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CoolEmAll D5.1 White paper on Energy-and Heat-aware metrics for computing modules

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Project acronym: **CoolEmAll**

Project full title: **Platform for optimising the design and operation of modular configurable IT infrastructures and facilities with resource-efficient cooling**



D5.1 White paper on Energy- and Heat-aware metrics for computing modules

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Abstract

This deliverable provides a set of selected metrics to assess the energy efficiency of the different Data Centre Efficiency Building Blocks (DEBBs). It also addresses the requirements of the Work Packages where these metrics can be used, which are the SVD Toolkit (WP2), ComputeBox Prototype (WP3), the Workload and Resource Management Policies (WP4), the Validation Scenarios (WP6) and the Dissemination activities (WP7).

It's a fact that some of the aspects that CoolEmAll has to evaluate for a correct energy efficiency assessment on data centres and its components, are not covered by the existing metrics. Some other metrics are redundant or irrelevant for CoolEmAll. Therefore the project not only includes a review of useful metrics but also attempts to define new ones where possible.

This White Paper, in one hand collects the present state of the art about metrics for data centres and on the other hand establishes a first selection of metrics for CoolEmAll purposes. However, the assessment and checking of the metrics with Validation Scenarios (WP6) will permit to refine these metrics definition and conclude with a useful selection that will be reported on D5.6

Keywords

Metric, Data centre Efficiency Building Block (DEBB), Boundaries, Energy efficiency assessment, Watts, Kilowatthour, Temperature, Heat-aware, Performance, Applications, Productivity, Power Usage Effectiveness (PUE), partial PUE, PUE Scalability, Deployment Hardware Utilisation Ration (DH-UR), Space-Watt-and-Performance (SWaP), Data Centre Utilisation (DCU), Data Centre Infrastructure Efficiency (DCiE), Data Centre Density (DCD), Energy Efficiency Ratio (EER), Fixed to Variable Energy Ratio (FVER), Primary Energy Balance, Carbon emissions balance, GEC (Green Energy Coefficient), Carbon Usage Effectiveness (CUE), Water Usage Effectiveness (WUE), Global KPI of Energy Efficiency (KPI_{EE}), Data centre performance per energy (DPPE), Payback return, Return of investment (ROI), Carbon credits, Standardisation

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1 Introduction

The awareness of significant data centres energy footprints and the increase in energy prices have stimulated investigations into possible metrics to define and quantify the energy efficiency of data centres. A first step towards this direction was taken by the Uptime Institute in 2003 with the introduction of the Triton Coefficient of Effectiveness, defined as the total utility energy required for operating a data centre divided by the critical electrical load in the computer room [1]. Up to this date, the only point of view was the one of raw performance, defined by simple metrics such as Operation per second [2] or Request per second [3]. Since then, the urgent need of establishing energy efficiency evaluation methodologies pushed most of the important players in the field to set own metrics, leading to the advent of several figures. Among them, the PUE (Power Usage Effectiveness) [4] has been widely adopted since 2007, with the support of The Green Grid institution. Actually the wide adoption of PUE has resulted in a corresponding common understanding or a shared calculation methodology for PUE. Only in 2010 did several organizations joined their efforts in a taskforce to agree on standard approaches and reporting conventions for key energy efficiency metrics [5].

The CoolEmAll project wishes to contribute to a common understanding of existing metrics towards the establishment of a consistent approach for the energy evaluation of a data centre from the points of view of infrastructure, equipment and applications. To this end, a review of existing metrics has been done and an overview on energy uses in data centres is outlined in this report.

2 Energy uses in data centres

At the CeBit forum 2008 in Hannover, some estimates were published proclaiming that in 2005 worldwide data centres needed the equivalent of 17 power plants of 1GW to power the required servers and their infrastructure such as cooling [6]. This use was estimated to grow at a rate of 17% a year, and this rate seems to increase as well. A study made by Gartner [7] shows that data centres account for 0.5% of global CO₂ emissions, a quarter of the whole ICT production, being on a par with the aviation industry but rising at a faster pace.

First alarms on consumption in data centres came in 2007, when the EPA (Environmental Protection Agency) published a report assessing the energy used by government, commercial servers and data centres in the U.S. on the basis of best publicly available data [8]. The main energy use relates to electricity, being the driving energy of IT equipment and thereby the energy carrier mostly used for providing auxiliaries services as well, such as cooling.

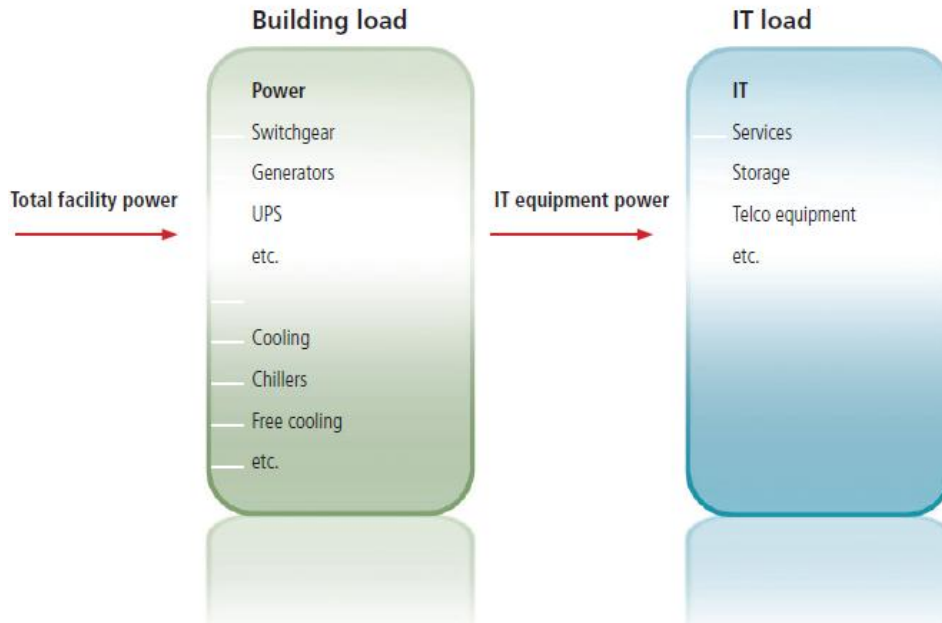
As of 2006, the electricity use attributable to the nation's servers and data centres was estimated at about 61 billion kWh, or 1.5% of total U.S. electricity consumption. Compared with year 2000 data, this electricity use was estimated to have more than doubled. Such estimation called a higher and higher attention to data centres energy footprint, as long as needs for digital services were documented to increase in a wide range of business fields, from industries to universities, from governmental institutions to banks, and for both applications types computing and storage [8].

