Relevance: Medium, Complexity: Low – This metric is informative and easy to measure. Latency is relevant in every modern real-time service. This is important information for network designers. Better energy efficiency is often seen as less performance; latency is one of the key performance indicators and must not be compromised in designing energy efficient networking solutions.

Uplink/Downlink Hop Distance UDHD: Very similar metric to the UDCL, the only difference is that UDHD measures how many hops there are between computing servers and gateway router. The higher the metric value, more processing thus energy usage and latency it will bring. It is good to recognize that on top of energy efficiency and performance considerations there are also security and network management considerations that need to be addressed. [17]

Impact: Informative, Relevance: Medium, Complexity: Low – This metric is easy to measure. Compared to the previous UDLC metric, which had indirect energy efficiency impacts, hop distance has direct impact on energy efficiency. The more hops the networking solution has, the more processing needs to be done in each of these hops. This needs to be taken into account when designing networks. Energy efficiency must be one of the main drivers together with performance, security, network management and cost.

Inter-Server Communication Latency ISCL: This metric measure the time (in seconds) it takes for one task to communicate with another task executed on a different server. ISCL is particularly relevant for cloud applications, where execution can be parallelized. The objective is to exchange data and it will perform faster in network architectures with fewer hops between servers and smaller inter-server delays. Thus inter-server delays will make no difference for standalone applications, where execution is confined to single server. In addition to measuring average values, it is important to analyze deviation in the distribution of inter-server delays. Small deviation values will characterize data center networks with small distances between computing servers, for example switch centric architectures, and allow placement of interdependent tasks at any server, not depending on its location. However, for data centers with highly variable inter-server delays, such as server-centric architectures like BCube and DCell, it becomes highly beneficial to consolidate heavily communicating tasks to reduce network delays and improve performance. [17] The concept of ISCL is presented in Figure 25.

Impact: Tactical, Relevance: Medium, Complexity: Low – This metric is essential feedback into the network and system architecture design. In addition, this metric is easy to measure. Inter-Server latency effects service performance especially in low latency demanding services, meaning almost all real-time services of modern time. ISCL can be used as an indirect verification metric of effective energy efficiency solution that does not compromise quality of service (QoS).

Database Access Latency DAL: DAL is defined as an average Round-Trip Time (RTT) measured between computing servers and the data center database. DAL is measured in seconds. An overwhelming majority of cloud applications store and obtain data from databases. Thus, reducing the time required for sending a query and receiving data can significantly speed up performance and improve energy efficiency. As an alternative to bringing databases physically closer, a number of data replication techniques can also be employed. Data replication reduces DAL for the cached data, but can also introduce traffic overhead for propagating replica updates in the system. [17]

Impact: Tactical, Relevance: High, Complexity: Low – This metric is essential feedback into the system and network architecture design. Databases are found in almost all familiar and popular applications and systems, which mean that it is relevant to optimize its performance thus energy efficiency. In addition, this metric is easy to measure but the reasoning of the actual results could be complicated. DAL is a tactical metric but in some environments it can also have a strategic meaning.

Bandwidth Oversubscription Ratio BOR: Bandwidth oversubscription can be defined as the ratio between the aggregate ingress and aggregate egress bandwidth of a network switch. For example, in a typical three-tier topology (see Figure 25), Top-of-Rack (ToR) switches are equipped with two 10 Gb/s links to the aggregation network, and can support up to 48 servers in the access network, each connected with a 1 Gb/s link. This entails Bandwidth Oversubscription Ratio (BOR) of 48 Gb/s = 20 Gb/s = 2:4:1, which corresponds to a per-server bandwidth of 1 Gb/s = 2:4 = 416 Mb/s under full load. Further bandwidth aggregation of 1,5:1 occurs at the aggregation level, where each switch has eight 10 Gb/s links to the core network, and twelve 10 Gb/s links to the access network. As a result, the per-server available bandwidth can be as low as 416 Mb/s = 1:5 = 277 Mb/s in a fully loaded topology. [23] Server-centric architectures do not introduce points of bandwidth oversubscription. As a result, BOR is equal to 1. [17]

Impact: Tactical, Relevance: High, Complexity: Low – Computing BOR is important to estimate the minimum non-blocking bandwidth available to every server. When the computing servers produce more traffic than the available bandwidth, ToR and aggregation switches can become congested, and start to drop packets from the overflowed buffers. This significantly degrades performance of cloud applications, and consumes more energy. Sizing of capacity is one of the most essential parts of energy efficient designs. A decision on the acceptable BOR level is a tactical decision that influences QoS, resiliency and latency.

Inter-Server Error Rate ISER: ISER evaluates the average error rate of inter-server communications meaning Bit-Error-Rate (BER) in network paths between computing servers. The BER in question is formed from the path interconnecting server i and server j. The ISER is calculated as a sum of BERs of all links between servers i and j. [17]

Impact: Operative, Relevance: High, Complexity: Medium – Packets that need to be resend or are lost are a problem from many perspectives. Resending consumes energy and lost packet effect QoS. BER is a standard measurement, and combining several BERs to form an overall picture is advisable from troubleshooting purposes and design purposes to system architects, as well as network architects. Error rate affects the system performance as such. BER calculation is not a very complicated task, but combining different BERs along the data path between servers can be challenging to construct, thus once set up, it is an automatic metric. ISER is an operative metric that needs to be addressed if BER levels worsen as a function of time.

Average Server Degree Connectivity ASDC: Depending on the design strategy, data center topologies are either switch centric or server-centric. In switch-centric architectures, such as fat-tree, each server is usually connected to a single Top-of-Rack (ToR) switch with only one link. In server-centric architectures, instead, the computing servers are connected to several switches (BCube) and/or a number of other servers (DCell) to increase network capacity and provide resilience to node and switch failures. A higher degree of connectivity increases network capacity and makes the whole topology fault tolerant and helps to balance the load. However, having a high number of connections increases network power consumption as more links and NICs have to be deployed and utilized. To analyze how well the computing servers are connected, Average Server Degree Connectivity (ASDC) can be computed. ASDC measures total number of data center servers, and a number of network links that connects specific server to other devices, switches and/or servers. [17]

Impact: Tactical, Relevance: High, Complexity: Low – ASDC metric pinpoints relevant design aspect regarding the tradeoff between connectivity, resilience and energy use. This is a very important system optimization question, and getting actual measured data to optimize this factor is essential for decision making. ASDC is also relevant for parallel distributed Hadoop tasks, and it is the most effective in distributed data center architectures. ASDC is a tactical level metric, and it works as a policy for network designers.

Table 5. Metrics for energy efficiency of computing elements (EEM 3).

EEM 3	Index Name	Main purposes	EEM Category	DCT Category
6.	Performance/Watt [36]	Metric of the energy efficiency of particular computer architecture or computer hardware.	EEM 3	DCT 1
10.	Workload Power Efficiency WPE [36]	Energy efficiency metric for a specific workload running on a specific HPC system.	EEM 3	DCT 1 and 3

In Table 5 there are the metrics, which are connected to energy efficiency in computing domain. Thus, not too many metrics belong directly to computing equipment; it is covered indirectly in more general, strategic level metrics.

Performance per Watt (PPW): PPW is a very straightforward metric solution. The PPW metric measures the actual energy efficiency of every device in the data center and how it is used. The PPW approach uses a relative performance indicator for each individual asset. This indicator is calculated by the types of hardware and capabilities learned from an asset inventory of that device. Performance Indicator (PI) is a simple measurement for getting relative performance of the device in question. When the device is at maximum efficiency, the PPW number is higher. The lower the PPW number, the more power that device is wasting. When combining PI with live utilization of an asset, along with real-time energy draw of that asset, it becomes a simple process for measuring PPW. Capability to measure PPW will help data center managers to identify devices that are wasting energy. PPW enables a global evaluation, and selection of the best geographic location and configuration to enable a given computer service in the compute utility of the future. [36]

Impact: Strategic, Relevance: High, Complexity: High – PPW metric shows whether the devices are using excess electricity that is needed for the jobs they are doing. It is also possible to identify if servers are wasting electricity by powering dead servers. Old switches and routers that are costing more in power than it would cost to replace them *are identified. PPW emphasizes virtualization of newer, more energy efficient servers, allowing retirement of old servers completely. PPW is one of the main benchmark metrics in data centers. It is an overall metric and strategic level by nature. Work load is not easy to separate from total load, and this brings complexity into this metric. Workload needs to be defined, and after this time series will reveal how well energy efficiency is developing before and after new solutions.*

Workload Power Efficiency WPE: The WPE metric is needed because current PPW measurement methodologies do not always require the measurement of the complete system power consumption. For example, the Green500 list only requires the measurement of the power consumption for all participating sub-systems. In most cases this value does not include the power consumption of storage, networking, and cooling subsystems, nor does it incorporate losses in the power supply chain. WPE is a Performance/W metric for a HPC system, which includes applications, HPC system software and system hardware. The best way to determine WPE is to gather the measurements for the complete HPC system during the benchmarking process. [36] WPE covers domains presented in Figure 28.

Impact: Strategic, Relevance: High, Complexity: High – Firstly WPE is needed to calculate Data Center Workload Power Efficiency DWPE. WPE provides wider coverage as a metric than PPW, and combines power per watt calculations from applications, system software and hardware. It is not easy to calculate but the results are very relevant. Benchmarking option is available and it raises this metric to a strategic level.

Table 6. Metrics for network energy efficiency (EEM 4).

EEM 4	Index Name	Main purposes	EEM Category	DCT Category
20.	Communication Network Energy Efficiency CNEE [17]	Measures the amount of energy required to deliver a single bit of information by the network.	EEM 4	DCT 2
21.	Network Power Usage Effectiveness NPUE [17]	NPUE specifies which fraction of the power consumed by the IT equipment is used to operate data center communication system.	EEM 4	DCT 2
26.	Inter-Server Hop Distance ISHD [17]	Measures number of hops, it takes for one task to communicate with another task executed on a different server.	EEM 4	DCT 1
29.	Uplink/Downlink Error Rate UDER [17]	Measures error rate of the paths between data center gateway and servers.	EEM 4	DCT 2
31.	Average Link Utilization Ratio ALUR [17]	Measures average link occupancy.	EEM 4	DCT 2
33.	Internal Traffic Ratio ITR [17]	Measures traffic exchanged within the data center.	EEM 4	DCT 2
34.	External Traffic Ratio ITR [17]	Measures traffic destined outside the data center.	EEM 4	DCT 2
35.	Management and Monitoring Traffic Ratio MMTR [17]	Measures traffic generated by management and monitoring operations.	EEM 4	DCT 2
36.	Management and Monitoring Traffic Energy MMTE [17]	Measures energy consumption of management and monitoring traffic.	EEM 4	DCT 2

In Table 6 are presented the metrics for network energy consumption domain. Each metric is introduced and evaluated below.

Communication Network Energy Efficiency CNEE: The communication network turns the supplied electricity into the job of information delivery. The efficiency of this process can be measured by the CNEE metric. The data center network equipment includes all the hardware components that take part in information delivery between servers, including network switches, routers, load balancers, security devices, communication links, and Network Interface Cards (NICs) of the servers. The effective network throughput capacity is a maximum end-to-end throughput offered by the network to the computing servers. The CNEE is measured in Watts/bit/second, which is equivalent to joules/bit, or the amount of energy spent by the network to deliver a single bit of information. [17]

Impact: Strategic, Relevance: High, Complexity: Medium – CNEE besides being sensitive to bandwidth over subscription also depends on the overall network power consumption. This is the reason why CNEE is higher for some topologies than for others. CNEE is very useful general metric to describe energy efficiency in the data center. CNEE is a strategic level metric that gives an overall view on energy efficiency in networking inside the data center. CNEE is quite challenging to measure but it is not complex as such.

Network Power Usage Effectiveness NPUE: NPUE defines the fraction of the power consumed by the IT equipment used to operate the network. Similarly, PUE measures the portion of the amount of energy used by a data center facility that is delivered to power IT equipment. NPUE values can range from one to infinity. For example, for NPUE equal to four for every four Watts consumed by IT equipment, one Watt is devoted to operate network equipment. The NPUE value equal to one corresponds to the system where all the IT-related power is consumed by the network equipment, which is a not desirable target: if all the IT power is consumed by the network equipment, there is nothing left for computing servers. However, NPUE values approaching one are not necessarily symptoms of network inefficiency. It can signal that the computing servers were upgraded, and became more energy efficient. For obtaining CNEE and NPUE it is necessary to calculate the power consumption of the computing servers and network equipment as the load of the data center increases. This increase cannot be linear as waking up new servers in already operational racks does not require waking up additional network switches. However, starting up a new rack would require powering on the top-of-rack switch, and possibly aggregation and core switches. [17] Figure 26 clarifies the calculation of NPUE metric.

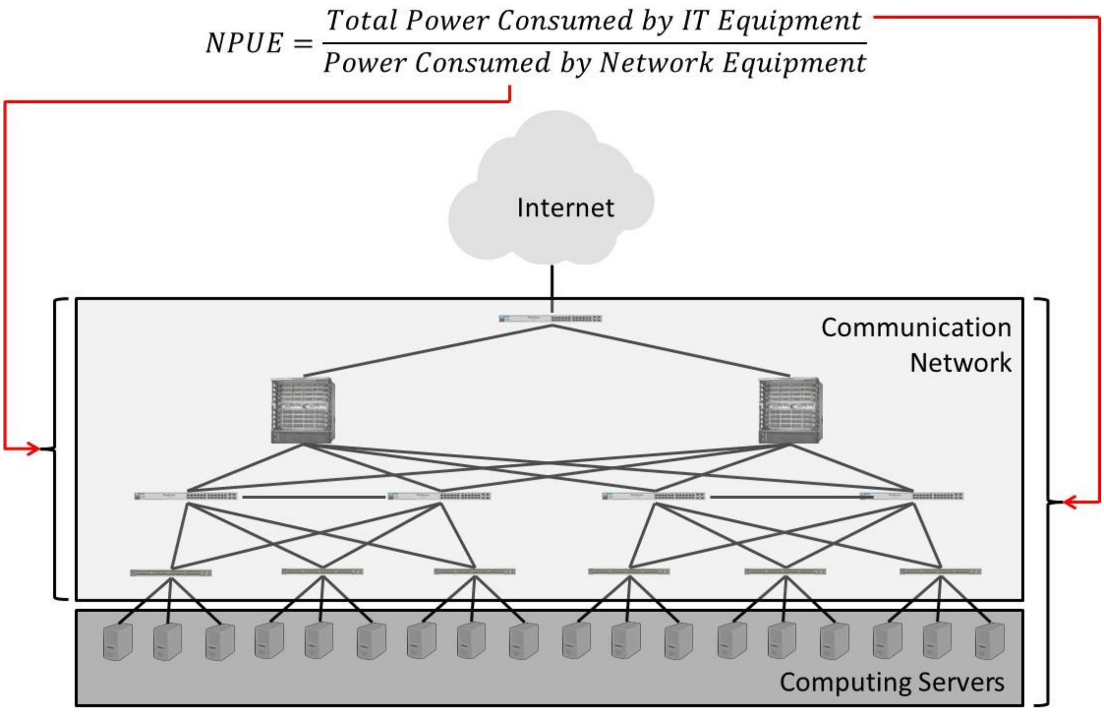


Figure 26. NPUE description and equation.[17]

Impact: Strategic, Relevance: Medium, Complexity: Medium – NPUE assesses the energy efficiency of the network with fine granularity, and allows data center operators to optimize their investments in networking equipment and interconnects. NPUE is not so easy to measure, but it is one of the main energy efficiency measures, and directed specifically towards developing energy efficiency in the networking domain. NPUE is a strategic level metric thus its relevance is moderate as it has the same challenges as all PUE based metrics. Relativity is not always the best measure of actualized energy efficiency.

Inter-Server Hop Distance ISHD: ISHD measures the number of hops it takes for one task to communicate with another task executed on a different server. It is closely related to Inter-server Latency ISCL metric. It has the same purpose and same benefits as explained in the description of the ISCL metric. The idea of this metric can be seen from Figure 25 that describes Inter-Server Communication Latency metric. Practically ISHD is the hop count of the same path that the latency is measured from. [17]

Impact: Informative, Relevance: Medium, Complexity: Low – This metric is essential feedback into the network architecture design. In addition, this metric is easy to measure. From energy efficiency perspective hop distance is essential as more hops mean more processing thus consuming more energy.

Uplink/Downlink Error Rate UDER: UDER measures average Bit Error Rate (BER) on the paths between data center gateway and computing servers. UDER considers number of computing servers and the number of hierarchical layers in network topology and also BER of the different links in different layers, which are interconnecting server with the data center gateway. Generally BER measurements provide a fine grain indication of the quality of a link. However, repeated computations of this metric are required over extended periods of time. The BER computation introduces significant overheads, since it requires the processing of a large amount of pre-known data, and involves the removal of packet outliers. [17]

Impact: Operative, Relevance: High, Complexity: Medium – This metric is essential especially in the age of the real-time flows of data. Error correction and resending of packets consume energy and affect QoS. While the concept of BER is simple, measuring the BER is a non-trivial task; BER measurements consider a pseudorandom data sequence transmission. Combining different BERs along the data bath between servers can be challenging to build thus once set up, it is automatic metric. UDER is an operative metric, which needs to be addressed if BER levels worsen as a function of time.

Average Link Utilization Ratio ALUR: ALUR measures average traffic load on data center communication links. ALUR is an aggregate network metric, and is designed to improve analysis of traffic distribution and load levels in different parts of the data center network. ALUR helps to define proper traffic management policies, and it can be used to detect network hot spots. ALUR becomes an essential tool for preventing performance degradation of cloud applications due to network congestion. For a fat-tree, a three-tier topology, ALUR can be measured separately for the access, aggregation and core segments of the network. A high congestion in any of these segments will signal the need to increase capacity of network links and switches or even reconsider bandwidth oversubscription ratios between these segments. For other topologies, ALUR can be measured on server-to-server and server-to-switch segments of the network. [17]

Impact: Tactical, Relevance: High, Complexity: High – ALUR enables detailed monitoring and assessment of network throughput, delay and error rate performance. They are especially relevant for the largest class of SaaS cloud applications, which often communicate intensively with the end users and also internally. The analysis of these metrics helps to ensure and guarantee QoS and SLA to the customers and helps to optimize energy efficiency. Computing ALUR metric requires having per-link traffic statistics, which can be obtained either from detailed traces or, more realistically, directly measured in real data centers during runtime. ALUR is a tactical metric, and an important one. It is quite difficult to measure, and requires specialized monitoring systems to do the job.

Internal Traffic Ratio ITR and External Traffic Ratio ETR: With ITR and ETR the proportion between internal and external data center traffic can be estimated. ITR is the ratio of the traffic, which remains inside the data center to the total data center traffic. ETR is the fraction of traffic that leaves the data center network. [17]

Impact: Tactical, Relevance: High, Complexity: Medium – The proportion of Internal and External traffic compared to the total traffic is essential for analyzing how efficient the networking and computing solution in a data center is. Reducing internal traffic enhances also energy efficiency. ITR and ETR metrics are quite easy to measure directly from the gateways.

Management and Monitoring Traffic Ratio MMTR: It is important to distinguish user or application-related messaging from the rest of the traffic, which includes network management and monitoring. The latter is required to operate communication networks. Management operations include transmissions for address resolution, for example ARP and routing protocols like OSPF and RIP. Control messaging and problem detection like ICMP can also be attributed to management operations, while SNMP traffic is related to monitoring operations. The MMTR helps to unveil traffic overhead for network management. [17]

Impact: Tactical, Relevance: Medium, Complexity: Medium – The proportion of management and motoring traffic compared to the total traffic is essential for analyzing, how efficient the management and motoring solution in a data center is. Reducing unnecessary management and motoring traffic enhances energy efficiency. Traffic ratio is quite easy to measure from gateways through monitoring systems. MTTR is a tactical metric.

Management and Monitoring Traffic Energy MMTE: To obtain the energy spent on network management, and not for transporting application-related traffic, one can use the CNEE metric and compute MMTE. MMTE is measured in Joules and shows the amount of energy consumed by the communication equipment to keep the network operational. In an ideal case MMTE should assume values close to zero, when most of the consumed energy is attributed to application related traffic delivered at the full effective network capacity. [17]

Impact: Tactical, Relevance: Medium, Complexity: Medium – Understanding data center traffic is very important. Network traffic analysis at the micro- and macroscopic levels can help in estimating the impact on network processes, design traffic engineering solutions, capture interdependencies between executed workloads, and optimize communication between several geographically distributed data centers. Network management and monitoring solutions have taken huge leaps and today such a systems provides real-time traffic distributions by utilizing Netflow, IPFIX, J-Flow and so on. It is essential to know how much these activities consume bandwidth and energy. Measuring these is a common feature in modern monitoring systems, thus they are quite expensive.

Table 7. Metrics for general energy efficiency (EEM 5).

EEM 5	Index Name	Main purposes	EEM Category	DCT Category
4.	Thermodynamic efficiency [11]	Ratio of useful work produced by the system to the total energy expanded to produce this useful work.	EEM 5	DCT 7
7.	PUE (Power Usage Effectiveness) [28]	Ratio of total power draw of the datacenter to the total power consumed by the IT equipment within the racks.	EEM 5	DCT 7
8.	Revised PUE (example) [18]	There are several revised PUE metrics for different purposes.	EEM 5	DCT 7
9.	Cloud Data Center Energy Efficiency CDCEE [7]	Cloud Data Center Energy Efficiency CDCEE is a metric for especially Cloud service provider.	EEM 5	DCT 7
11.	System Power Usage Effectiveness sPUE [36]	sPUE is intended to capture the effectiveness of a specific HPC system for a specific data center.	EEM 5	DCT 7
12.	Data Center Workload Power Efficiency DWPE [36]	DWPE will make the connection between workload energy efficiency of the HPC system and the data center infrastructure by combining the Performance/W metric of the HPC system with the PUE for the system in a data center.	EEM 5	DCT 7
13.	Fixed to Variable Energy Ratio (FVER) [13]	Could be used instead of PUE. Combines and meets all the needed criteria for better energy efficiency assessment in data centers.	EEM 5	DCT 7
15.	Data Center energy Productivity DCeP [29]	Correlates the data center throughput with the consumed power.	EEM 5	DCT 1
22.	Energy Proportionality Coefficient EPC [17]	EPC is measured as energy consumption of a system or a device as a function of the offered load.	EEM 5	DCT 1, 2 and 3

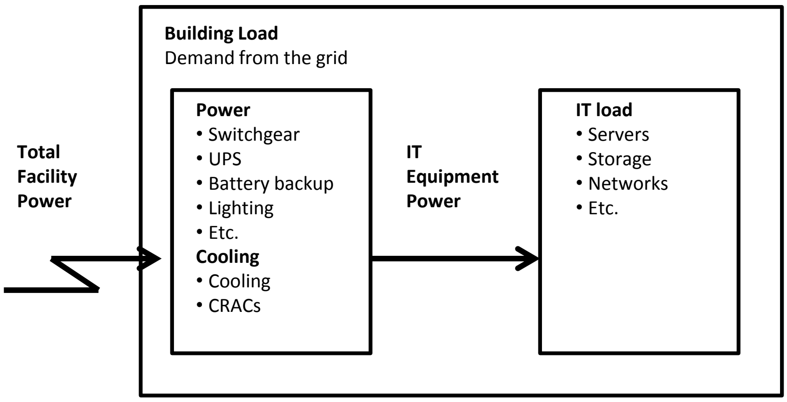
In Table 7 the metrics belonging to general energy efficiency domain are introduced. All of these metrics create an overall picture of the data center energy consumption. In the next part there is more detailed description of the metrics in this domain.

Thermodynamic Efficiency: The thermodynamic efficiency of a system is commonly defined as the ratio of useful work produced by the system to the total energy expanded to produce this useful work. This general thermal efficiency definition can be applied to data centers by defining the useful work as the power used to run actual jobs or applications on the servers, and the total energy expanded is the energy used to operate and support these activities. The total energy expanded includes the energy required to run the information technology systems, the electrical delivery systems and support, and the cooling systems infrastructure. The IT infrastructure consists of the servers, storage, telecom, and management racks. The electrical delivery system includes the Power Distribution Units (PDU) and Uninterrupted Power Supply (UPS). The cooling system includes the centralized chillers, pumps, and CRAC units. A typical server system consumes a fixed amount of power to maintain a minimum active level known as the idle state during which a portion of its maximum rated power is consumed to maintain this status level. This amount of power is typically constant, contributing to the data center fixed power required to maintain the servers active and ready to perform useful work, but in itself is not useful work from the thermodynamic point of view. Once the server is activated by a query or an application, the server system exits its idle state phase and starts its busy phase. The amount of work done during this phase is proportional to how busy the server is and that depends on each job's requirements, and the number of applications running at the same time. [11]

Impact: Strategic, Relevance: Medium, Complexity: High – Thermal efficiency is a very important metric for any data center. It gives a good insight into the actual energy consumption as a function of the useful work that the system is doing. The time series is essential in this metric. From this metric can be seen how changes in the architectures or devices affect the thermal efficiency thus energy consumption. This metric has a downside similar to PUE, it is a relative metric. When both the numerator and denominator change at the same time, it seems to indicate good efficiency but the overall consumption is still increasing. It is quite complex to measure useful work but once defined, it can be automated. Thermal efficiency is a strategic metric as it covers energy consumption of the whole data center, and is also one of the benchmarked metrics in the market.

Power Usage Effectiveness PUE: Most common metric used for energy efficiency in the industry is the Power Usage Effectiveness (PUE). PUE and Data Center Efficiency (DCE) are formed from the total facility power, and IT equipment power. PUE is a benchmark metric used for analyzing a data center infrastructure in relation to its existing IT load. It is defined as the ratio of total power used by a building site divided by the amount of power used by the Information Technology (IT) equipment. The total power used by the site includes the total power used to operate, back-up, cool and protect the IT equipment. A lower the PUE ratio is better. A PUE ratio of two indicates that the IT equipment uses about 50% of the measured building power and the rest is used for cooling and other supporting resources. [28]

Main components and equations of PUE and DCE are presented in Figure 27.



$$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power}$$

$$DCE = \frac{1}{PUE} = \frac{IT\ Equipment\ Power}{Total\ Facility\ Power}$$

Figure 27. Illustration of PUE and DCE metrics. [10]

PUE of one means that there is no additional overhead when running the HPC system, it is optimal. Table 8 presents efficiencies as a function of PUE values:

Table 8. PUE Efficiency values. [10]

PUE	DCE	Level of Efficiency
3	33 %	Very Inefficient
2,5	40 %	Inefficient
2	50 %	Average
1,5	67 %	Efficient
1	83 %	Very Efficient

More technical work is needed to make these, and other PUE based metrics useful for meaningful data center energy analysis. For example, the variables used to calculate the PUE metric could be difficult to measure if the data center is housed in a mixed-use building. Hence, the site power may misrepresent the actual power used by the data center due to inclusion of power used for lighting, employees' offices and other non-IT related activities. In addition, the metric is overly simplified, and does not provide the technical base both necessary and required for proper engineering analysis. For example, if all the servers in a data center are idle and producing no useful work and the cooling resources are well provisioned so the power consumed by the cooling and other supporting resources is only an additional 20% of the IT power, the resulting PUE value would be a perfect 1,2. In this instance, the PUE metric gives the indication that the data center is very well optimized, however the data center is actually wasting energy since no real work is being performed. [10]

In summary, the PUE metric does not address how data center efficiency changes as the IT load changes and it does not address how well the data center is being utilized; therefore, this metric would not be of value to real efficiency analysis. In general there is inconsistency and confusion in the way PUE variables are determined and measured which may render the results inaccurate. It is also important to mention that PUE does not have any system performance indices such as systems CPU utilization. The PUE is a simple measure of the data center site power relative to the IT power, and should be used with extreme caution to avoid misrepresentation of the actual data center performance. The area that PUE metric covers can be seen from Figure 28.

Impact: Strategic, Relevance: High, Complexity: Medium – PUE measures how efficient is data center facility in delivering power to IT equipment. PUE is a classic metric and has been adopted widely. PUE definitely has its drawbacks but as it is a norm in the industry so it should be calculated. PUE is a poor indicator of a data center's actual energy efficiency; it is also a poor indicator of how green a data center actually is. One must use caution in interpreting PUE results of the metric as it is non-trivial to understand what lies behind the actual numerical PUE value. PUE is moderately complex metric, it can be calculated thus it must be automated. PUE impact is on a strategic level, and it is a must have metric and relevant for any data center.

Revised PUE (example): The PUE metric as currently defined has significant gaps. These gaps were developed when PUE was for practical purposes defined using energy in the form of grid-based electricity. No consideration was made for on-site energy such as diesel/natural gas used in testing the generators or running them in an outage. Further, though a bit more difficult to sort out but far from impossible there was no consideration made for the energy content of water. The PUE formula can easily be refined (RPUE) to account for diesel (or other fuel source). This is just one example of Refined PUE. There are numerous revised versions of PUE that address different phenomena in the data center of GreenIT. [18]

Impact: Strategic, Relevance: Medium, Complexity: High – PUE is a de facto standard in the data center industry as a metric that everyone must have. Revised PUE alternatives could be useful but once there is an alternation to the original PUE one loses the benchmarking effect, which is very important factor in PUE. There are better alternative metrics that can be used if revision is needed for PUE. Revised PUE is similar to measure as PUE, quite demanding but doable. Even though RPUE is an enhanced version of original PUE, it is still a relational metric.

Cloud Data Center Energy Efficiency CDCEE: CDCEE is a metric especially for Cloud service provider. It uses IT Utilization (ITU) which denotes the ration of average IT use over the peak IT capacity in the cloud data center and ITE which stands for IT efficiency, meaning the amount of useful IT work done per joule of energy. After multiplying ITU and ITE the result is divided by PUE. [7]

Impact: Strategic, Relevance: Medium, Complexity: High – CDCEE is a useful metric thus it is using PUE which has certain drawbacks built in the metric .The fact that this metric takes into account utilization rate and efficiency is relevant. CDCEE is a quite complex metric to measure. CDCEE is a strategic level metric.

System Power Usage Effectiveness sPUE: sPUE is intended to capture the effectiveness of a specific High Performing Computing (HPC) system for a specific data center. PUE depends on multiple factors like cooling power used in the data center and the power consumption of the IT equipment. In reality, the PUE of a data center will change if the current HPC system is replaced with a different system. This is especially true if the cooling technology changes, as all electrical power going into a HPC system is converted into heat and needs to be removed by the data center cooling system. The most commonly used cooling technologies are: air cooling - where heat is removed using air as the transfer medium and water cooling - where heat is removed directly or indirectly by using water. Each of these cooling technologies has a different overhead, meaning how much additional power is needed to remove one Watt of heat from the system. Using the physical process of Joule heating, which describes the increase in temperature of an electrical conductor due to conversion of electrical to thermal energy, one can substitute IT equipment power with IT heat quantities. Figure 28 illustrates coverage of PUE, sPUE, WPE and DWPE. [36]

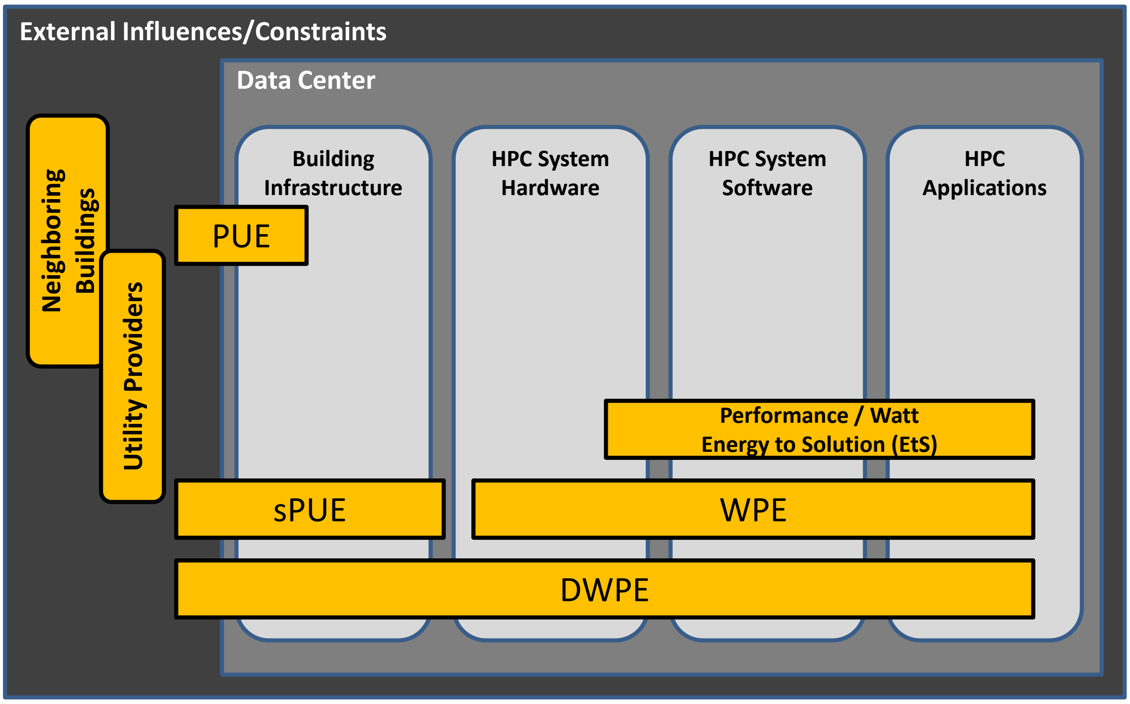


Figure 28. PUE, WPE, sPUE and DWPE coverage[36].