Such a trend is documented in Europe as well [9] and still visible nowadays. According to the last annual survey carried out by the Digital Realty Trust on 205 European enterprise sized companies (€650M/£600M+ or more in revenues and/or 2,000 total employees), an average enterprise company has three data centres in operation and 83% of reporting companies indicated that they definitely/probably would expand their data centre capacity in 2011 [10]. Also projections foresee an increasing in the data centres consumption unless specific energy efficiency measures are implemented [8] [11].

The high electricity consumption in a data centre is not only due to the specific IT power demand but also to the long operation time, due to the fact that data centres are expected to run 24 hours per day and all over the year, including the supporting systems necessary for its operation. So data centres energy demand has been considered belonging to two groups (Figure 2-1).

- **IT loads:** Relevant to the IT equipment, namely servers, storage and network equipment.
- **Building load (referring to the supporting systems):** relevant to the mechanical and electrical systems that support the IT.

Figure 2-1 Simple schematic with the key data centre subsystems [12]



Typically only about half the power entering the data centre is used by the IT equipment [8]. The rest is used in the IT operation supporting facilities. Such a percentage actually varies in data centres according to the computing load intensity and the efficiency of the mechanical and electrical systems. The usual electricity breakdown in a data centre derived from a study carried out on 14 data centres is shown in Figure 2-2 [13]. Nevertheless, percentages can largely vary as shown in Figure 2-3 where the case on the left utilised a highly efficient system that was designed using best practices with better than standard HVAC (Heating, Ventilation and Air Conditioning) components and controls. The centre represented by the chart on the right utilised traditional distributed air-cooled CRAC (Computer Room Air Conditioners).

Figure 2-2 Representative Energy End Use Breakdown [13]

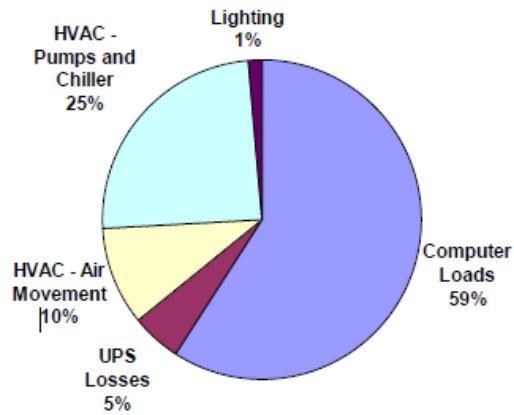
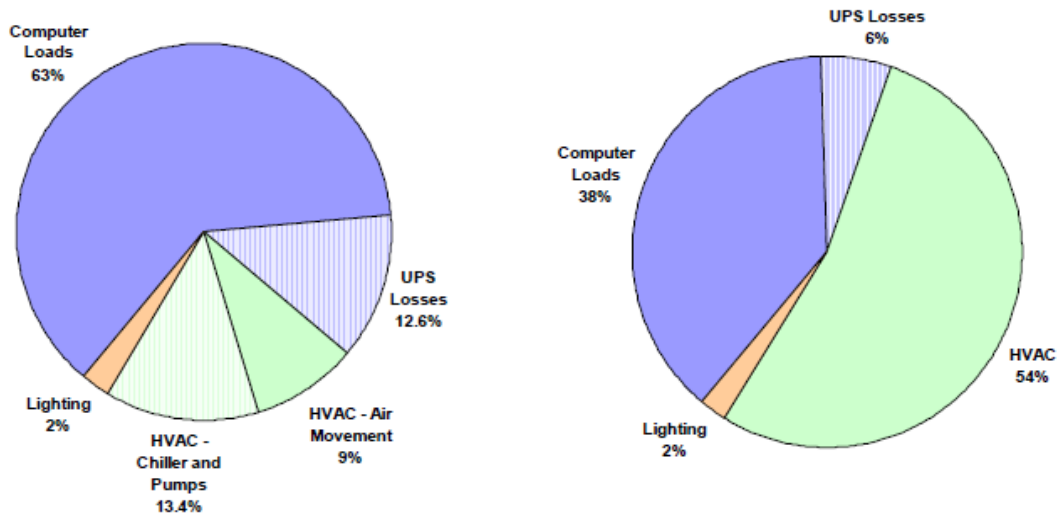


Figure 2-3 Benchmarking examples [13]



More recent data confirm the general breakdown attributed to the IT equipment, HVAC system and UPS (Uninterruptable Power System) the larger electricity uses (

Figure 2-4, Figure 2-5 and Figure 2-6).

Figure 2-4 Data Centre electricity breakdown: Source IBM

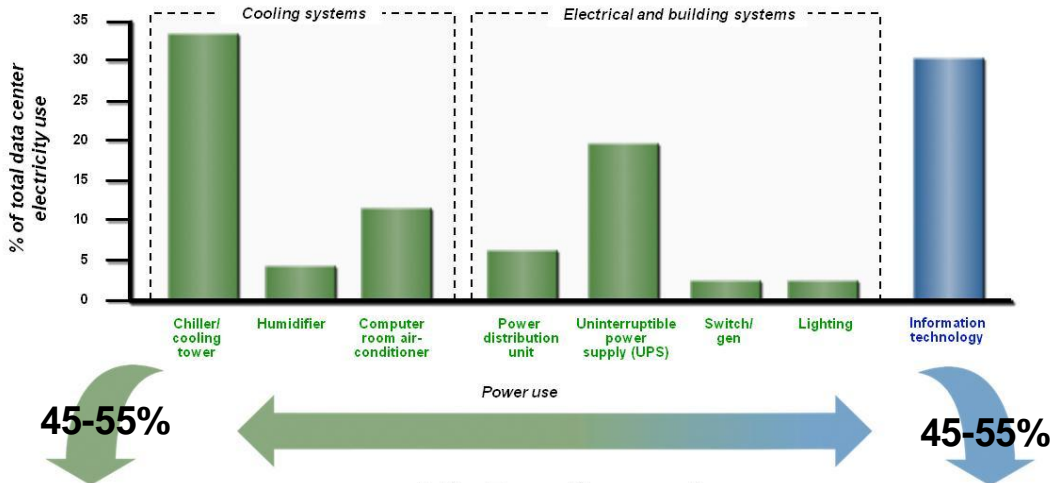


Figure 2-5 Data Centre electricity breakdown: Source APC

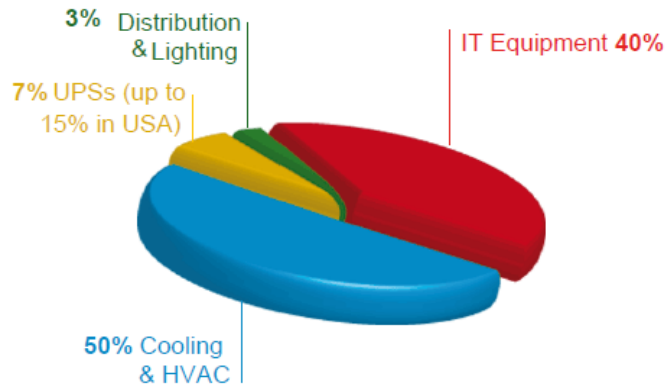
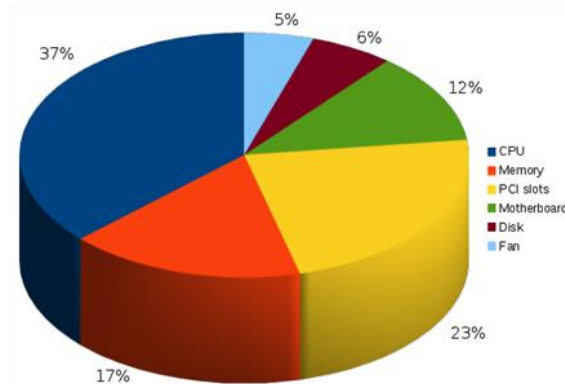
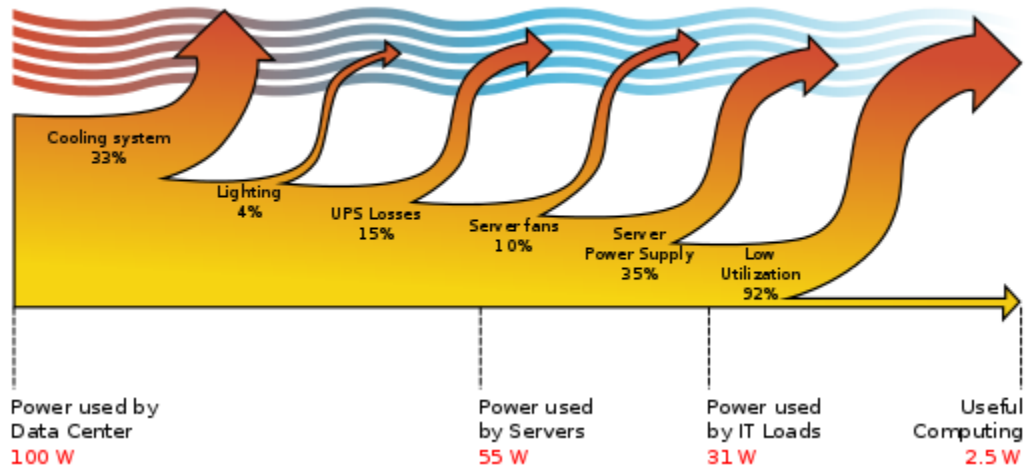


Figure 2-6 Data Centre electricity breakdown: Source Google



When accounting for the energy uses in IT equipment, servers demand high energy than storage and network does, being the CPU (Central Processing Unit) the most energy consuming component [14]. It has to be highlighted that the power provided to a server is not fully used for providing IT work, as shown in Figure 2-7. In fact, the power feeding a server is used for a large number of operations like powering memory, disks or the motherboard [15] [16].

Figure 2-7 Data Centre electricity breakdown, taking into account low utilisation [17]



The energy uses in data centres have been herein documented to identify the main energy consuming system for which it is necessary to define a minimum set of metrics.

3 Classification of metrics

This section explains the justification of choosing a concrete classification of metrics which best-fit the goals of CoolEmAll. The result of this justification process drives the selection of a particular way of classifying and selecting metrics useful for CoolEmAll.

3.1 Metric general description

In 2005 Herrlin defined how to develop be a good cooling index [18]. This is a good starting point to obtain guidelines on the selection of existing data centre metrics. From such approach we can extract a general view about what should be a suitable and useful metric for CoolEmAll.

- Treat energy performance and “green” aspects of the data centre, which ideally should depend on the geographic location.
- Be defined in a precise and accurate way, indicating how they must be measured in terms of measuring point location and time frames.
- Be measurable in such as CFD (Computational Fluid Dynamics) models as testbed as real data centres.
- Be simple and easy understandable for data centre industry.
- Be suitable for comparison between different data centres.
- Be suitable to be represented graphically.

Other desirable features of such a metric would be:

- Be dimensionless.
- Content the target value. E.g. PUE target value is 1, and it is also the lower value possible.

3.2 Metrics requirements

3.2.1 General requirements

As result of the analysis of the data centre literature, most metrics were initially defined on a power basis: they could be easily related to the equipment features declared by the manufacturers and be used to assess the data centre in the design phase on peak power capacity. A peak power based metric can then be used to evaluate the investment. Any improvement of such a metric is then reflected in a diminishment of the investment costs: for this reason so defined metrics are more interesting for the data centre owner [19].

The increasing sensitivity about energy consumption has moved the attention from the design/peak power data to the operation data. Of course also during the operation it is possible to obtain power-based metrics. Nevertheless instantaneous power at a data centre varies over time in a cyclic fashion 50 to 60

times a second [20]; thereby a correct evaluation would require an average power which is derived by measuring energy use over a period of time and then dividing by that time period. The energy-based metrics quantify the energy carriers used in a data centre and they enable an estimation of the operating cost and also equivalent emissions, which is the core of the “Green” concept.

With the increasing awareness of the importance of both the power and energy based metrics, metrics initially defined in terms of power have been then extended to energy based metrics, like in the case of PUE for which it is recommended to use annual energy consumption for all energy types as the unit of measure [21].

The Uptime Institute groups the energy and power efficiency metrics for a green data centre into four categories addressing different functions and responsibilities (Table 3-1). This state of the art will mention the stakeholders for different metrics but without addressing specific functions within an enterprise. Hereby a higher importance is attributed to different levels of detail in metrics as they require different measurements effort. Nevertheless efficiency metrics can be defined within each area, reaching the level of detail of single energy systems efficiency and applications. The CoolEmAll approach will go in deep with metrics review and definition in both the areas, addressing onsite generation efficiencies, RES (Renewable Energy Source) utilisation, heat reuse, IT operational utilisation and work productivity in line with the latest development in the field [22].

Table 3-1 Critical Environment Teams concerning data centres [19]

	Site Infrastructure Overhead	IT Productivity Per Watt
Strategic	Quadrant 4 (Q4): EVP Corp Real Estate <ul style="list-style-type: none"> • Benchmark SI-EOM with peers • Manage Corporate Social Responsibility • Manage the organization’s global data center asset portfolio 	Quadrant 1 (Q1): CIO/CTO <ul style="list-style-type: none"> • Benchmark existing hardware asset utilization and <i>harvest</i> lowest hanging fruit • Change IT governance to better allocate resources • Incorporate energy efficiency in hardware selection decisions • Benchmark IT Productivity Per Watt with peer organization • Incorporate energy considerations into IT Strategy
Operations	Quadrant 3 (Q3): Facility Manager <ul style="list-style-type: none"> • <i>Measure and manage</i> SI-EOM • <i>Implement</i> known SI Overhead best practices • <i>Utilize</i> more free-cooling • <i>Install</i> more energy efficient infrastructure components (when possible) 	Quadrant 2 (Q2): Data Center Manager <ul style="list-style-type: none"> • <i>Implement</i> Q1 harvesting decisions • <i>Implement</i> known computer room best practices

3.2.2 CoolEmAll requirements

Before we identify metrics concerning energy-awareness and heat-awareness in data centres, firstly the project needs are herein identified. In that way, the energy efficiency characterisation of the DEBBs (Data centre Efficiency Building Block) requires information about the energy consumption, productivity and the

capacity of the data centre on different levels of granularity. In addition it requires information about the behaviour of several components and sets of components within the data centre under specific conditions. This is also required by the energy efficiency characterisation of applications and workload schedulers. The workload is understood as a set of jobs, ranging from single sequential jobs, through parallel and distributed jobs, up to the whole workflows containing time dependencies between them. The energy consumption may vary for a given application, depending on the workload configuration (sequential jobs vs. parallel, etc.) and also on other characteristics like the size of the jobs. Therefore the workload is not directly measurable and must be understood as a set of factors that determines the energy consumption of the IT equipment (as a result of workload execution) and consequently on the supporting systems.