Impact: Strategic, Relevance: High, Complexity: High – sPUE is used to calculate data center WPE. The idea behind sPUE is solid; it can address a specific HPC system and indicate its power usage effectiveness. sPUE is difficult to measure on an ongoing basis.

Data Center Workload Power Efficiency DWPE: DWPE is energy efficiency metric for a specific workload, running on a specific HPC system and covering all four pillars in Figure 28. DWPE will make the connection between workload energy efficiency of the HPC system and the data center infrastructure by combining the Performance/W metric of the HPC system with the PUE for the system in a data center. DWPE will help data centers with tracking their energy efficiency over time. It can be used as a reference point against which other things can be evaluated, and it will help data centers to better understand their energy consumption by requiring additional measurements. To help with the definition of DWPE two additional metrics are also needed, namely WPE and sPUE. [36]

Impact: Strategic, Relevance: High, Complexity: High –This metric is very useful for comparing the energy efficiency of different HPC systems and cooling solutions for running one particular workload. Estimating their DWPE should be straightforward for most HPC data centers today. With this information condensed in one metric, data center operators can identify whether it is better to invest into infrastructure or system renewal. The tests have also shown the significance of matching the system architecture to the actual workload for increased energy efficiency. Therefore, each data center operator needs to find representative benchmarks that reflect well the workload mix of their data center. DWPE is a strategic level metric.

Fixed to Variable Energy Ratio (FVER): FVER is a metric that can be used to measure the data center energy efficiency, instead of using the classic PUE metric. FVER metric combines and meets all the needed criteria for better energy efficiency assessment in data centers. These assessments include the usage of IT and software applications in data centers. FVER provides a clear, preferably intuitive understanding of the measure and a clear, preferably intuitive direction of needed improvement. FVER describes clearly defined part of the energy to useful work function of the IT services. It is persistent, meaning that the metric is designed to be stable and extensible as the scope of efficiency measurement increases, rather than confusing the market with rapid replacement. FVER demonstrates the improvements available in a modern design of facility, and the improvements available through upgrade of existing facilities using more efficient systems. In addition FVER provides a clear, intuitive understanding of the impacts of changes, and it is possible to determine the energy use at the electrical input to the data center for any specified device or group of devices within the data center. FVER supports also 'what if' analysis for IT and data center operators in determining the energy improvement, and Return On Investment (ROI) for improvements and changes to either the facility or the IT equipment it houses. [13] Figure 29 illustrates what FVER covers compared to classic PUE.

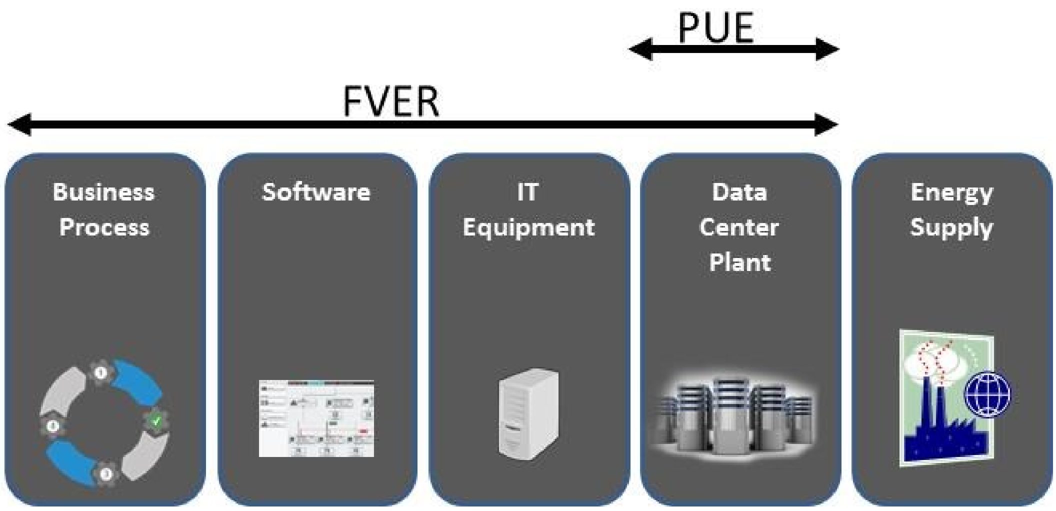


Figure 29. FVER and PUE coverage.[13]

Impact: Strategic, Relevance: High, Complexity: High – The theory behind FVER is sound, as normally a data center environment's power consumption can be modelled as approximately linear (ax+b), the sum of a fixed load (b) and a variable load (ax) that is approximately directly proportional to utilization. [13] By targeting the ratio one can start to think about reducing the fixed load, which means an underutilized data center will become much more efficient. FVER is strategic level metric, and a very relevant complement to PUE.

Data Center energy Productivity DCeP: DCeP metric correlates the data center throughput with the consumed power. DCeP presents, how much work IT equipment can do in data center facility. DCeP is the first attempt to define a useful work metric. Useful work depends on two readings; the tasks performed by the hardware and the assessment window. Tasks should be as specific as possible, while the assessment window should be no shorter than about 20 times the mean run time of any of the tasks initiated in the assessment window, according to the Green Grid, 2008. A data center should define both figures according to their workload and business model. DCeP acknowledges that some tasks are more important than others. Some may be mission critical while others may involve a response time that is an integral part of an SLA time-based utility function. To simplify the calculation, the task value and utility function can be assigned as (1), meaning that all tasks are weighted the same. From there, useful work boils down to the number of tasks (jobs, transactions) carried out by the hardware during the assessment window. [29]

Total DCeP calculation involves two figures: the kWh of the hardware in question and the PUE of the facility. If the hardware and infrastructure are efficient, this reading will improve. To arrive at this answer, a facility must have an efficiency benchmarking program for PUE/ DCiE and the ability to measure power at the device level. While not all data centers have this capability, new software, the latest rack power products, and power meters can all track power consumption at the device level. This consumption in kWh is multiplied by the PUE figure to arrive at the total energy consumed during the assessment window. [29]

DCeP represents a necessary progression in metrics, for the efficiency conversation must include productivity. By measuring PUE/DCiE consistently, users can identify and remediate infrastructure deficiencies through sealing cable cutouts, tuning hot/cold aisles, and adjusting temperatures. Small improvements in physical infrastructure go a long way, and users should begin the process with the initial PUE/DCiE benchmark. [29]

With these improvements in place, users can then focus on the output of their data center and the productivity of their computing systems. This process may open doors to consolidation, virtualization, and the decommissioning of idle, older compute platforms. [29]

Impact: Strategic, Relevance: High, Complexity: High – The mantra of the moment is right-sizing. Calculating DCeP allows users to right-size virtual and physical infrastructures to support business needs. The DCeP factor gives an estimate of the performance of the data center. DCeP is very comprehensive, very accurate but difficult to measure. It is a strategic level metric.

Energy Proportionality Coefficient EPC: Ideally, energy consumption of network devices should be proportional to their workload. However, in reality neither computing servers nor network switches are energy-proportional. Many servers consume up to 66% of their peak power consumption when idle. For network switches this ratio is even higher and can reach 85%. EPC is measured as energy consumption of a system or a device as a function of the offered load. In the ideal case, EPC is represented by a straight line; every increase in load should correspond to the equivalent increase in power consumption. In reality, the observed power consumption is often non-linear. Its energy-proportionality varies depending on the incline with the respect to the ideal case. Energy-proportionality has been first discussed for computing servers and then for network equipment. [17]

Impact: Strategic, Relevance: High, Complexity: High – EPC is a very important metric. Energy-proportionality is in the very core of GreenIT concepts. EPC is difficult to measure. EPC is important input to design processes. It is one of the most important strategic level metrics for energy efficiency.

Table 9. Metrics for CO_2 and reneweables use (EEM 6).

EEM 6	Index Name	Main purposes	EEM Category	DCT Category
1.	WUE Water Usage Effectiveness [40]	Metric for water usage in the data center.	EEM 6	DCT 7
2.	CUE Carbon Usage Effectiveness [40]	Measures carbon emissions associated with data centers.	EEM 6	DCT 7
3.	REF Renewable Energy Efficiency [40]	Metric to quantify the effort to use renewable energy managed by owner/operator for their data center.	EEM 6	DCT 7

In Table 9 are the metrics for the CO_2 emissions and usage levels for renewable energy. These metrics are presented and evaluated in more detail next.

Water Usage Effectiveness WUE: WUE is a metric developed by The Green Grid to help data centers measure how much water a facility uses for cooling and other building needs. According to The Green Grid, a water use metric allows a data center manager to understand the effect water consumption has on the local electric grid. By using WUE in conjunction with power usage effectiveness and carbon usage effectiveness metrics, an organization can reduce energy use and, in effect, reduce the amount of water and electrical power needed to run the data center efficiently. [40]

To calculate simple WUE, one must divide the annual site water usage in liters by the IT equipment energy usage in kilowatt hours (kWh). Water usage includes water used for cooling, regulating humidity and producing electricity on-site. IT equipment energy includes any power drawn by hardware used in the day-to-day functioning of the data center. [40]

Impact: Strategic, Relevance: High, Complexity: Low – With WUE metric in place, organization can reduce energy use and, in effect, reduce the amount of water and electrical power needed to run the data center efficiently. This is essential target in overall GreenIT concept. WUE is relevantly easy to measure once the metering system is in place. It is advisable to set strategic WUE target level.

Carbon Usage Effectiveness CUE: CUE is used to address carbon emissions associated with data centers. The impact of operational carbon usage is emerging as important in the design, location, and operation of current and future data centers. When used in combination with the PUE metric, data center operators can quickly assess the sustainability of their data centers, compare the results, and determine if any energy efficiency and/or sustainability improvements need to be made. CUE represents the second metric in the family of xUE metrics designed to help the data center community better manage the energy, environmental, societal, and sustainability-compliance parameters associated with building, commissioning, operating, and de-commissioning data centers. [40]

Like PUE, CUE uses the familiar value of total IT energy as the denominator. Once determined for PUE, the same value should be used as the denominator for the new metric as well. This commonality of structure will not only simplify CUE use, but it also will ensure that the metric stays linked to the xUE family and speed its adoption. Unlike PUE, CUE has dimensions while PUE is unit-less; its value is energy divided by energy. Another important difference is the range of values. PUE has an ideal value of

1,0 which implies that all energy used at the site goes to the IT equipment, and there is no theoretical upper boundary for PUE. CUE has an ideal value of 0, indicating that no carbon use is associated with the data center's operations. Like PUE, CUE has no theoretical upper boundary. [40]

Both CUE and PUE simply cover the operations of the data center. They do not cover the full environmental burden of the life-cycle of the data center and IT equipment. For example, attempting to determine the carbon generated in the manufacturing of the IT equipment and its subsequent shipping to the data center would make the metric far too difficult to measure, calculate, or use. Full life-cycle will be important to the overall sustainability of the industry but, for practical considerations, they are excluded from this metric. [40]

Impact: Strategic, Relevance: High, Complexity: Low – CUE and future xUE metrics will have the same positive impact on the industry as did PUE. It is advisable that industry stakeholders to adapt CUE, and participate in further developing measurement and reporting guidelines for CUE and other xUE metrics. The use of CUE is essential, even though refinement is needed for this metric. CUE is moderately easy to measure once PUE is implemented.

Renewable Energy Factor REF: REF is an operational Key Performance Indicators (KPI) corresponding to the use of renewable energy. REF is the ratio of local renewable energy over the total data center energy consumption. It is a dimensionless number. [40]

Impact: Strategic, Relevance: High, Complexity: Low – REF is a metric that investigates the ratio of renewable energy used compared to total energy used. Even though onsite renewables is more interesting, it is a good indicator of the GreenIT ideology in management agenda. REF is moderately easy to measure once PUE is implemented. REF is the main metric for the renewables usage.

In the next part all metrics are reviewed against technology domains. The idea is to ensure that all technology domains are covered either directly or indirectly. There can be no areas without metering, which would cause inaccurate overall understanding of the energy efficiency in the data center.

4.5 Data Center Technology Metric Category

Similarly to the previous part analysis, the objective of this part is to go through each of the data center technology domains separately, and evaluate the energy efficiency metric coverage from the technology perspective.

Table 10. Metrics for servers (DCT 1).

DTC 1	Index Name	Main purposes	EEM Category	DCT Category
6.	Performance/Watt [36]	Metric of the energy efficiency of particular computer architecture or computer hardware.	EEM 3	DCT 1
10.	Workload Power Efficiency WPE [36]	Energy efficiency metric for a specific workload running on a specific HPC system.	EEM 3	DCT 1and 3
15.	Data Center energy Productivity DCeP [29]	Correlates the data center throughput with the consumed power.	EEM 5	DCT 1
22.	Energy Proportionality Coefficient EPC [17]	EPC is measured as energy consumption of a system or a device as a function of the offered load.	EEM 5	DCT 1, 2 and 3
25.	Inter-Server Communication Latency ISCL [17]	Communication latency between computing servers.	EEM 2	DCT 1
26.	Inter-Server Hop Distance ISHD [17]	Measures number of hops, it takes for one task to communicate with another task executed on a different server.	EEM 4	DCT 1
30.	Inter-Server Error Rate ISER [17]	Measures error rate of the network paths between computing servers.	EEM 2	DCT 1
32.	Average Server Degree Connectivity ASDC [17]	Measures average number of links per server.	EEM 2	DCT 1

Coverage: Sufficient - There are many metrics that address the servers directly and indirectly in Table 10. There are metrics for workloads, productivity, energy-proportionality, inter-server communications and network distance. Servers are covered from energy efficiency, and performance perspective.

Table 11. Metrics for networks (DCT 2).

DTC 2	Index Name	Main purposes	EEM Category	DCT Category
20.	Communication Network Energy Efficiency CNEE [17]	Measures the amount of energy required to deliver a single bit of information by the network.	EEM 4	DCT 2
21.	Network Power Usage Effectiveness NPUE [17]	NPUE specifies which fraction of the power consumed by the IT equipment is used to operate data center communication system.	EEM 4	DCT 2
22.	Energy Proportionality Coefficient EPC [17]	EPC is measured as energy consumption of a system or a device as a function of the offered load.	EEM 5	DCT 1, 2 and 3
23.	Uplink/Downlink Communication Latency UDCL [17]	Communication latency between data center gateway and computing servers.	EEM 2	DCT 2
24.	Uplink/Downlink Hop Distance UDHD [17]	Hop distance between data center gateway and computing servers.	EEM 2	DCT 2
28.	Bandwidth Oversubscription Ratio BOR [17]	Ratio between the aggregate ingress and aggregate egress bandwidth of a network switch. Important to estimate the minimum non-blocking bandwidth available to every server.	EEM 2	DCT 2
29.	Uplink/Downlink Error Rate UDER [17]	Measures error rate of the paths between data center gateway and servers.	EEM 4	DCT 2
31.	Average Link Utilization Ratio ALUR [17]	Measures average link occupancy.	EEM 4	DCT 2
33.	Internal Traffic Ratio ITR [17]	Measures traffic exchanged within the data center.	EEM 4	DCT 2
34.	External Traffic Ratio ITR [17]	Measures traffic destined outside the data center.	EEM 4	DCT 2
35.	Management and Monitoring Traffic Ratio MMTR [17]	Measures traffic generated by management and monitoring operations.	EEM 4	DCT 2
36.	Management and Monitoring Traffic Energy MMTE [17]	Measures energy consumption of management and monitoring traffic.	EEM 4	DCT 2

Coverage: Sufficient - Similar to servers, energy efficiency metrics cover widely the network domain as can be seen from Table 11. It is covered on network level as well as on device level. Also the energy-proportionality is measured. Naturally, there are many network specific metrics that give good insight and opportunities for energy efficient architecture design and changes to existing design. Also network management is covered with two different metrics.

Table 12. Metrics for storage (DTC 3).

DTC 3	Index Name	Main purposes	EEM Category	DCT Category
10.	Workload Power Efficiency WPE [36]	Energy efficiency metric for a specific workload running on a specific HPC system.	EEM 3	DCT 1and 3
22.	Energy Proportionality Coefficient EPC [17]	EPC is measured as energy consumption of a system or a device as a function of the offered load.	EEM 5	DCT 1, 2 and 3
27.	Database Access Latency DAL [17]	Measures average latency of accessing database from computing server.	EEM 2	DCT 3

Coverage: Moderate - Storage is essential for data center infrastructure. This being said, there is very little mentioning about metrics that directly address storage. It Table 12 workloads, energy-proportionality and access latency are indirectly taking storage into account though. For future research this area could be studied in more detail.

Table 13. Metrics for cooling (DTC 4).

DTC 4	Index Name	Main purposes	EEM Category	DCT Category
5.	Thermal Correlation Index TCI [26]	Quantifies the response at the i:th rack inlet sensor to a step change in the supply temperature of j:th CRAC.	EEM 1	DCT 4
16.	Rack Cooling Index RCI [28]	RCI evaluates how effectively the IT equipment inside the racks is maintained within the recommended rack intake temperature range.	EEM 1	DCT 4

Coverage: Sufficient - Cooling is one of the most energy hungry technologies in the data center. In this research review only two metrics directly address cooling solutions were found and they are presented in Table 13. But the amount is not everything that counts, when it comes to energy efficiency metric coverage. TCI is sensor based metric that provides clear energy efficiency overview over cooling. RCI controls the racks, which are the main heat source in the data center.

Table 14. Metrics for air movement (DTC 5).

DTC 5	Index Name	Main purposes	EEM Category	DCT Category
17.	Return Temperature Index RTI [28]	RTI was proposed to measure air management effectiveness.	EEM 1	DCT 5
18.	Supply and return Heat Indexes SHI, RHI [28]	The level of separation of cold and hot air streams can be measured by the supply and return heat indices. SHI is defined as the ratio of sensible heat gained in the cold aisle to the heat gained at the rack. RHI is defined as the ratio of heat extracted by the cooling system to the heat gained at the rack exit.	EEM 1	DCT 5

Coverage: Sufficient - As goes for cooling, goes also for air movement metrics. Only two relevant metrics were found and they are presented in Table 14. RTI is an overall metric especially for air movement inside the data center. SHI and RHI are dynamic metrics that are based on sensor networks data. They illustrate heat flow inside the racks. These two directly air movement addressing metrics together with general metrics provide sufficient coverage to air movement solution energy efficiency.

Table 15. Metrics for uninterruptable power supply UPS (DTC 6).

DTC 6	Index Name	Main purposes	EEM Category	DCT Category
37.	UPS Efficiency Rating	Shows how much of the original incoming utility power is used to power your critical load versus how much is lost in the operation of the UPS.	EEM 1	DCT 6

Coverage: Moderate - Only one direct energy efficiency metric is found for the UPS systems as presented in Table 15. This can be seen quite surprising. UPS systems consume much energy inside a data center but metrics that address UPS systems directly are limited in quantity. UPS efficiency rating is still a valid metric to illustrate energy-proportionality of an UPS system as a function of load. It is a dynamic metric and needs to be monitored actively. Also vendors provide fixed diagrams on empirically measured data that can be used for sizing purposes. UPS is taken into account in many of the general level metrics.

Table 16. Metrics that apply to all equipment (DTC 7).

DTC 7	Index Name	Main purposes	EEM Category	DCT Category
1.	Water Usage Effectiveness WUE [40]	Metric for water usage in the data center.	EEM 6	DCT 7
2.	Carbon Usage Effectiveness CUE [40]	Measures carbon emissions associated with data centers.	EEM 6	DCT 7
3.	Renewable Energy Efficiency REF [40]	Metric to quantify the effort to use renewable energy managed by owner/operator for their data center.	EEM 6	DCT 7
4.	Thermodynamic efficiency [11]	Ratio of useful work produced by the system to the total energy expanded to produce this useful work.	EEM 5	DCT 7
7.	Power Usage Effectiveness PUE [28]	Ratio of total power draw of the datacenter to the total power consumed by the IT equipment within the racks.	EEM 5	DCT 7
8.	Revised PUE (example) [18]	There are several revised PUE metrics for different purposes.	EEM 5	DCT 7
9.	Cloud Data Center Energy Efficiency CDCEE [7]	Cloud Data Center Energy Efficiency CDCEE is a metric for especially Cloud service provider.	EEM 5	DCT 7
11.	System Power Usage Effectiveness sPUE [36]	sPUE is intended to capture the effectiveness of a specific HPC system for a specific data center.	EEM 5	DCT 7
12.	Data Center Workload Power Efficiency DWPE [36]	DWPE will make the connection between workload energy efficiency of the HPC system and the data center infrastructure by combining the Performance/W metric of the HPC system with the PUE for the system in a data center.	EEM 5	DCT 7
13.	Fixed to Variable Energy Ratio (FVER) [13]	Could be used instead of PUE. Combines and meets all the needed criteria for better energy efficiency assessment in data centers.	EEM 5	DCT 7
14.	Data center infrastructure energy DCiE [28]	Expresses the fraction of the total power supplied to the data center and is delivered to the IT load	EEM 1	DCT 7
19.	Power Density Efficiency PDE [28]	A variation of PUE. Provides insight into the improvements to both the IT equipment and the supporting cooling system. Enables evaluation of impact of physical changes inside the racks on energy efficiency, which is not possible using the common metrics.	EEM 1	DCT 7

Coverage: Sufficient - There are several metrics that cover every device in the data center indirectly, and create an overall map of energy efficiency in the data center. These metrics are presented in Table 16. There are also many metrics that address the renewables use which affect the CO_2 emissions. Thermodynamic efficiency is also one of the key energy efficiency metrics available. PUE based metrics give opportunities of some kind of industry benchmark thus it has its problems in data reliability. DWPE and FVER address the dynamic nature of data center loads and finally the power density efficiency is a sensor network based metric that creates overall picture on where the energy is consumed and how efficiently.

4.6 Selection of the Energy Efficiency Metrics to the Framework

In the previous parts it was evaluated how well different energy efficiency metrics fit for generic data center and especially for Sonera HDC purposes. In addition it was evaluated, how complex these metrics are to measure. On top of that, it was analyzed how well these metrics cover different data center technology domains. The area of impact was also evaluated. All of the metrics were placed into one of the four impact areas. In Appendix 2 there is a summary of the analysis and findings.

After filling in the analyzed dimensions to the table, the importance is calculated by multiplying the relevance with the complexity. Most important metrics are marked with green color and important, but too complex, in the first phase, are marked with yellow. Red indicates that there are questionable results coming from the metric, or that it is too complex metric compared to the relevance. All of these metrics are important in some way regardless of the importance index. But as there cannot be 37 different metrics, prioritization needs to take place. Validity of the metric dimension weighting is done by evaluating scientific articles regarding the pros and cons of each metric. Relevance dimension is partly based on subjective analysis but reasoning backed up with scientific articles regarding known challenges in each of the metric. Evaluation is valid for any large data center that emphasizes sustainability and green values.

After this analysis the most important metrics were selected, and marked with green color. In order to ensure that all main domains of energy efficiency are covered as well as main technological domains, few additional metrics were selected to fill the gaps. Table 17 presents the selection of the final metrics for the framework.

It is important to evaluate the order in which metrics are implemented. It is advisable to start with the strategic level metrics as it is important to get an overall picture of the energy efficiency first. Next, it is advisable to start to measure the tactical level metrics, followed by the operational and informative metrics. One can also consider that there are three different ways to measure these indicators. There are eight metrics that require sensor network for data collection in real-time. Even though sensor network is implemented, it does not result as working energy efficiency metric bundle as analysis and presentation software needs to be in place. Especially if there are also control mechanisms in use. There are also metrics that require some sort of measuring device and computation on top of the device. The third way is to get the metric values from the existing systems. This is the simplest way. All of these metrics are deterministic in a way. They have similarities, but they all require individual design and deployment. It is easier to implement other sensor network based metrics once the sensor network is in place, but it is only a fraction of the actual implementation of the whole metric as the data analytics is the hardest part.

Table 17. Selected metrics for the framework.

Id	Index Name	EEM Category	DCT Category	Impact Area	Relevance	Complexity	Importance
1.	Water Usage Effectiveness	EEM 6	DCT 7	Strategic	High (3)	Low (3)	(9)
2.	Carbon Usage Effectiveness CUE	EEM 6	DCT 7	Strategic	High (3)	Low (3)	(9)
3.	Renewable Energy Efficiency REF	EEM 6	DCT 7	Strategic	High (3)	Low (3)	(9)
20.	Communication Network Energy Efficiency CNEE	EEM 4	DCT 2	Strategic	High (3)	Medium (2)	(6)
10.	Workload Power Efficiency WPE	EEM 3	DCT 1 and 3	Strategic	High (3)	High (1)	(3)
22.	Energy Proportionality Coefficient EPC	EEM 5	DCT 1, 2 and 3	Strategic	High (3)	High (1)	(3)
25.	Inter-Server Communication Latency ISCL	EEM 2	DCT 1	Tactic	Medium (2)	Low (3)	(6)
27.	Database Access Latency DAL	EEM 2	DCT 3	Tactic	High (3)	Low (3)	(9)
28.	Bandwidth Oversubscription Ratio BOR	EEM 2	DCT 2	Tactic	High (3)	Low (3)	(9)
32.	Average Server Degree Connectivity ASDC	EEM 2	DCT 1	Tactic	High (3)	Low (3)	(9)
33.	Internal Traffic Ratio ITR	EEM 4	DCT 2	Tactic	High (3)	Medium (2)	(6)
34.	External Traffic Ratio ITR	EEM 4	DCT 2	Tactic	High (3)	Medium (2)	(6)
37.	UPS Efficiency Rating	EEM 1	DCT 6	Tactic	High (3)	Medium (2)	(6)
16.	Rack Cooling Index RCI	EEM 1	DCT 4	Tactic	High (3)	High (1)	(3)
17.	Return Temperature Index RTI	EEM 1	DCT 5	Tactic	High (3)	High (1)	(3)
29.	Uplink/Downlink Error Rate UDER	EEM 4	DCT 2	Operative	High (3)	Medium (2)	(6)
30.	Inter-Server Error Rate ISER	EEM 2	DCT 1	Operative	High (3)	Medium (2)	(6)
23.	Uplink/Downlink Communication Latency UDCL	EEM 2	DCT 2	Informative	Medium (2)	Low (3)	(6)
24.	Uplink/Downlink Hop Distance UDHD [17]	EEM 2	DCT 2	Informative	Medium (2)	Low (3)	(6)
26.	Inter-Server Hop Distance ISHD	EEM 4	DCT 1	Informative	Medium (2)	Low (3)	(6)

4.7 Summary of the Chapter

As we can see from the table in Appendix 1, there are plenty of relevant metrics available to be used for objectively assessing energy efficiency in a data center. Some of the metrics are more complex than others, and all of them serve a different purpose, and provide a window to the world of energy efficiency. Energy efficiency is a complex matter. It is evident that improving energy efficiency requires analytical skills and expertise, sometimes tough optimization decisions between opposing forces. This chapter introduces the whole set of relevant metrics from which the most important metrics are selected to the actual metric framework.

After evaluation, presented set of metrics provide a holistic approach to energy efficiency, and ensures sufficient input for the Deming Cycle for continual improvement. Deming Cycle ensures, that energy efficiency activities are visible to all levels, namely to the strategic, tactical and operational levels. There are many good metrics available but after the evaluation and analysis some of them are more important than others. Also some of them measure the same outcome, and only the most relevant was selected. All the metrics presented and analyzed are relevant but it is not advisable to have close to forty metrics as it is both complex and costly. In addition, having overlapping metrics is not rational, and it creates confusion instead of concrete areas for improvement.

In Chapter five the results on different energy efficient solution are presented. These solutions are examples of the means to improve energy efficiency that the metrics in Chapter five are measuring. It is important to understand the impact of different solutions to overall energy efficiency, and based on this understanding select the best fit solutions for data centers purposes.

5 RESULTS ON DIFFERENT ENERGY EFFICIENT TECHNOLOGIES

In this part, answer to the second main question is presented: What energy efficient technologies should be implemented, and in what order to gain most impact? The idea is to evaluate the ideas presented in the previous literature and research part of this thesis and present phased action plan for solutions that would create greener and more energy efficient data center. As Sonera HDC is under construction as this thesis is being written, it can contain some of the most advanced energy efficient technological solutions available. But having the equipment does not necessarily mean that they are used in an optimal way, and thus this phasing can have relevance to other organizations trying to implement similar project.

In this chapter the previously presented energy efficient solutions are analyzed and rated based on, how realistic and relevant these solutions are from the implementation perspective. Some of these ideas are in the R&D phase and most of them are non-standard solutions, which has significant impact on their attractiveness even though they would be very beneficial from the energy efficiency perspective. Even though Sonera HDC project is ongoing and some initial solutions have already been made, this is no obstacle to review future development opportunities for the Sonera HDC as it is being deployed as modular from space and technology perspective. There can be server rooms with different solutions and different requirements. Analysis is starting from the main technology categories and solutions are placed to these categories. After briefly describing the potential of the solution, an analysis of the relevance and urgency of each of these solutions is done. The final phased plan is presented in the conclusion Chapter seven. Naturally these conclusions cannot be holistic as financials, meaning that CAPEX/OPEX information for each solution is not available.

5.1 Selecting the Example Solutions

Evaluating energy efficient solutions is very important. There are various methods for doing such an evaluation. Firstly simulations can be created. There are plenty of simulators available to simulate cloud-based environments. Simulations become even more convenient when the implementation of a solution does not yet exist. Secondly small scale empirical experiments can be created. In this methodology the experiment setup is prepared in hardware testbeds in small scales. The number of devices and links is much lower than in reality making it more convenient to use instead of full deployment. Thirdly there is the numerical analysis where the output results from literature study are used as a reference for the reasoning process. Lastly there is the option of doing empirical experiments in the production data center. This can be seen best way for evaluating a solution as it is tested in real world scenarios. By using real data center for experimentation the results are more realistic and accurate. However, it is not always easy to get a production data center for testing purposes. [9]

All of the energy efficient solutions selected for this thesis have been evaluated by at least one of the previously presented methodologies, so there are no imaginary solutions presented. Still the actual wide scale production data center testing is missing from some of the solutions. In order to gain competitive edge as an data center provider wide adaptation to move forward with some novel solution cannot always be waited, but rather testing must be done by themselves to find out whether the solution gives competitive edge or not.

Solutions are divided into five different energy efficiency solution technology categories (EESTC) based on the structure of the previous literature review in Chapter three. Categories are presented below in the Figure 30. All of the presented solutions are placed into these categories for ensuring that at least indirect coverage is achieved for all the main categories. There are many solutions that target the telecommunication network, which is quite obvious as virtualization is already widely adopted globally in the telecommunication industry.

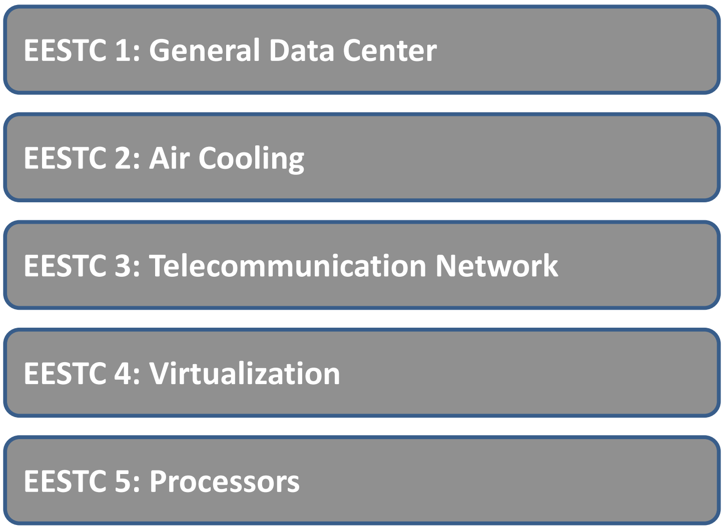


Figure 30. Energy Efficiency Solution Technology Categories (EESTC).

After reviewing energy efficiency solutions from the scientific reference articles the findings of the most commonly cited solutions are listed in Appendix 3.

5.2 Analysis of Presented Solutions

All the presented technology categories and solutions inside them are analyzed separately in this chapter. Analysis is based on evaluating four different dimensions. Firstly the solutions impact on the overall energy efficiency (IOEE) is evaluated. In this dimension, it is reviewed, how large energy efficiency impact the solution has. The second dimension analyzes how widely the solution is adopted in the data center market? This information is based on industry knowhow of the TeliaSonera and Cygate, and also on the data sheets of different vendors and service providers. Thirdly the complexity of an implementation is evaluated based on the scientific articles written on that solution. Finally the cost of the solution is estimated from available sources. All of these dimensions are then taken to the table for reasoning on the importance of solution from energy efficiency perspective. It is important to note that energy efficiency is only one of the main factors in finding optimal solutions for data center. This thesis proposes solutions for data centers that have publicly declared to emphasize energy efficiency. Figure 31 illustrates different solution evaluation dimensions, and their weight in the equation that that calculates the overall importance. This is a techno-economic benefit analysis.