Characterisation of the data centre types according the service they provide it is also required to identify the measurable work that addresses indirectly to the productivity of a data centre. This concept is widely known in the industry as the useful work produced in a data centre. Here is remarked the definition of proxy indicator introduced and developed by The Green Grid resulting on a list of methods of measuring indirectly the useful work in a data centre [20]. In that way, CoolEmAll has identified the following data centre types regarding the services provided and what is understood as useful work:

- **HPC (High Performance Computing):** FLOP or the number of floating-point operations.
- **Cloud:** Number of service invocations.
- **General-purpose:** Number of transactions.

Applications have a particular role concerning metrics. This role is symmetric as metrics can be used to evaluate applications, but at the same time, several metrics use applications (usually called benchmarks) to provide insight on other levels of the infrastructure. As an example, HPC centres are usually evaluated using the Linpack benchmark that provides an evaluation of the maximum floating point possibilities of a super-computer. In this part the focus is rather on evaluating application, not on using application for evaluation. Metrics concerning productive applications will be described, then metrics concerning the runtime environment.

In this case metrics are used to compare several applications or libraries given a fixed infrastructure. This field is comparable with classical performance evaluation of application, the difference being that usually physical resource usage (processor load, memory, etc.) is put in second to energy.

In this case, comparison between several application and libraries with the same goal is often achieved using “energy-to-solution”. It was demonstrated how to use energy-to-solution to compare and choose linear algebra kernels [23]. This metric is adaptable for HPC and Clouds systems which are the aims of CoolEmAll. For HPC, usually energy-to-solution is used for obtaining a final result, i.e. total

energy needed to compute a weather forecast. For Clouds, usually it is used at a finer granularity: energy-per-request.

The main limit of current approaches is their non-holistic and non-temporal approach. Usually energy-to-solution refers only to the energy of computing elements. In CoolEmAll, a more holistic approach taking into account also cooling and other energy consuming devices is proposed. Even more problematic is the non-temporality as two applications with different power profiles can have the same energy-to-solution. A parallel application consuming a constant power on all nodes and during the whole experiment will be completely different for the cooling infrastructure than another consuming the same total energy, but concentrating the power consumption on a few nodes during a limited time. The difficulty lies in being able to express such a diversity of power profiles in a simple mean.

Metrics concerning middleware evaluate how by using possible leverages (scheduling, DVFS, sharpshooting, switching off nodes, etc.) they either achieve energy reduction with reduced impact on performance, or reduce performance and productivity when subject on power or energy limits.

Depending on fields, middleware has to manage several types of performance and productivity. In HPC it usually means maximum and mean completion time, and delay. In clouds, it usually means delay and maximum and mean time-to-solution. For clouds it is usually expressed as SLA (Service Level Agreement) violations.

For middleware we extract three types of metrics:

- **Fixed performance:** These metrics evaluate the energy gains compared to doing nothing while having no impact on performance or productivity.
- **Fixed power:** These metrics evaluate the maximum performance or productivity reached with a constrained instantaneous budget.
- **Mixed objective:** Usually a Pareto function of power/energy and performance/productivity. It helps evaluate the middleware capacity of decision in complex environment.

Current middleware metrics have the same type of limits as application ones. There is a lack of temporal and temperature vision. For instance, a middleware that tries to limit the imbalance of heat dissipation is not, using current metrics, seen as better than one that do not take this into account.

3.3 Data centre boundaries

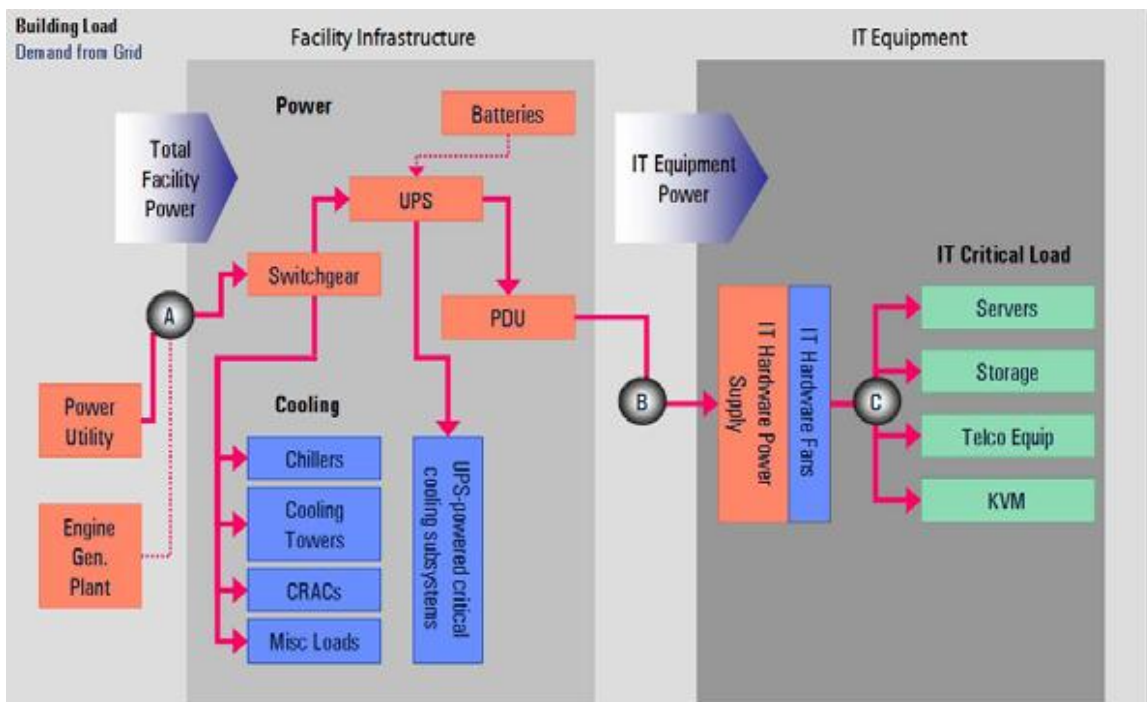
3.3.1 General description of boundaries in data centres

In order to identify possible needs for new metrics and to establish consistent efficiency evaluation approaches, it is useful to clearly define the boundaries, going much more in detail with respect to Figure 2-1. Once the physical boundaries are set, the energy streams used for different purposes can be easily identified, enabling the definition of metrics, such as in the example proposed by the Uptime Institute that actually considers the only electricity flows (Figure 3-1).