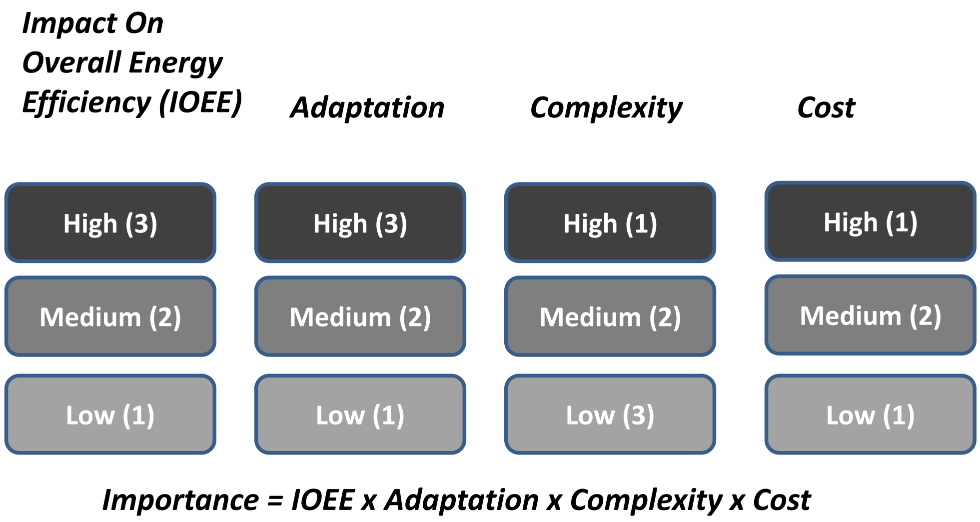


Figure 31. Energy efficiency solution dimensions and weights.

Each of the technology categories is presented separately. Solutions, which belong to each category, are evaluated individually, starting from the EESTC1 category presented in Table 18.

Table 18. Energy efficiency general solutions for data center (EESTC 1).

EESTC1	Solution	Main purposes	EESTC Category
1.	Sleeping mode / Switching Off	Aim is to improve the energy efficiency by deactivating idle devices.	EESTC1
10.	Traffic minimization	The smaller the traffic becomes, the less energy will be consumed in the data center.	EESTC1
11.	Green energy	Energy produced from renewable and nonpolluting resources.	EESTC1
15.	Modular data center	Aim is to have outside air fans and louvers on top of the racks to increase energy efficiency. Standard hardware solution and easy to increase capacity. Project Blackbox is a good example of this solution.	EESTC1 and EESTC2

Sleeping mode/ Switching Off
IOEE: High, Adaptation: Low, Complexity: Medium, Cost: High – The power consumption of the devices is quite surprisingly almost independent from the network load. It can be shown that the energy demand for heavily loaded devices is only about 3% greater than that of idle ones. It is necessary to develop and use energy efficient architectures exploiting the ability to temporarily switching off or putting into energy saving mode devices or sub-systems. Putting entire nodes to sleep mode may be unpractical, especially for large and highly connected devices, since many very expensive transmission links can become unused. There are also considerations on the reliability and load balancing. Putting single interfaces to sleep mode can introduce considerable energy savings especially when operating at high speeds. Sleeping mode or switching off devices has significant impact on energy efficiency thus it has drawbacks on reliability and load balancing; these are the main obstacles for full

adaptation in the data center market. [48] Many vendors support this functionality but in order to be effective, an overlay control system is required to manage these state changes network wide. Cost is a relative question. Naturally if one is to implement these new features the devices need to be selected accordingly, the marginal added cost might not be a huge addition to investment but if one needs to transform existing devices to new devices the cost can be substantial.

Traffic minimization
IOEE: High, Adaptation: Low, Complexity: High, Cost: High – Virtualization has not changed the distribution, composition, or invocation of the application. In other words, virtualization has not changed the usage model of the application, nor has it changed the run-time model of the application - what it has done is changed the management model of the infrastructure of an application. Cloud computing offer the application components as services. The application itself transforms into lightweight services that can reside anywhere, and can be invoked from anywhere on an Internet scale on any device. The management of these services is governed by a service level agreement (SLA) between the cloud provider and the end user, and a substantial portion of the management function is delegated to the end user. Data centers are evolving to adopt a cloud service model. Whether the deployment model is public or private, the challenges that face application architectures are the same. To overcome these challenges, infrastructure used by the applications needs to evolve to support the cloud service models. Of the three models - PaaS, IaaS, and SaaS - IaaS and PaaS are expected to guide the evolution of Layer 4-7 services. [49] Unfortunately there are no widely adopted Green application guidelines that would target towards overall traffic decrease. Evidences show quite the opposite. The amount of data is increasing on gigantic scale and faster than the processing power of devices. Data center service providers can use incentives to increase the need to optimize application traffic to lower levels. The lower the amount of traffic the less energy is required. Cost of this solution is seen high because application development is expensive and developing energy efficient application is even more expensive.

Green energy
IOEE: Low, Adaptation: Medium, Complexity: Low, Cost: Medium – Green energy is a strategic choice for data center provider. Selecting renewable energy source from the grid with some Green electricity smart grid is just a mechanical choice. Utilizing off-grid renewables and heat re-circulation are the strategic choices that make a difference in wider picture. Naturally demand for grid based renewables is also essential that supports indirectly the building of new renewable energy capacity and reduces CO_2 emissions. Therefore it is essential to move towards sustainable decision making regarding the energy sources that are used. Choosing renewable energy sources does not impact energy efficiency directly but it is easy to implement and marginal cost addition for such an action is not significant compared to the impact of climate. Green energy utilization can also be seen as company image marketing.

Modular data center
IOEE: Medium, Adaptation: High, Complexity: Low, Cost: Medium – Through the short history of modular solutions and vendor marketing, a definition and categorization of solutions has emerged. A modular data center can be defined as more of an approach to a data center design that incorporates contained units, many times in the form of prefabricated modules. The modular data center market has evolved to a

fledgling market of vendors that produce everything from containers to a variety of modular designed products and solutions for IT, power and cooling. In some ways the shift in IT such as cloud computing has been in parallel with modular data center approaches. Modular elements for both IT and the data center exist in two alternative concepts. [50]

Firstly a data center product called container incorporates customized infrastructure to support power or cooling infrastructure, or racks of IT equipment. Containers are built using an ISO (International Standards Organization) intermodal shipping container. [50]

Secondly a modular approach to data center design implies either a prefabricated data center module or a deployment method for delivering data center infrastructure in a modular, quick and flexible method. The primary confusion in terms stems from container versus modular. A data center container is a particular package that is engineered and delivered as such — in an ISO shipping container. A container is not the same thing as modular, but a container can be a part of a modular data center. A modular data center references a deployment method and engineered solution for assembling a data center out of modular components in, many times, pre-fabricated solutions that enable scalability and a rapid delivery schedule. [50]

After the early development of containers, theories evolved and the hype cycle played out for a data center in a box. Numerous hardware vendors, independent companies and data center providers embraced the modular concept and presented their own engineered solution. Modular data centers are becoming more widely used. Data center in a box is provided by several vendors globally. [50] By standardizing equipment the complexity lowers. The cost can thus be higher and might lead to some excess capacity in some areas as everything is bundled into a single type box.

Table 19. Energy efficiency solutions for air cooling (EESTC 2).

EESTC2	Solution	Main purposes	EESTC Category
9.	Heat minimization	Aim is to reduce the total heat in data centers, which improves energy efficiency of cloud-based environments. To mitigate temperature growth in data centers, the load distribution takes place.	EESTC2
13.	Liquid cooling and direct free cooling	Aim is to cool with liquid to the chip level and to use outside air as much as possible for cooling purposes.	EESTC2
15.	Modular data center	Aim is to have outside air fans and louvers on top of the racks to increase energy efficiency. Standard hardware solution and easy to increase capacity. Project Blackbox is a good example of this solution.	EESTC1 and EESTC2
16.	Dynamic Smart Cooling DSC	DSC is a set of real-time control systems that can directly manipulate the distribution of cooling according the needs of the computer equipment.	EESTC2

Solutions that belong to the air cooling category are presented in Table 19. They are evaluated in more detail below.

Heat minimization
IOEE: High, Adaptation: Medium, Complexity: High, Cost: High – Heat minimization is an overall target for any data center. Excess heat can damage the hardware as well as decrease energy efficiency in a data center. There are numerous technologies to deal with the heat but it is only treating the symptom. The effort should be in solving the problem of reducing heat generation as such. All activities that can bring the heat generation lower are advisable. Device vendors are working to lower the heat generation of the devices. Energy-proportionality and sleep modes are being developed. Rule of thumb is that regardless of the heat level the closer one can couple the cooling solution to the heat source, the more effective the cooling is. Air is the heat transfer medium. The more effectively cool air is delivered to the server and hot air is removed back to the CRAC unit, the better the heat transfer and thus the energy efficiency. Hot or cold aisle, increased server inlet air temperatures and variable frequency drives are adopted widely due to their minimal investments. But technologies that require large investments are not so widely used thus considered much. Such technologies are air-side and water side economization, evaporative cooling and liquid cooling.

Liquid cooling and Direct free cooling
IOEE: High, Adaptation: Medium, Complexity: Medium, Cost: High – Most of today's data centers are equipped with servers that rely on air cooling, which is well known to have low cooling efficiency due to undesired air recirculation. As a result, many data centers have started to adopt liquid cooling and free air cooling for improved cooling efficiency. Two important observations can be made; since data centers normally replace only a portion of their servers at a time, an important problem is where in the data center to place those new liquid-cooled servers for the best return on their investment. Given the complex thermal dynamics in a data center the process of deploying liquid-cooled servers, different placement strategies lead to significantly different cooling power consumption. Second observation is that different cooling techniques, including traditional air cooling, liquid cooling, and the emerging free air cooling, must be intelligently coordinated with dynamic workload allocation in order to minimize the cooling and server power of a data center. [51]

Liquid cooling and direct free cooling are becoming widely used in new data center projects. They have a significant impact on the energy efficiency as cooling is one of the major areas that consumes energy in the data center. Systems are quite complex thus there are many available solutions that can be adopted. Cost of liquid cooling and direct free cooling are high but the payback can be quite fast and the both support sustainability and energy efficiency targets.

Modular data center
Evaluated already above.

Dynamic Smart Cooling (DSC)
IOEE: High, Adaptation: Low, Complexity: High, Cost: High – DSC is a technology used to monitor power and cooling in data centers. DSC uses a feedback-based control system in order to provide hot spot control to data center managers. DSC uses sensors that are placed throughout a facility, such as in computer racks, to provide feedback to a central server. System software indicates hot spot locations and increases/decreases cooling as needed. The purpose of DSC is to improve power and cooling efficiency and reduce energy costs. This is similar to the widely-used feedback-based control systems

used in manufacturing. [52] Even though the overall impact on energy efficiency is high because of automated dynamic nature of DSC, it is not so widely adopted. This is mainly because setting up such a system is a complex task. On top of sensor network one needs also the actual control system. Configuring such an automation is time consuming and expensive. DSC is essential for all data centers that aim at energy efficiency even though it is costly and complex.

Table 20. Energy efficiency solutions for telecommunication network (EESTC 3).

EESTC3	Solution	Main purposes	EESTC Category
2.	Traffic Consolidation	Idea is to aggregate network traffic into fewer numbers of links and devices to utilize networking resources and increase energy efficiency.	EESTC3
4.	Optical devices	Aim is to replace current electrical networking devices with optical devices, which consumes less energy and provide more throughput.	EESTC3
5.	Energy-aware routes	Idea is that selection of networking path is based on the energy consumption of switches. Either the switches with less energy consumption will be on the path of total energy consumption of the path will be kept in its minimum level.	EESTC3
6.	Traffic patterns	Aim is to take into account traffic patterns to discover behavior of applications and make intelligent decisions based on that information.	EESTC3 and EESTC4
7.	Traffic locality	Aim is to save networking resources by localizing the traffic in some specific parts of data centers. Fewer networking devices will be involved in data transmission, which consumes less energy.	EESTC3
8.	Energy-aware devices	Aim is to use modified electrical switches that are able to increase their energy efficiency by aggregating the traffic into fewer number of ports and putting idle ports into sleep mode.	EESTC3
12.	Energy Efficient Network Architecture	Aim is to use architectures like FatTree, Bcube, VL2, FlattenedButterfly, Dcell, BalancedTree, VL2N-Tree, Hybrid WDM PON, Torus for example.	EESTC3
14.	Energy efficient scheduling algorithms	Aim is to minimize the total energy consumption of data center by selecting best-fit computing resources for execution of job based on load level and communication potential of the device. DENS is a good example of this technology.	EESTC3 and EESTC4

Solutions that belong to the telecommunication network category are presented in Table 20. They are evaluated in more detail below.

Traffic consolidation

IOEE: Medium, Adaptation: High, Complexity: Medium, Cost: Medium – The power consumed depends on the number of active ports. Consolidating traffic into fewer links and ports reduces the need for excess ports and increases port utilization. Disabling unused ports on a line card reduces the device power consumption. Similarly as the number of active ports increase, power consumed increases linearly. The power *consumed depends on the line speed each port is configured to. This is due to the extra energy required to operate physical layer at higher line speed. Traffic through the device does not have a significant effect on power consumed. Power consumption is independent of packet size. Traffic aware energy efficiency approaches are inspired by the fact that network components are often underutilized. The key principle is to turn on or off network components based on the traffic load. For instance, when the traffic load is low, for example during night time, this approach has the potential to save up to 50% of the total energy consumption. Typically, an elastic tree topology is used to represent the network components that can grow and shrink with the dynamic traffic load. The key challenge is to determine which components to turn off and turn on without compromising the required quality of service. Impact of traffic consolidation is important as it decreases the need to keep underutilized active ports. [53] Traffic consolidation is already in use in many data centers. Configuring traffic consolidation is not a simple task. Cost is relatively low but it takes time to configure it working.*

Optical devices
IOEE: High, Adaptation: High, Complexity: Medium, Cost: Medium – The role of optics in reducing the energy wastage can be significant. Optical technologies emerged as the winning solution for long-distance transmissions due to the very large bandwidth and low attenuation distance figures of optical fibers. Optical solutions are now gaining interest even in short-distance applications, such as high-performance computing, networks on chip, and routers/switches systems, in which a large number of processing units or line cards need to be interconnected to exchange large amounts of information. In this context, both the complexity and the power requirements of electronic interconnection systems do not scale well with the information density. Indeed, electronic solutions carrying higher aggregate bandwidths and operating at higher bitrates need higher wire-counts, and to impose limits to the distance that electronic signals can span without being regenerated. On the contrary, optical systems exhibit a complexity which is almost constant, or slightly increasing, with the information density and the bitrate. In particular, it is possible to achieve a communication bandwidth on a single fiber (or waveguide) of multiple terabits per second with limited power dissipation. In the photonic domain, power requirements are almost independent from both the bitrate and the distances covered by optical signals. [54]

Nowadays, photonic technologies seem to be a promising solution to contain, and even to reduce, power supply and dissipation requirements in modern interconnection systems needing to carry information densities that are constantly increasing. The actual power trend characterizing the electronic technologies seems to be unsustainable; thus, moving some switching operations from the electronic to the optical domain can be a viable alternative to deeply cut down network power consumption. [54] A deep penetration of optical technologies in routers and switches might lead to major changes in networking paradigms, offering the opportunity to re-engineer the network to better suit emerging technologies so as to enable to offer new services. Impact of using optical devices and cabling have a significant impact in energy consumption and it is widely used. Complexity is higher compared to traditional solutions and even though cost of fibers has come down, it is still more expensive than alternatives.

Energy-aware routes
IOEE: High, Adaptation: Medium, Complexity: Medium, Cost: Medium – There are several technologies implemented for routing and switching protocols that improve

energy efficiency. Some of them are used widely and some are only tested in scientific articles but no commercial implementations exist. Widely used technologies include Equal-Cost Multipath (ECMP) which focuses to making use of several routing paths that have equal cost. The forwarding decision on sending the data through more output ports, are made by each router. In data centers, which provide richly connected network architectures, ECMP is used to distribute the load over multiple paths and also increase the total bandwidth for that load. Secondly the classic shortest path selects the shortest path between two alternative nodes thus minimizing the number of nodes along the path resulting in less processing and less energy consumption.[40]

High Performance Routing (HPR) is typically used in commercial solutions. The key idea behind HPR is to provide the highest network throughput for each flow. The procedure is done in steps. First, the routing paths for each flow are identified. Secondly the paths with the lowest number of assigned flows will be selected. All of the previous technologies have indirect effects on energy efficiency.[40]

Green VLAN is adopted into commercial solutions and it has direct impact into energy efficiency. This technology tries to organize VLANs in a more energy efficient way. It starts by checking out each VLANs impact on energy consumption according to some constraints. If they do not satisfy the requirements, they will be split into several VLANs. [40]

There are also technologies that are not widely used, thus they are studied and they are trying to gain a position as dominant technology in energy efficient routing and switching. Energy-Aware Routing (EAR) minimizes the number of switches and links. Energy Efficient Routing (EER) uses minimum number of aggregation or core switches in a data center based on traffic load at a specific time interval. In Max-Flow Min Energy technology the data transfer among remote data centers is done by aggregating the traffic flows as trunks, and then routing them through the least energy consuming paths. Express Path (ExP) is introduced for optical networks; the routing process takes place based on flows, not packets. Considering that all packets of a same flow contain the same values of identification parameters, routing only the first packet of each flow would be sufficient and the rest of the packets would follow the same route. [40]

Selecting energy consumption aware routing and switching technology has a significant impact as it improves energy efficiency on a massive scale of whole traffic. Some of the technologies are widely used already but some are not commercially used at all. Energy efficient routing and switching protocols can become a competitive advantage but it must be supported by major vendors in order to becoming widely accepted. Implementing new protocols is not a trivial task and requires much configuration work. It is not cheap.

Traffic patterns
IOEE: Medium, Adaptation: Medium, Complexity: High, Cost: Medium – The idea in traffic patterns is to analyze the network traffic and create traffic patterns that have similar flows inside the pattern. Usually this means identifying similar applications. The result of this analysis can be divided into pattern according to application names, network protocols used, traffic profile, content type or web applications. Utilizing similar traffic engineering for each of the flow type ensures fit for purpose routing and switching that reduces energy consumption.[40] Routing and switching by using traffic patterns can lower energy consumption significantly but is a complement to many other more effective technologies. This technology is widely known but not so often used.

Configuring traffic engineering for traffic pattern based routing is a complex task and requires good analysis systems and experienced network specialist. Cost of utilizing traffic pattern is mainly the time that specialists have to use to get the system up and running.

Traffic locality
IOEE: High, Adaptation: Medium, Complexity: High, Cost: High – When computing resources are consolidated in a few huge data centers, a massive amount of data is transferred to each data center over a wide area network (WAN). This results in increased power consumption in the WAN. A content delivery network (CDN), can reduce the traffic from/to the data center, thereby decreasing the power consumed in the WAN. Numerical evaluations show that, when there is strong traffic locality and the router has ideal energy-proportionality, the system's power consumption is reduced to about 50% of the power consumed in the case where a CDN is not used; moreover, this advantage becomes even larger (up to about 30%) when the data center is located farthest from the center of the network topology. CDN has a large impact on energy efficiency since it reduces the amounts of traffic that would be required to route through WAN network. [55] CDN technologies are used but the adaptation rate is still quite low. Implementing CDN is not easy and it is quite expensive.

Energy-aware devices
IOEE: High, Adaptation: Medium, Complexity: Medium, Cost: High – A large amount of the consumed energy goes to waste due to lack of energy-proportionality in the energy consumption profile of IT devices, which tend to consume close to maximum power independently of their actual workload. Making devices energy-proportional is becoming a priority for component and system manufactures but this long term objective is expected to take several years until fully realized. An alternative solution that can be applied relatively fast is to permit groups of devices. Examples of such groups are server farms and network segments that behave collectively as an energy-proportional ensemble, despite being made of energy un-proportional devices. The key to achieving this objective is putting some of the devices to sleep or on lower power modes when the aggregate workload subsides, thus permitting the group to handle the offered load with fewer devices kept online.[56]Adaptation is high on the server side but significantly lower in the networking domain. Complexity is based on the solution or device provider. Cost of investing into new energy efficient devices can be significant.

Energy efficient network architecture
IOEE: High, Adaptation: High, Complexity: Medium, Cost: Medium – There are several different energy efficient architectures that can be implemented. All of them have pros and cons. Selection must be based on best suitability to the environment. The FatTree network architecture is a switch-centric physical topology, richly connected, and scalable. In this architecture, the network switches are classified in three tiers: core, aggregation, and ToR. If n shows the number of ports in a switch, in a Fat Tree architecture there will be (n/2)2 core switches with n ports and n pods with n switches having n ports (n/2 aggregation switches + n/2 ToR switches). The BCube network architecture is a server-centric physical topology that can easily be extended in a recursive manner. If k shows the level number and n shows the number of ports in a switch, then BCube(k) consists of n BCube(k –1) architectures that are connected by n switches having n ports. The VL2 network architecture is a switch-centric physical topology. There are bipartite-like connections between core and aggregation switches

in this topology. VL2 uses load balancing techniques to distribute the load from aggregation switches to core switches. [9]

The main idea with Flattened Butterfly network architecture is to minimize the number of hops for each route. It is scalable and can be extended in a recursive manner. DCell is an example of a server-centric data center network architecture that can be extended in a recursive way. If k shows the level number and n(i) shows the number of servers at the i:th level, then DCell(k) consists of (n(k – 1) + 1) DCell(k–1) architectures that are connected only through servers. In Balanced Tree topology, there is only one switch, as root has n ports. The idea behind this architecture is to distribute the servers between switches uniformly, which all are similar in number of ports. The resulting topology looks regular and symmetric, but it has the possibility of a single point of failure. [9]

The VL2N-Tree network architecture is a combination of traditional network architecture 2N-Tree and VL2. Thus, there is a bipartite graph between core switches and aggregation switches, and the rest of the connections (among aggregation switches and ToR switches and servers) follow the rules of a 2N-Tree data center network architecture. Generalized flattened butterfly is a hierarchical extendible network architecture that tries to benefit from the "minimum hop" feature of the Flattened Butterfly network architecture and the "high bandwidth" feature of the DCell network architecture. [9]

Selecting most suitable topology and architecture for servers and networking can have a significant impact on energy efficiency. Different topologies are widely used and some of them are more complex to implement than others. Cost of energy efficient architecture comes from the cost of devices and specialist needed to set it to an operational state.

Energy efficient scheduling algorithms

IOEE: High, Adaptation: Medium, Complexity: High, Cost: Medium – There are many different scheduling algorithms. One of the main algorithms is the data center energy-efficient network-aware scheduling (DENS). DENS algorithm minimizes the total energy consumption of a data center by selecting the best-fit computing resources for job execution based on the load level and communication potential of data center components. The communicational potential is defined as the amount of end-to-end bandwidth provided to individual servers or group of servers by the data center architecture. Contrary to traditional scheduling solutions that model data centers as a homogeneous pool of computing servers, the DENS methodology develops a hierarchical model consistent with the state of the art data center topologies. Energy efficient scheduling algorithms can have a significant impact on energy consumption. They are well known but not so widely used as setting them up is quite complex. [57]The actual cost of coming from systems that are required to implement DENS and specialist work needed to implement DENS.

Table 21. Energy efficiency solutions for virtualization (EESTC 4).

EESTC4	Solution	Main purposes	EESTC Category
3.	Virtual Machine Consolidation	Aim is to aggregate VMs into fewer numbers of physical machines to reduce the total amount of energy consumption in data centers.	EESTC4
6.	Traffic patterns	Aim is to take into account traffic patterns to discover behavior of applications and make intelligent decisions based on that information.	EESTC3 and EESTC4
14.	Energy efficient scheduling algorithms	Aim is to minimize the total energy consumption of data center by selecting best-fit computing resources for execution of job based on load level and communication potential of the device. DENS is a good example of this technology.	EESTC3 and EESTC4
17.	Green Hadoop Distributed File System (Green HDFS)	Aim is to trade performance and power by separating Hadoop cluster logically to hot and cold zones based on the popularity of the data.	EESTC4

Solutions that belong to the virtualization category are presented in Table 21. They are evaluated in more detail below.

Virtual machine consolidation
IOEE: High, Adaptation: High, Complexity: Low, Cost: Low – The high energy consumption of data center has made it inevitable to move toward designing and deployment of energy efficient techniques for building a green data center. In recent years, many efforts have been made to improve the energy efficiency of virtualized data center from different aspects including processor, storage and, network energy management. Moreover, visualization is one of the important techniques to reduce energy consumption of data centers. In this technique, virtual machines (VMs) are assigned to minimum number of physical machines such that the utilization of turned on physical machines is also maximized. [58]

Virtual machine consolidation is the de facto way of providing computing services today. It is widely adopted and has a significant impact on energy efficiency. Technologies are mature and well understood. Consolidating virtual machines can be one of the potential competitive edges for any data center. There are many heuristics that can optimize the consolidation process and selecting or developing own heuristics can fine tune energy consumption in the data center, thus increase profitability and CO_2 foot print.

Traffic patterns
Evaluated already above.

Energy efficient scheduling algorithms
Evaluated already above.

Green Hadoop distributed file system (Green HDFS)
IOEE: Medium, Adaptation: Low, Complexity: High, Cost: High – Green Hadoop seeks to maximize the green energy consumption within the jobs' time bounds. If brown energy must be used, Green Hadoop selects times when brown energy is cheap, while also managing the cost of peak brown power consumption. Results demonstrate that

Green Hadoop can increase green energy consumption significantly and decrease electricity cost to one third, compared to traditional Hadoop solution. Based on these positive results it can be concluded that green data centers and software that is aware of the key characteristics of both green and brown electricity can have an important role in building a more sustainable and cost-effective IT ecosystem.[30]

Big Data platforms are being implemented in rapid phase to various solutions. Green HDFS and other Hadoop or similar systems that provide distributed computing are providing better energy efficiency as such. Impact of such systems to energy efficiency of a data center can be significant. Green Hadoop or Hadoop are not so widely deployed yet but they can become the norm in Internet of Things analytics and on many other types of data analytics domains, like network performance management. Implementing Green Hadoop of any Big Data system is a complex task and can have high cost also.

Table 22. Energy efficiency solutions for processors (EESTC 5).

EESTC5	Solution	Main purposes	EESTC Category
18.	Dynamic Voltage Frequency Scaling DVFS	Aim is to reduce the power consumption of the IT equipment. Decreasing the processor voltage and frequency will lower down the performance of the processor.	EESTC5

Solution that belong to the processor category is presented in Table 22. It is evaluated in more detail below.

Dynamic Voltage Frequency Scaling (DVFS)
IOEE: High, Adaptation: High, Complexity: Low, Cost: Low – DVFS is a commonly-used power-management technique where the clock frequency of a processor is decreased to allow a corresponding reduction in the supply voltage. This reduces power consumption, which can lead to a significant reduction in the energy required for a computation, particularly for memory-bound workloads. However, recent developments in processor and memory technology have resulted in the saturation of processor clock frequencies, larger static power consumption, smaller dynamic power range and better idle/sleep modes. Each of these developments limits the potential energy savings resulting from DVFS. While DVFS is effective on the older platforms, it actually increases energy usage on the most recent platform, even for highly memory-bound workloads.[59]DVFS improves energy efficiency of the processor and they are everywhere. DVFS technologies (or similar energy-proportional technologies for processors) are widely used and should be adopted in some way to all devices. Even though the recent studies have shown some that sleep modes and other solutions have eaten some of its popularity away.

5.3 Summary of the Chapter

After evaluating all of the example energy efficiency solutions according to previously presented dimensions, the results are gathered in Table 23. Solutions are organized from highest importance to the lowest based on overall techno-economic benefit valuation. It is obvious that solutions, which bring the highest benefit, should be implemented in the first phase and the rest in the following phases. It should be noted though those solutions that are widely adopted or simple to implement do not give competitive edge to data center provider. This is why lower scoring solutions should be investigated carefully; they are candidates for potential differentiation from the competitors. As a general remark, developing some own heuristics or algorithms, which are a perfect fit for purpose in order to gain leading edge, should be considered. In addition, data center provider should review all of these solutions against the vision for sustainability and evaluate how much premium price is attainable from the market based on the sustainability factors. Sustainability and GreenIT can become future trends and they are used in somewhat unspecific way in marketing. It can be a competitive edge once the data center provider can objectively show that it is energy efficient, and that it has very low CO_2 emissions. This can make a difference, not only among customers but also among the employees of the data center provider.

Table 23. Phasing of energy efficiency solutions based on overall benefit valuation.

Id	Solution	EESTC Category	Impact On Overall Energy Efficiency	Adaptation	Complexity	Cost	Importance
4.	Optical devices	EESTC3	High (3)	High (3)	Medium (2)	Medium (2)	36
12.	Energy Efficient Network Architecture	EESTC3	High (3)	High (3)	Medium (2)	Medium (2)	36
15.	Modular data center	EESTC1 and EESTC2	Medium (2)	High (3)	Low (3)	Medium (2)	36
3.	Virtual Machine Consolidation	EESTC4	High (3)	High (3)	Low (3)	Low (1)	27
18.	Dynamic Voltage Frequency Scaling DVFS	EESTC5	High (3)	High (3)	Low (3)	Low (1)	27
2.	Traffic Consolidation	EESTC3	Medium (2)	High (3)	Medium (2)	Medium (2)	24
5.	Energy-aware routes	EESTC3	High (3)	Medium (2)	Medium (2)	Medium (2)	24
8.	Energy-aware devices	EESTC3	High (3)	Medium (2)	Medium (2)	High (1)	12
9.	Heat minimization	EESTC2	High (3)	Medium (2)	High (1)	High (1)	12
11.	Green energy	EESTC1	Low (1)	Medium (2)	Low (3)	Medium (2)	12
13.	Liquid cooling and direct free cooling	EESTC2	High (3)	Medium (2)	Medium (2)	High (1)	12
14.	Energy efficient scheduling algorithms	EESTC3 and EESTC4	High (3)	Medium (2)	High (1)	Medium (2)	12
10.	Traffic minimization	EESTC1	High (3)	High (3)	High (1)	High (1)	9
6.	Traffic patterns	EESTC3 and EESTC4	Medium (2)	Medium (2)	High (1)	Medium (2)	8
1.	Sleeping mode / Switching Off	EESTC1	High (3)	Low (1)	Medium (2)	High (1)	6
7.	Traffic locality	EESTC3	High (3)	Medium (2)	High (1)	High (1)	6
16.	Dynamic Smart Cooling DSC	EESTC2	High (3)	Low (1)	High (1)	High (1)	3
17.	Green Hadoop Distributed File System (Green HDFS)	EESTC4	Medium (2)	Low (1)	High (1)	High (1)	2

Phase 1 (rows 4, 12, 15, 3, 18, 2, 5)
Phase 2 (rows 8, 9, 11, 13, 14, 10, 6)
Phase 3 (rows 1, 7, 16, 17)
Possibility for competitive edge (rows 1, 7, 16, 17)

Reasoning behind this evaluation is naturally subjective in some ways but it is based on findings from the scientific articles and by interviewing some of the leading data center and networking experts from TeliaSonera and Cygate. Reliability and validity of the findings are based on the actual empirical data from the research articles. The impact and complexity dimensions are close to objective judgement thus adaptation and cost are based on actual data that is available in the market. If no data is available it is evaluated by reasoning the cost by its investment and specialist work required for this kind of solution. Similarly the adaptation is evaluated from the information from the market but if no data is available, consulting the specialists of each domain is used. The phasing covers all of the solution domains which creates full coverage and leaves no domain without proper solution that advances energy efficiency.

In Chapter seven the conclusions of this thesis are presented. First the metric framework is presented. A phased plan for implementing energy efficiency solutions as an example is introduced. The actual content of the implementation plan is up to the data center provider, but the logic of evaluating the solutions is essential.

6 CONCLUSIONS

The first main research question regarding the most suitable set of energy efficiency metrics for large data center that emphasizes energy efficiency is presented below in Figure 32. It is applicable to Sonera HDC and similar data centers. It is in a spider web form, and contains twenty deterministic metrics that cover all levels of attention, namely the strategic, tactical, operational and informational. In addition, the framework covers all main technology domains with overlay and direct metrics. The idea of the spider web is to illustrate current situation (marked with blue line) and the target level (marked with red line). Chapter 3 presents example solutions that reduce the gap between the target and actual measurements. In Figure 32, the current and target level presented are only artificial examples, not actual data. Target levels need to be defined and current levels need actual measurement data. The target level can vary from 0-100. All metrics are normalized to this scale.