Usually there is a distinction between:

- **IT Equipment** that mainly includes servers, storage, network and hardware fans.
- **Data centre Facility Infrastructure** that mainly includes the HVAC facilities and the power facility. The HVAC facilities include the cooling system, ventilation system and auxiliaries such as distribution pumps, valves and power facility by power generator, UPS (Uninterruptable Power System), PDU (Power Distribution Unit), batteries and switchgears.

Figure 3-1 Data centre Electricity Flow and Metric Measurement Points: Source Uptime Institute

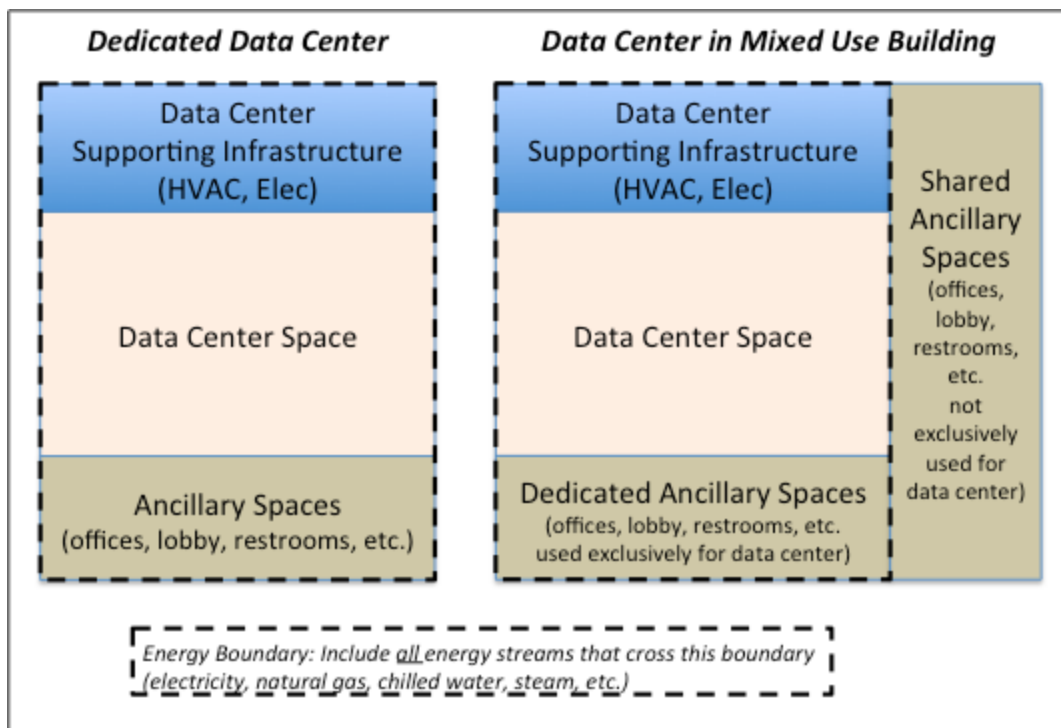


Such a distinction is visible in Figure 3-1 developed by the Uptime Institute to point out the measurements points for the definition of metrics. It can be noted

that any power generation system available on site is not included within the facility infrastructure. Its energy use is not accounted but its electricity supply to the facility infrastructure. The rationale behind this is that it is not of interest how the electricity is produced but only how it is used within a data centre and such an approach is not coherent with any energy efficiency assessment and improvement. Here some key points need to be pointed out:

- Last developments on metrics [21] differentiate between:
 - **Dedicated Data centre** as a free-standing building.
 - **Mixed-Use Data centre** with dedicated supporting systems. The data centre is within a larger building that has other uses, but the data centre has dedicated HVAC and electrical systems.

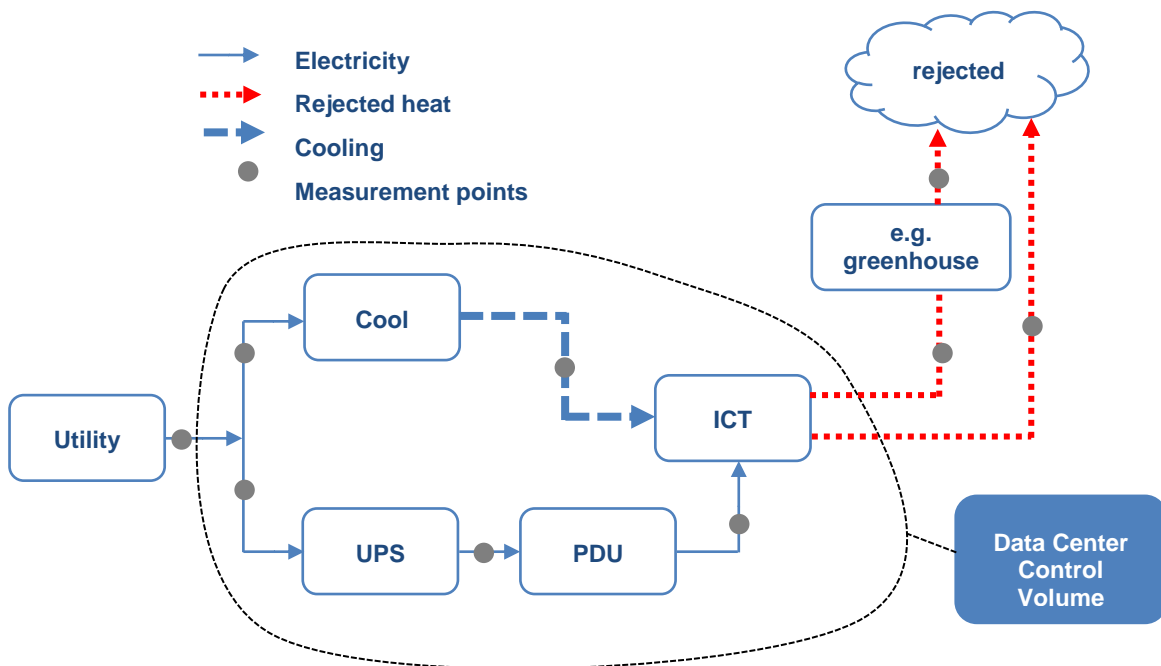
Figure 3-2 Energy use boundaries for Dedicated Data centres and Mixed-Use Data centres



Such an approach (Figure 3-2) apparently mixes physical spaces, like the ancillary spaces, and energy use areas like the data centre supporting infrastructure. A CRAC unit is a data centre supporting system but can be still part of the data centre space. Indeed, for the evaluation of data centre efficiency it is only necessary to account for the energy which is produced by shared systems but used for purposes not related to the data centre operation, e.g. electricity use for lighting the main building or heating use and so on.