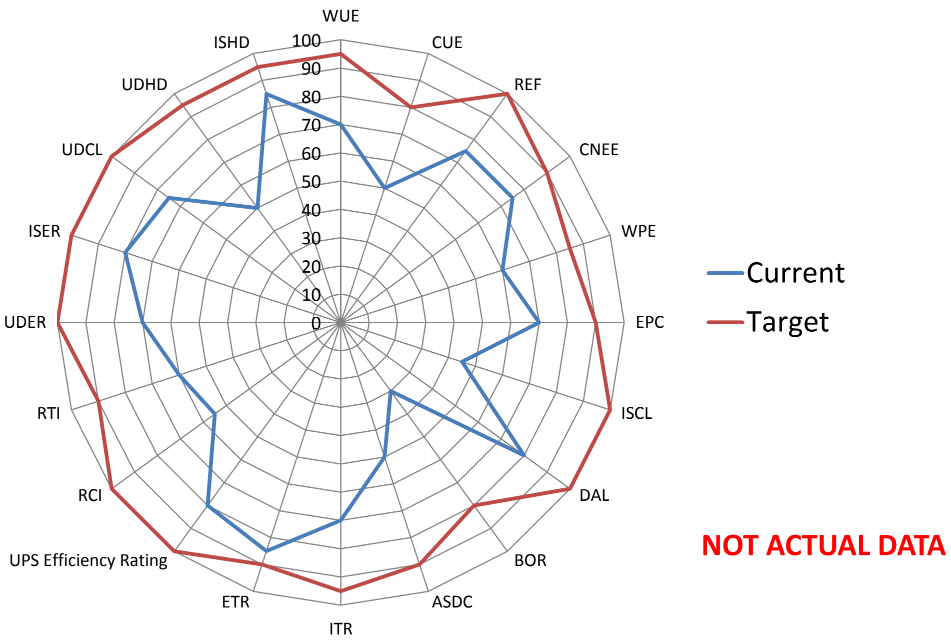


Figure 32. Holistic energy efficiency metric framework.

The second main research question regarding the energy efficient technologies and solutions and their relevance is summarized in Figure 33. In this figure, the phased implementation suggestion for the most beneficial technologies as they are perceived by the customers and the data center providers is presented. Even though some of the dimensions of the evaluation are subjective, it is based on industry knowledge of many experts. The actual implementation phasing that a generic data center provider selects eventually depends on their vision and strategy for energy efficiency, and how they plan to capitalize the benefits of sustainable operations.

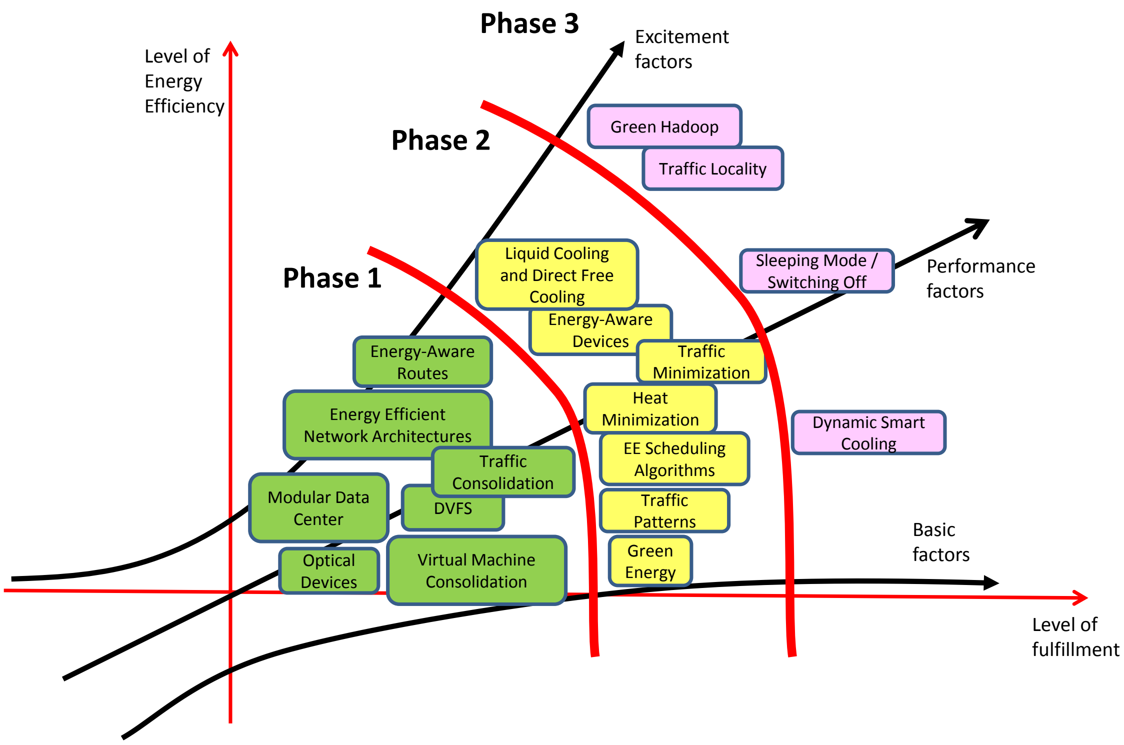


Figure 33. Perception of energy efficiency and a phasing plan.

Other way of selecting energy efficiency solutions for implementation can be done by investigating the cost of the solution in more detail. Some of the solutions are CAPEX intensive and some are OPEX intensive. CAPEX intensive solutions are usually related to either the replacement of old solutions with new ones, or to investing into a totally new data center. OPEX related solutions target the operational phase. They usually require a smaller initial investment but more system management activities. As a definition CAPEX includes costs related to hardware, software and facilities. Correspondingly OPEX includes costs related to engineering, installation, maintenance and electricity. Figure 34 presents all the selected solutions in a two by two matrix. In the figure the y-axle is divided to ICT and Infrastructure parts. The x-axle is divided to CAPEX and OPEX driven parts. Some of the solutions cover multiple fields, meaning that the nature of the solution represents many qualities at the same time.

Placing solutions into the matrix is based on understanding of the solution in question. All solutions incur both CAPEX and OPEX to some extent, but from TCO perspective one cost model usually dominates.

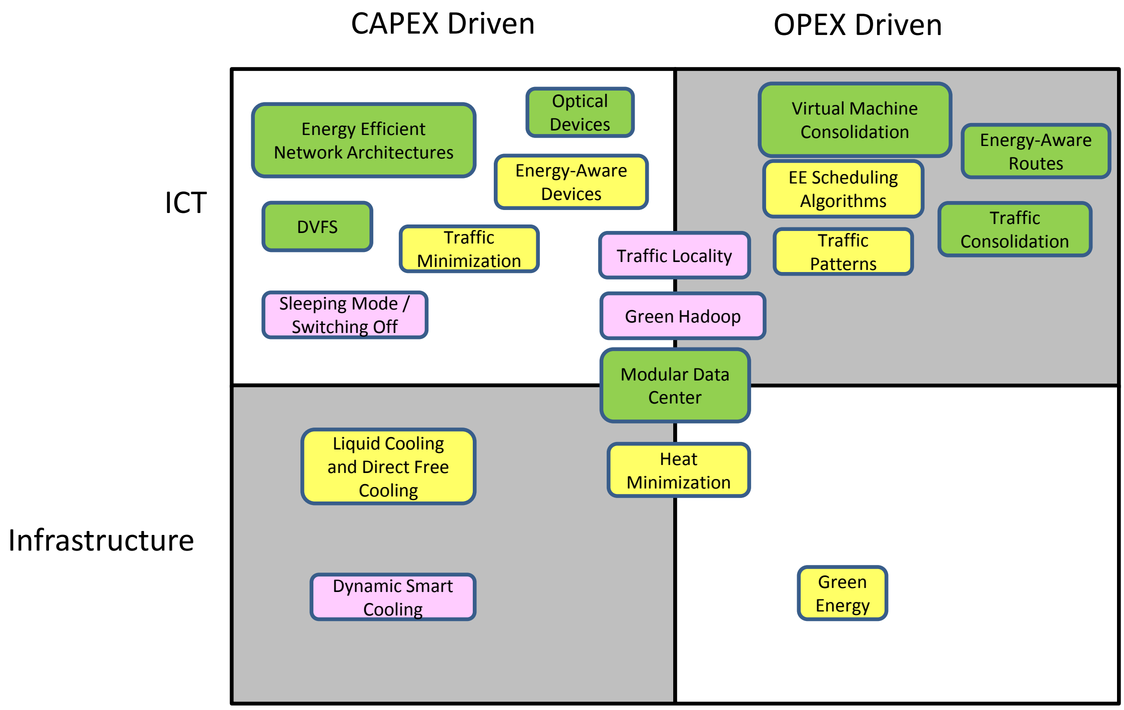


Figure 34. Nature of the energy efficiency solutions.

Figure 34 shows there are solutions that are clearly CAPEX driven and suitable to be implemented especially in the building phase of a data center. In theory all CAPEX costs are immediate. In practice everything can be financed by a monthly fees plus interests. OPEX driven solutions can be implemented later and they usually incur costs as salaries. Combining the conclusions from both, the phasing and the nature of the solutions, it can be seen that it is a balancing act between CAPEX and OPEX related costs.

The conclusions are relevant. Future research can be done to map the solutions to specific metrics. Other research that is required includes giving standard acceptable target levels to all of the metrics based on different ambition levels of data center providers. Energy efficiency is a strategic initiative and may require regulative enforcement to become a norm. All data center providers are not seeking full energy efficiency. Fortunately energy efficiency is not an “all or nothing” situation - it can also be an iterative process.

There are many open challenges in the field of data center energy efficiency. Firstly there is the energy-aware dynamic resource allocation. Currently, resource allocation in a Cloud data center aims to provide high performance while meeting SLA, without a focus on allocating VMs to minimize energy consumption. [12] Secondly there is the area of QoS-based resource selection and provisioning. This requires optimization of virtual network topologies, and autonomic optimization of thermal states, and cooling system operation. Also efficient consolidation of VMs for managing heterogeneous workloads is needed. [12] The selection of efficient software is problematic as no software markets itself as being energy efficient, however it seems that many organizations have developed procurement clauses that would require an energy efficient software decision point, in some cases the use of virtualization software or work stream dynamically control resource software is being used. Due to the absence of global "green coding" guidelines or standards, it is difficult for applicants to understand and implement the practice "develop efficient software". However, green coding is gaining ground and workshops are available in certain countries, and it may be the case that in the future a general coding best practice includes energy efficiency techniques. [8]

Adaptation of energy efficiency introduces challenges as presented in this thesis. Many values need to change in the attitudes of the clients before energy efficiency can become a significant factor as a purchasing criterion. Demand drives supply. Awareness of energy related costs must meet the decision makers in the field of ICT. In addition there needs to be sufficient activities from the government and legislative changes further enabling transformation towards energy efficient solutions. Ideas can be taken from the changes in auto-, airplane or light pulp industries where transformation has already happened or is advancing rapidly. Peter Senge from MIT said in "Systems Thinking for a Better World" 30th Anniversary Seminar of the Systems Analysis Laboratory at Aalto University; “Nobody wants to produce the systemic outcomes that destroy our planet but yet we do it every day”. The growth of energy consumption is a global issue affecting all industries, ICT being no exception. ICT reduces global energy usage and CO_2 emissions through the solutions it provides, but the reduction can also be done in an energy efficient way. GreenIT is currently perceived as hype technology, but it can become important once attitudes towards sustainability change. And change will come eventually.

It is advisable that data center providers take energy efficiency as a strategic initiative. The reason for this is not only cost savings and higher profits but also contributing to the global solution of reducing energy consumption and CO_2 emissions.

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APPENDIX 1 – ALL RELEVANT ENERGY EFFICIENCY METRICS

Id	Index Name	How to calculate?	Unit	Main purposes
1.	Water Usage Effectiveness WUE [40]	$\text{WUE} = \frac{\text{Annual Water Usage}}{\text{IT Equipment Energy}}$	Liters/kilowatt-hour (L/kWh)	Metric for water usage in the data center [40].
2.	Carbon Usage Effectiveness CUE [40]	$CUE = \frac{Total\ Data\ Center\ CO2\ Emissions}{IT\ Energy\ Consumption}$ [34]	Kilograms of carbon dioxide (kg CO_2eq) per kilowatt-hour (kWh)	Measures carbon emissions associated with data centers [34].
3.	Renewable Energy Efficiency REF [40]	$REF = \frac{Renewable\ Energy\ Consumption}{Total\ Energy\ Consumption\ of\ the\ DC}$	Number	Metric to quantify the effort to use renewable energy managed by owner/operator for their data center [40].
4.	Thermodynamic efficiency [11]	$Thermal\ Efficiency = \frac{Useful\ Work}{Total\ Energy\ Expanded}$	MFLOPS/Joule	Ratio of useful work produced by the system to the total energy expanded to produce this useful work [11].
5.	Thermal Correlation Index TCI [26]	$TCI_{i,j} = \frac{\Delta T_i}{\Delta T_{CRAC,j}}$	Number Can be calculated numerically or in-situ in the data center with deployed sensor network.	Quantifies the response at the i:th rack inlet sensor to a step change in the supply temperature of j:th CRAC [26].
6.	Performance / Watt [36]	$\frac{MFLOPS\ (or\ MIPS)}{Watt}$	FLOPS/watt	Metric of the energy efficiency of particular computer architecture or computer hardware [36].
7.	Power Usage Effectiveness PUE [28]	$PUE = \frac{P_{inf} + P_{IT}}{P_{IT}}$ P_{inf} = power draw of supporting infrastructure, mainly cooling system P_{IT} = power consumed by the IT equipment in the racks	Number	Ratio of total power drawn of the datacenter to the total power consumed by the IT equipment within the racks [28].
8.	Revised PUE (example) [18]	$RPUE = \frac{IT\ equipmen\ power + Cooling\ Power + etc.}{IT\ Equipment\ Power - Server\ Fan\ power}$	Number	There are several revised PUE metrics for different purposes [18].
9.	Cloud Data Center Energy Efficiency CDCEE [7]	$CDCEE = \frac{(ITU \times ITE)}{PUE}$ ITU = IT Utilization which denotes the ration of average IT use over the peak IT capacity in the cloud data center ITE = IT efficiency is the amount of useful IT work done per joule of energy.	MFLOPS/Joule	Metric that presents IT utilization and IT efficiency factors in relation to the PUE. This metric is especially for cloud service providers. [7]
10.	Workload Power Efficiency WPE [36]	$WPE = \frac{Average\ Achieved\ Performance}{Average\ HPC\ System\ Power\ Used}$ HPC = High Performance Computing	Performance / Watt FLOPS / Watt	Energy efficiency metric for a specific workload running on a specific HPC system [36].
11.	System Power Usage Effectiveness sPUE [36]	Coefficient of Performance (COP) $COP = \frac{Q}{P_{used}}$ $sPUE = 1 + overhead_{PDLC} + \sum_{k=1}^{n}\left(w_k \times \frac{1}{COP_k}\right)$ $1 = \sum_{k=1}^{n} w_k$ Where w_k is the distribution for each heat removal technology k used in the HPC system and the sum of all w_k is one (equaling 100% heat removal) and $overhead_{PDLC}$ is the additional power needed to provide one Watt of heat via heat removal technology k	Number	sPUE is intended to capture the effectiveness of a specific HPC system for a specific data center [36].
12.	Data Center Workload Power Efficiency DWPE [36]	$DWPE = \frac{WPE}{sPUE}$	Performance / Watt MFLOPS / Watt	DWPE will make the connection between workload energy efficiency of the HPC system and the data center infrastructure by combining the Performance/W metric of the HPC system with the PUE for the system in a data center [36].
13.	Fixed to Variable Energy Ratio		Number	Could be used instead of PUE. Combines and meets all the

	FVER [13]	$FVER = 1 + \frac{Fixed\ Energy}{Variable\ Energy}$		needed criteria for better energy efficiency assessment in data centers [13].
14.	Data center infrastructure energy DCiE [28]	$DCiE = \frac{P_{IT}}{P_{IN}} = \frac{1}{PUE}$	Percentage 0 < DCiE < 1	Expresses the fraction of the total power supplied to the data center and is delivered to the IT load [28].
15.	Data Center energy Productivity DCeP [29]	$DCeP = \frac{Useful\ Work\ Produced}{Total\ Data\ Center\ Energy\ Consumed\ Over\ Time}$ $= \frac{\sum_{i=1}^{m}[V_i \times U_i(t,T) \times T_i]}{E_{DC}}$ $U_i(t, T)$ = Utility value of a transaction, subjective and can vary between organizations	MFLOPS/Joule	Correlates the data center throughput with the consumed power [29].
16.	Rack Cooling Index RCI [28]	$RCI_{HI} = \left[1 - \frac{\sum(T_{intake} - T_{max-rec})}{(T_{max-all} - T_{max-rec})}\right] \times 100\%$ $RCI_{LO} = \left[1 - \frac{\sum(T_{min-rec} - T_{intake})}{(T_{min-all} - T_{min-rec})}\right] \times 100\%$	Percentage	RCI evaluates how effectively the IT equipment inside the racks is maintained within the recommended rack intake temperature range [28].
17.	Return Temperature Index RTI [28]	$RTI = \left[\frac{T_{Return} - T_{Supply}}{\Delta T_{Rack}}\right] \times 100\%$	Percentage	RTI was proposed to measure air management effectiveness [28] [11] [19] [2]. RTI evaluates the degree to which cooling air bypasses the rack equipment, as well as capturing the effect of air re circulation within the racks [28].
18.	Supply and return Heat Indexes SHI, RHI [28]	$SHI = \frac{T_{intake} - T_{Supply}}{T_{exit} - T_{Supply}}$ $RHI = \frac{T_{return} - T_{Supply}}{T_{exit} - T_{Supply}}$	Number	The level of separation of cold and hot air streams can be measured by the supply and return heat indices. SHI is defined as the ratio of sensible heat gained in the cold aisle to the heat gained at the rack. RHI is defined as the ratio of heat extracted by the cooling system to the heat gained at the rack exit. [28]
19.	Power Density Efficiency PDE [28]	$PDE = \frac{\frac{P_{IT}}{v_r}}{\left(\frac{P_{IT}}{v_r} + \frac{P_{inf}}{v_s}\right)}$ v_r is the total volume of racks and v_s is the total volume of the IT equipment inside the racks	Number	A variation of PUE. Provides insight into the improvements to both the IT equipment and the supporting cooling system. Enables evaluation of impact of physical changes inside the racks on energy efficiency, which is not possible using the common metrics. [28]
20.	Communication Network Energy Efficiency CNEE [17]	$CNEE = \frac{Power\ Consumed\ by\ the\ Network}{Effective\ NW\ Throughput\ Capacity}$	Watts/bit/s	Measures the amount of energy required to deliver a single bit of information by the network [17].
21.	Network Power Usage Effectiveness NPUE [17]	$NPUE = \frac{Total\ Power\ Consumed\ Bu\ IT\ Equipment}{Power\ Consumed\ by\ Network\ Equipment}$ t	Number	NPUE specifies which fraction of the power consumed by the IT equipment is used to operate data center communication system [17].
22.	Energy Proportionality Coefficient EPC [17]	$\tan\alpha = \frac{dP}{dl}$ $EPC = \int_0^1 \sin\alpha\, dl = \int_0^1 \frac{2\tan\alpha}{1+\tan^2\alpha} dl$ l = Load P = Power consumption	Radian	EPC is measured as energy consumption of a system or a device as a function of the offered load [17].
23.	Uplink/Downlink Communication Latency UDCL [17]	Average RTT	Seconds	Communication latency between data center gateway and computing servers [17].
24.	Uplink/Downlink Hop Distance UDHD [17]		Number	Hop distance between data center gateway and computing servers [17].
25.	Inter-Server Communication Latency ISCL [17]	Average RTT	Seconds	Communication latency between computing servers [17].
26.	Inter-Server Hop Distance ISHD [17]	$ISHD = \frac{1}{N(N-1)} \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} h_{ij}$ N = Total Number of Servers h_{ij} = Number of hops between the servers I and j	Number	Measures number of hops, it takes for one task to communicate with another task executed on a different server [17]

27.	Database Access Latency DAL [17]	Average RTT	Seconds	Measures average latency of accessing database from computing server [17].
28.	Bandwidth Oversubscription Ratio BOR [17]	Example: Ingress of 48 1 Gb/s ports and egress of 2 10 Gb/s. BOR= 48 Gb/s / 20 Gb/s = 2,4 : 1 Per server bandwidth 1 Gb/s / 2,4 = 416 Mb/s under full load	Number	Ratio between the aggregate ingress and aggregate egress bandwidth of a network switch. Important to estimate the minimum non-blocking bandwidth available to every server [17].
29.	Uplink/Downlink Error Rate UDER [17]	$UDER = \frac{1}{N} \times \sum_{n=1}^{N} \sum_{l=1}^{L} BER_{nl}$ BER_{nl} = BER of the path interconnecting server I and server j N = Number of servers L = Number of hierarchical layers in network topology	Number	Measures error rate of the paths between data center gateway and servers [17].
30.	Inter-Server Error Rate ISER [17]	$ISER = \frac{1}{N(N-1)} \times \sum_{i=1}^{N} \sum_{j=1,j\neq i}^{N} BER_{ij}$ N = Number of servers BER_{nl} = BER of the path interconnecting server I and server j	Number	Measures error rate of the network paths between computing servers [17].
31.	Average Link Utilization Ratio ALUR [17]	$ALUR = \frac{1}{N_i} \times \sum_{n=1}^{N_i} u_n$ N_i = number of links of type i u_n = utilization ratio of link n	Number	Measures average link occupancy [17].
32.	Average Server Degree Connectivity ASDC [17]	$ASDC = \frac{1}{N} \times \sum_{n=1}^{N} c_n$ N = total number of data center servers c_n = number of network links connecting server n to other devices, switches and/or servers	Number	Measures average number of links per server [17].
33.	Internal Traffic Ratio ITR [17]	$ITR = \frac{Internal\ Traffic}{Total\ Data\ Center\ Traffic}$	Number	Measures traffic exchanged within the data center [17].
34.	External Traffic Ratio ITR [17]	$ETR = 1 - ITR = \frac{External\ Traffic}{Total\ Data\ Center\ Traffic}$	Number	Measures traffic destined outside the data center [17].
35.	Management and Monitoring Traffic Ratio MMTR [17]	$MTTR = \frac{Management\ and\ Monitoring\ Traffic}{Total\ Data\ Center\ Traffic}$	Number	Measures traffic generated by management and monitoring operations [17].
36.	Management and Monitoring Traffic Energy MMTE [17]	$MMTE = CNEE \times Management\ and\ Monitoring\ Traffic$	Joules	Measures energy consumption of management and monitoring traffic [17].
37.	UPS Efficiency Rating	*UPS efficiency = UPS's potential - fixed and proportional losses.* While proportional losses — in the forms of heat-dissipation ("I2R" losses), are tied directly to increases in load, a UPS's fixed losses (or "no-load" losses) remain constant independent of the amount of current running through the UPS	Percentage	Shows how much of the original incoming utility power is used to power your critical load versus how much is lost in the operation of the UPS.

APPENDIX 2 - METRIC EVALUATION SUMMARY

Id	Index Name	Main purposes	EEM Category	DCT Category	Impact Area	Relevance	Complexity	Importance
1.	WUE Water Usage Effectiveness [40]	Metric for water usage in the data center.	EEM 6	DCT 7	Strategic	High (3)	Low (3)	(9)
2.	CUE Carbon Usage Effectiveness [40]	Measures carbon emissions associated with data centers.	EEM 6	DCT 7	Strategic	High (3)	Low (3)	(9)
3.	REF Renewable Energy Efficiency [40]	Metric to quantify the effort to use renewable energy managed by owner/operator for their data center.	EEM 6	DCT 7	Strategic	High (3)	Low (3)	(9)
4.	Thermodynamic Efficiency [11]	Ratio of useful work produced by the system to the total energy expanded to produce this useful work.	EEM 5	DCT 7	Strategic	Medium (2)	High (1)	(2)
5.	TCI Thermal Correlation Index [26]	Quantifies the response at the i:th rack inlet sensor to a step change in the supply temperature of j:th CRAC.	EEM 1	DCT 4	Tactic	Medium (2)	High (1)	(2)
6.	Performance/Watt [36]	Metric of the energy efficiency of particular computer architecture or computer hardware.	EEM 3	DCT 1	Tactic	High (3)	High (1)	(3)
7.	PUE (Power Usage Effectiveness) [28]	Ratio of total power draw of the datacenter to the total power consumed by the IT equipment within the racks.	EEM 5	DCT 7	Strategic	Medium (2)	Medium (2)	(4)
8.	Revised PUE (example) [18]	There are several revised PUE metrics for different purposes.	EEM 5	DCT 7	Strategic	Medium (2)	High (1)	(2)
9.	Cloud Data Center Energy Efficiency CDCEE [7]	Cloud Data Center Energy Efficiency CDCEE is a metric for especially Cloud service provider.	EEM 5	DCT 7	Strategic	Medium (2)	High (1)	(2)
10.	Workload Power Efficiency WPE [36]	Energy efficiency metric for a specific workload running on a specific HPC system.	EEM 3	DCT 1 and 3	Strategic	High (3)	High (1)	(3)
11.	System Power Usage Effectiveness sPUE [36]	sPUE is intended to capture the effectiveness of a specific HPC system for a specific data center.	EEM 5	DCT 7	Strategic	High (3)	High (1)	(3)
12.	Data Center Workload Power Efficiency DWPE [36]	DWPE will make the connection between workload energy efficiency of the HPC system and the data center infrastructure by combining the Performance/W metric of the HPC system with the PUE for the system in a data center.	EEM 5	DCT 7	Strategic	High (3)	High (1)	(3)
13.	Fixed to Variable Energy Ratio (FVER) [13]	Could be used instead of PUE. Combines and meets all the needed criteria for better energy efficiency assessment in data centers.	EEM 5	DCT 7	Strategic	High (3)	High (1)	(3)
14.	Data center infrastructure energy DCiE [28]	Expresses the fraction of the total power supplied to the data center and is delivered to the IT load	EEM 1	DCT 7	Strategic	Medium (2)	Medium (2)	(4)
15.	Data Center energy Productivity DCeP [29]	Correlates the data center throughput with the consumed power.	EEM 5	DCT 1	Strategic	High (3)	High (1)	(3)
16.	Rack Cooling Index (RCI) [28]	RCI evaluates how effectively the IT equipment inside the racks is maintained within the recommended rack intake temperature range.	EEM 1	DCT 4	Tactic	High (3)	High (1)	(3)
17.	Return Temperature Index RTI [28]	RTI was proposed to measure air management effectiveness.	EEM 1	DCT 5	Tactic	High (3)	High (1)	(3)
18.	Supply and return Heat Indexes SHI, RHI [28]	The level of separation of cold and hot air streams can be measured by the supply and return heat indices. SHI is defined as the ratio of sensible heat gained in the cold aisle to the heat gained at the rack. RHI is defined as the ratio of heat extracted by the cooling system to the heat gained at the rack exit.	EEM 1	DCT 5	Tactic	High (3)	High (1)	(3)
19.	Power Density Efficiency PDE [28]	A variation of PUE. Provides insight into the improvements to both the IT equipment and the supporting cooling system. Enables evaluation of impact of physical changes inside the racks on energy efficiency, which is not possible using the common metrics.	EEM 1	DCT 7	Strategic	High (3)	High (1)	(3)
20.	Communication Network Energy Efficiency CNEE [17]	Measures the amount of energy required to deliver a single bit of information by the network.	EEM 4	DCT 2	Strategic	High (3)	Medium (2)	(6)
21.	Network Power Usage Effectiveness NPUE [17]	NPUE specifies which fraction of the power consumed by the IT equipment is used to operate data center communication system.	EEM 4	DCT 2	Strategic	Medium (2)	Medium (2)	(4)
22.	Energy Proportionality Coefficient EPC [17]	EPC is measured as energy consumption of a system or a device as a function of the offered load.	EEM 5	DCT 1, 2 and 3	Strategic	High (3)	High (1)	(3)
23.	Uplink/Downlink Communication Latency UDCL [17]	Communication latency between data center gateway and computing servers.	EEM 2	DCT 2	Informative	Medium (2)	Low (3)	(6)
24.	Uplink/Downlink Hop Distance UDHD [17]	Hop distance between data center gateway and computing servers	EEM 2	DCT 2	Informative	Medium (2)	Low (3)	(6)
25.	Inter-Server Communication Latency ISCL [17]	Communication latency between computing servers.	EEM 2	DCT 1	Tactic	Medium (2)	Low (3)	(6)
26.	Inter-Server Hop Distance ISHD [17]	Measures number of hops, it takes for one task to communicate with another task executed on a different server	EEM 4	DCT 1	Informative	Medium (2)	Low (3)	(6)
27.	Database Access Latency DAL [17]	Measures average latency of accessing database from computing server.	EEM 2	DCT 3	Tactic	High (3)	Low (3)	(9)

28.	Bandwidth Oversubscription Ratio BOR [17]	Ratio between the aggregate ingress and aggregate egress bandwidth of a network switch. Important to estimate the minimum non-blocking bandwidth available to every server.	EEM 2	DCT 2	Tactic	High (3)	Low (3)	(9)
29.	Uplink/Downlink Error Rate UDER [17]	Measures error rate of the paths between data center gateway and servers.	EEM 4	DCT 2	Operative	High (3)	Medium (2)	(6)
30.	Inter-Server Error Rate ISER [17]	Measures error rate of the network paths between computing servers.	EEM 2	DCT 1	Operative	High (3)	Medium (2)	(6)
31.	Average Link Utilization Ratio ALUR [17]	Measures average link occupancy.	EEM 4	DCT 2	Tactic	High (3)	High (1)	(3)
32.	Average Server Degree Connectivity ASDC [17]	Measures average number of links per server.	EEM 2	DCT 1	Tactic	High (3)	Low (3)	(9)
33.	Internal Traffic Ratio ITR [17]	Measures traffic exchanged within the data center.	EEM 4	DCT 2	Tactic	High (3)	Medium (2)	(6)
34.	External Traffic Ratio ITR [17]	Measures traffic destined outside the data center.	EEM 4	DCT 2	Tactic	High (3)	Medium (2)	(6)
35.	Management and Monitoring Traffic Ratio MMTR [17]	Measures traffic generated by management and monitoring operations.	EEM 4	DCT 2	Tactic	Medium (2)	Medium (2)	(4)
36.	Management and Monitoring Traffic Energy MMTE [17]	Measures energy consumption of management and monitoring traffic.	EEM 4	DCT 2	Tactic	Medium (2)	Medium (2)	(4)
37.	UPS Efficiency Rating	Shows how much of the original incoming utility power is used to power your critical load versus how much is lost in the operation of the UPS.	EEM 1	DCT 6	Tactic	High (3)	Medium (2)	(6)

APPENDIX 3 – ENERGY EFFICIENCY SOLUTION EXAMPLES FOR THIS THESIS (NOT COVERING ALL POSSIBLE SOLUTIONS).

Id	Solution	Main purposes	EESTC Category
1.	Sleeping mode / Switching Off [48]	Aim is to improve the energy efficiency by deactivating idle devices.	EESTC1
2.	Traffic Consolidation [53]	Idea is to aggregate network traffic into fewer numbers of links and devices to utilize networking resources and increase energy efficiency.	EESTC3
3.	Virtual Machine Consolidation [58]	Aim is to aggregate VMs into fewer numbers of physical machines to reduce the total amount of energy consumption in data centers.	EESTC4
4.	Optical devices [54]	Aim is to replace current electrical networking devices with optical devices, which consumes less energy and provide more throughput.	EESTC3
5.	Energy-aware routes [40]	Idea is that selection of networking path is based on the energy consumption of switches. Either the switches with less energy consumption will be on the path of total energy consumption of the path will be kept in its minimum level.	EESTC3
6.	Traffic patterns [40]	Aim is to take into account traffic patterns to discover behavior of applications and make intelligent decisions based on that information.	EESTC3 and EESTC4
7.	Traffic locality [55]	Aim is to save networking resources by localizing the traffic in some specific parts of data centers. Fewer networking devices will be involved in data transmission, which consumes less energy.	EESTC3
8.	Energy-aware devices [56]	Aim is to use modified electrical switches that are able to increase their energy efficiency by aggregating the traffic into fewer number of ports and putting idle ports into sleep mode.	EESTC3
9.	Heat minimization	Aim is to reduce the total heat in data centers, which improves energy efficiency of cloud-based environments. To mitigate temperature growth in data centers, the load distribution takes place.	EESTC2
10.	Traffic minimization [49]	The smaller the traffic becomes, the less energy will be consumed in the data center.	EESTC1
11.	Green energy	Energy produced from renewable and nonpolluting resources.	EESTC1
12.	Energy Efficient Network Architecture [9]	Aim is to use architectures like FatTree, Bcube, VL2, FlattenedButterfly, Dcell, BalancedTree, VL2N-Tree, Hybrid WDM PON, Torus for example.	EESTC3
13.	Liquid cooling and direct free cooling [51]	Aim is to cool with liquid to the chip level and to use outside air as much as possible for cooling purposes.	EESTC2
14.	Energy efficient scheduling algorithms [57]	Aim is to minimize the total energy consumption of data center by selecting best-fit computing resources for execution of job based on load level and communication potential of the device. DENS is a good example of this technology.	EESTC3 and EESTC4
15.	Modular data center [50]	Aim is to have outside air fans and louvers on top of the racks to increase energy efficiency. Standard hardware solution and easy to increase capacity. Project Blackbox is a good example of this solution.	EESTC1 and EESTC2
16.	Dynamic Smart Cooling DSC [52]	DSC is a set of real-time control systems that can directly manipulate the distribution of cooling according the needs of the computer equipment.	EESTC2
17.	Green Hadoop Distributed File System (Green HDFS) [30]	Aim is to trade performance and power by separating Hadoop cluster logically to hot and cold zones based on the popularity of the data.	EESTC4
18.	Dynamic Voltage Frequency Scaling DVFS [59]	Aim is to reduce the power consumption of the IT equipment. Decreasing the processor voltage and frequency will lower down the performance of the processor.	EESTC5