- The RES power systems like solar and wind are considered as part of external utilities according to the Data Centre Efficiency Task Force [21] and Global Taskforce [24]. Their energy provision is accounted as produced from the grid, even if on site built and dedicated to the data centre. The environmental benefit of RES is related with the property of Certified Green Credits instead of the concept of on-site generation and consumption or exportation to the network. The environmental benefit of RES, in other fields, are related with the concept of on-site generation and consumption, that contributes to minimize the related CO₂ emissions and primary energy consumption of electricity that comes from the grid. In that sense, it is relevant to define the boundaries of the building (or data centre) and the energy flows with the surroundings.
- When talking of energy reuse, also in case of data centres, relevant efforts are going on to clearly define these boundaries and the control volume to measure the metrics [25], [24]. The following schema shows the concepts introduced by The Green Grid and endorsed by Global Task Force.

Figure 3-3. Data centre control volume. Source: IREC based on [25] [24]



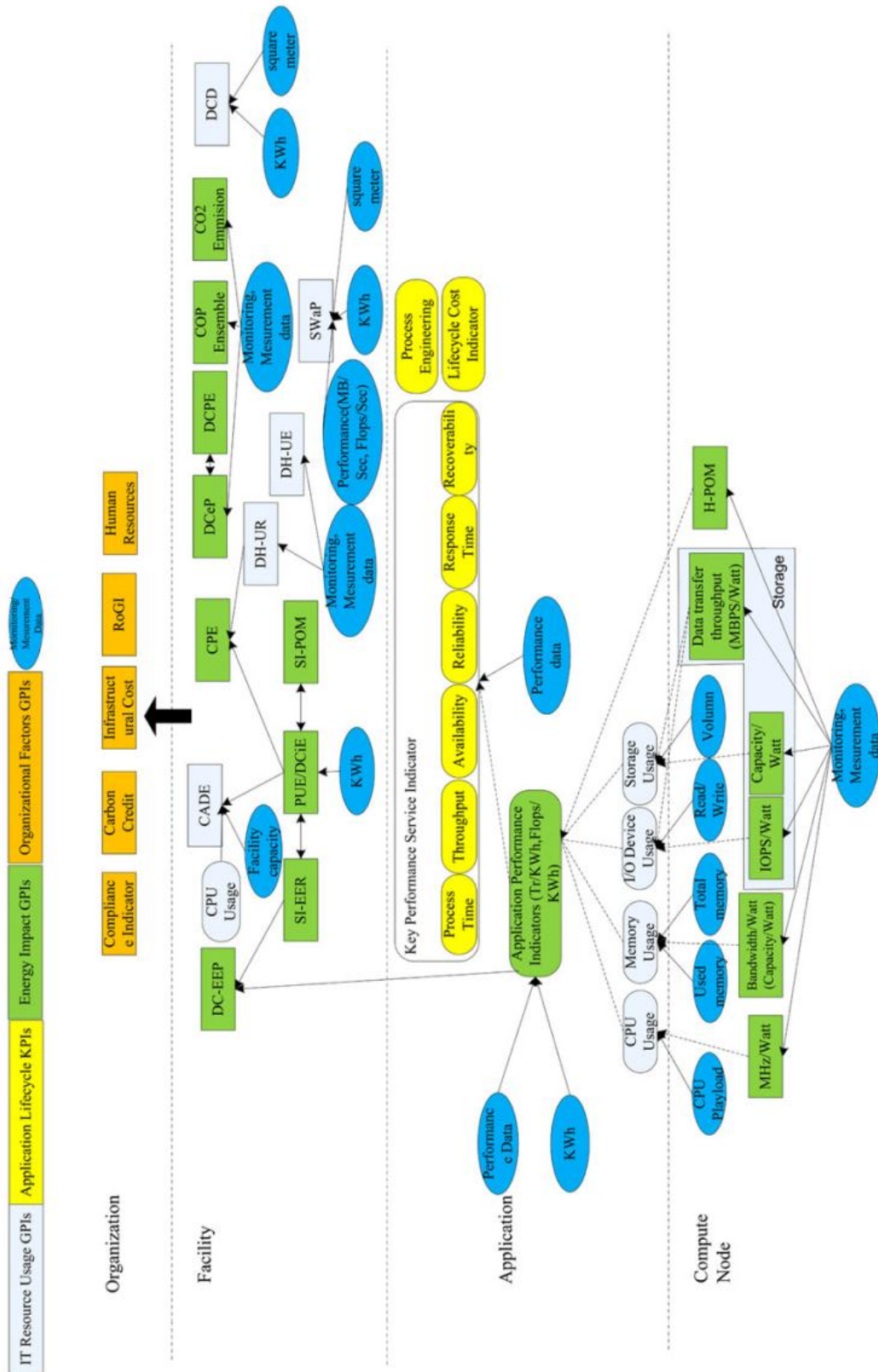
3.3.2 Metrics classification in GAMES

The classification proposed by the GAMES project classifies metrics, also called GPI (Green Performance Indicators) in four clusters according Jiang [26] and Kipp et al. [27]:

- **IT Resource Usage GPIs:** They characterise the IT resource usage of applications and their environment. The energy consumption of an application service is characterised as a function of resource utilisations by a given application service, whereas resources refer to CPU, Memory, I/O, Storage, etc. Their utilisation can be measured on various level of granularity and the values on higher levels can be obtained as a sum or the average value of the according lower level measurements.
- **Application Lifecycle KPIs (Key Performance Indicators):** Application Lifecycle indicators are not considered as GPIs as they do not directly impact the greenness or energy consumption of a data centre. This kind of indicators is a measure of performance of an application by characterizing service or process quality and efforts for designing and maintaining the process. The characterisation of service or process quality is done according to KPI, defined as a set of indicators that evaluate the quality measures of an application. In addition, the characterisation of effort for designing and maintaining the process can be expressed in terms of costs, reflected by Application Cost Indicators, including costs for analysis, design, coding, deployment and maintenance [26].
- **Energy Impact GPIs:** They describe the impact of a data centre on the environment considering power supply, consumed materials, emissions, and other energy related factors. It includes productivity and performance of data centres at any level of granularity.
- **Organizational GPIs:** They define the energy-related metrics that measure organisational factors in terms of impact on the infrastructural costs and serve as guidelines for managing data centres according to ecological related laws and regulations.

The metrics identified in the GAMES project are presented in a interrelation diagram shown in Figure 3-4. In this proposal four layers are identified: These are Compute Node, Application, Facility and Organisation as the highest layer. The relationship between the GAMES classification of metrics and CoolEmAll approach are discussed in sections 3.3.3 and 3.4.

Figure 3-4 Classification of metrics in GAMES project [26]



3.3.3 New boundaries proposal

In a future perspective of energy producing buildings, relying on renewable sources or high efficient systems, the data centre supporting systems actually includes three categories of facilities: energy producing systems, power distribution equipment and HVAC equipment, as shown in Figure 3-5.

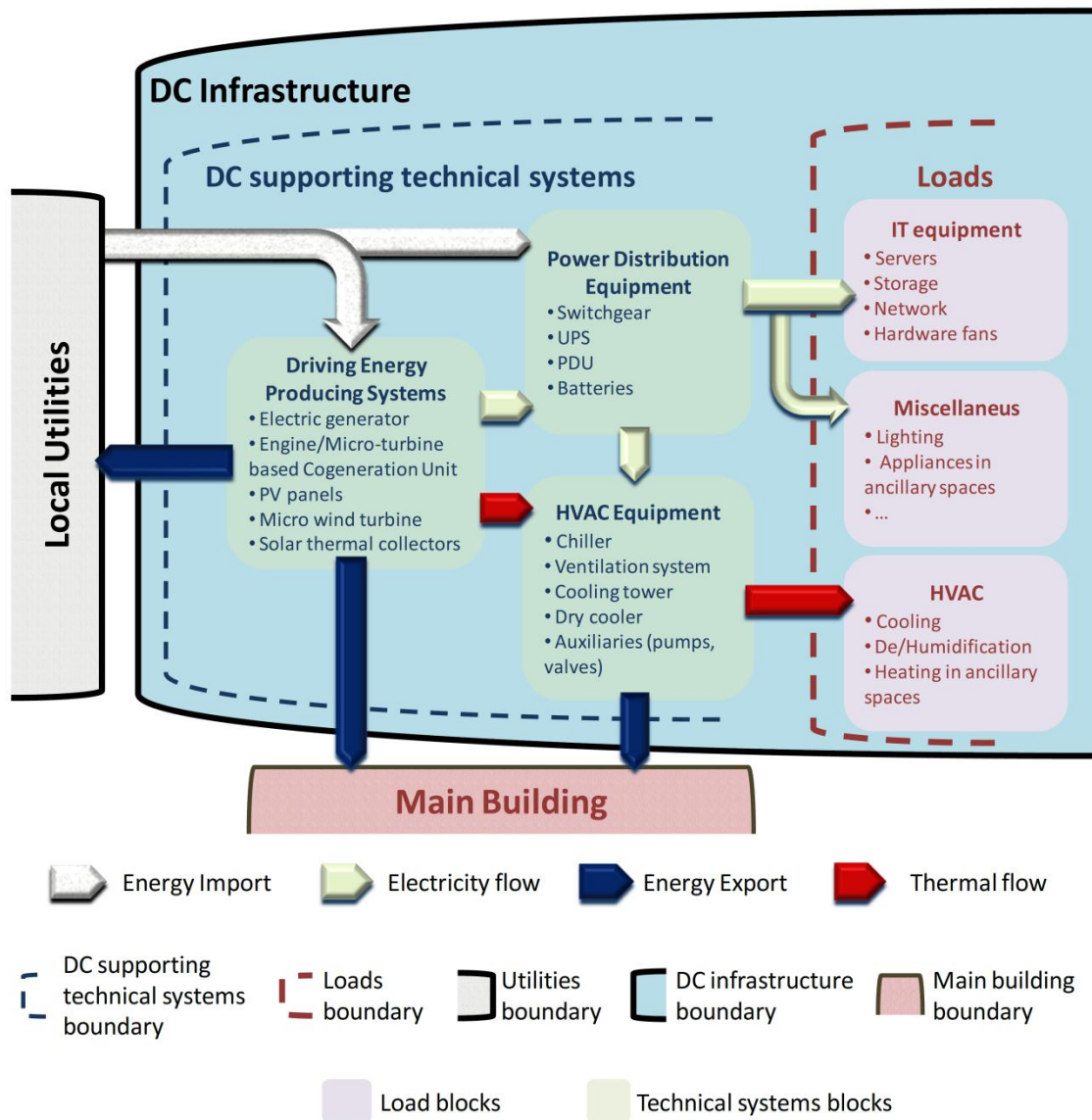
The IT Equipment includes all the loads associated with computing, storing, networking and supplemental equipment such as KVM switches, monitors, and workstations/laptops used to monitor or otherwise control the data centre. Whereas the Total Facility includes:

- Power delivery components, such as UPS, switch gear, generators, PDUs, batteries, and distribution losses external to the IT equipment;
- Cooling system components such as chillers, CRAC units, DX (direct expansion) air handling units, pumps, and cooling towers.
- Compute, network, and storage nodes.
- Other miscellaneous component loads such as data centre lighting

In fact, in a so called “Green Data Centre”, highly efficient or renewable sources driven on-site energy supply systems are probably going to be adopted, such as cogeneration unit, PV (Photovoltaic) panels or solar thermal surfaces. Thereby a wider group of technologies is interposed between the local grids from which the driven energy carriers are imported, like gas for a cogeneration unit, and the equipment which receive the energy from the supply systems before feeding it into the IT equipment. Such technologies can support the data centre operation by supplying electricity but also heat for cooling purposes, like in the case of tri-generation or solar cooling systems. Hence the scheme in the Figure 3-5 takes into account all the energy carriers flowing within a data centre infrastructure and the energy export as well.

Some of the energy supply systems supporting the data centre operation can export energy to the utility or can be shared with the main building where the data centre is installed. For an accurate energy efficiency evaluation of the data centre, it is needed to take into account the energy export towards the grid or the main building, especially when some energy carrier is used to run the supply systems. For instance in the case of a gas driven cogeneration unit, it is needed to subtract the amount of gas corresponding to the electricity and the heat exported to local grids or to the main building.

Figure 3-5 Major boundaries of a data centre for the assessment of metrics: Source IREC



The Figure 3-5 is not in contradiction with the system boundaries usually referred in the literature [1] [21] and within the established bodies working on metrics definition and standardization as for instance, U.S. Regional Task Force, Global Task Force [24] or The Green Grid [28]. There is still no standard about boundaries definition on data centre. It is expected that the EN 50600¹ standard series addressing the design of Data Centre facilities and infrastructures partly based on the criteria of energy efficiency will consider these issues. The first

¹ Standard developed by CEN-CENELEC. European Committee for Electrotechnical Standardisation

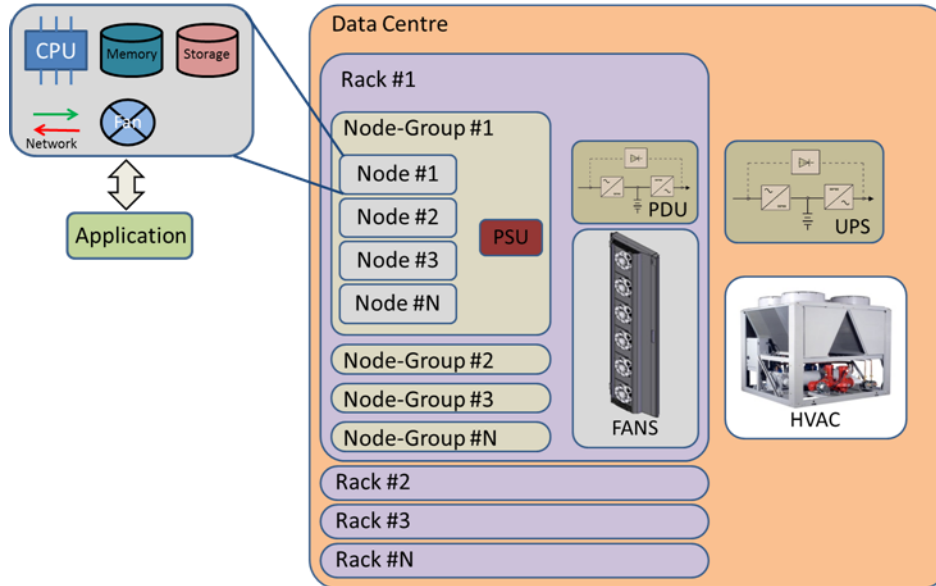
version of the standard has been ratified (September 2012), but is not yet available.

However, for CoolEmAll purposes, a deeper approach must be done rather on what is defined as the “Loads” boundary in Figure 3-5. In the mentioned figure and leveraging the DEBBs concept [29], it must be defined more levels of granularity differentiating the Node Level and the Node-Group Level both composed by typical IT hardware components. Here it can be noted that the Rack Level cannot be include on this “Loads” boundary due to it includes optionally elements from the “Data centre supporting technical systems” boundary like an rackable UPS and a water-cooled heat exchanger. Keeping on the Figure 3-5 the Data centre Level is coincident with “Data centre Infrastructure” boundary. At this point a definition of what includes physically the different DEBBs is necessary and given then.

- **Node:** A motherboard with CPU, cooling elements (including Fan), memory and optionally storage.
- **Node-Group:** An aggregation of Nodes in a common bus and including the PSU (Power Supply Unit).
- **Rack:** An aggregation of Node-Groups not necessarily in a common bus but placed in a single rack which optionally can include a heat exchanger and a UPS.
- **Data Centre:** The aggregation of Racks with HVAC systems, Power Distribution Equipment and Driving Energy Producing Systems as defined in Figure 3-5.

The components included in each boundary are represented in the Figure 3-6.

Figure 3-6 Components within boundaries in data centre: Source IREC



The relation of this proposal of boundaries with the layered APIs in GAMES project is shown in Table 3-2.

Table 3-2 Relation between GAMES' layers and CoolEmAll's boundaries

GAMES	CoolEmAll
Organization	Out of the focus of CoolEmAll
Facility	Data Centre
	Rack
Compute Node	Node-Group
	Node
Application	Application

3.4 Metrics classification in CoolEmAll

The CoolEmAll project goes further to the explained in previous Sections and defines DEBBs (Datacentre Energy Building Block) as an abstract description of a piece of hardware on different granularity levels [29] which is used to define levels of granularity in SVD Toolkit and ComputeBox blueprints. The global deliberation of how a metric should be, the identification of CoolEmAll's requirements and considering the proposal of GAMES about metrics classification drives to the following conclusions.

The characterisation of the energy impact of the applications is necessary to find out what workload management policies produce more productivity of data centre facilities and IT equipment, thereby a useful classification of metrics in CoolEmAll must include the application layer. Particularly the energy consumption of an application is characterised as function of IT components resource utilisations [26]. In addition, a fine-grained description of metrics for Facility layer defined by GAMES project (Figure 3-4) is necessary, taking node-group, ComputeBox1 (rack-level) and ComputBox2 level into account, as covered in DEBB concept [29].

Consequently the classification of metrics in CoolEmAll will follow the DEBB concept and will include the application boundary as well. This makes sense at the moment that the exercise of following the workflow in a data centre is done. In this way, the applications use the data centre facilities and the IT equipment to produce a useful work. In that way classifying metrics according DEBBs adds another advantage due to they are structured like an onion where each boundary includes the boundaries beneath. Therefore it makes sense that metrics will be defined from the lower physical boundary (Node Level) to the highest (Data Centre), such that metrics in a particular boundary will be based on the metrics of the boundary before and consequently there is no need to repeat the same metrics over and over again. Despite of that, in the literature there are defined metrics specially addressed to particular levels of granularity and useful to cover CoolEmAll's requirements. Due to facilitate the acceptance of this analysis of metrics in the data centre industry and in the standardization bodies, CoolEmAll will take advantage of them.

Moreover a sub-classification of metrics is needed according requirements on different CoolEmAll's tasks (Section 3.2.2) and where the approach made within the GAMES project (Section 3.3.2) makes advantage on that task. Therefore metrics on each boundary/DEBB-level will be classified as follow:

- **Resource Usage metrics:** The ratio of utilisation resulting in dividing the consumption of a particular resource by the total amount of that resource concerning a component or set of components.
- **Energy metrics:** It includes metrics addressed to the energy impact of data centre considering all its components and subsystems, whereas are distinguished:

- **Power-based metrics:** Metrics defined under power terms. The information provided is useful for designers because drives to peak power measurements.
- **Energy-based metrics:** Metrics defined under energy terms where the time of the measurement must be chosen.
- **Heat-aware metrics:** The heat-aware metrics take in account temperature to characterise the energy behaviour of the data centre.
- **Green metrics:** These metrics describe the impact of the operation of a data centre in the natural environment.
- **Financial metrics:** These metrics describe the financial impact of the operation of a data centre in a business organization.

4 Definition of metrics

In the present Section useful metrics for CoolEmAll have been selected and classified as per the criteria explained in the previous sections.

4.1 Node Level

The Node Level is the simplest and lower level of granularity in a data centre. It is coincident with the Node Level defined also as the simplest of the DEBBs [29]. Looking at the physical description it can be noted that the PSU is excluded, so power and energy must be measured just at the output of the PSU in DC (Direct Current) Voltage. The key components at this level have been identified as: CPU, Memory, Storage, Node Fan, Network bus and any additional I/O device.

4.1.1 Resource Usage

1) CPU Usage

CPU Usage is measured by evaluating the percentage amount of time that the allocated CPU spends for processing the instructions of the applications. It gives an indication of the CPU load, which is usually represented as a load average over a period of time [26]. CPU usage and load can be unified according to GAMES definition [26]. They are measured by evaluating how much CPU allocated to a process is used by a process over a given time interval.

$$CPU\ Usage = \frac{Amount\ of\ CPU\ Used}{Amount\ of\ CPU\ allocated} \quad \text{Eq. 1}$$

2) Server Usage

Being defined by The Green Grid, the Server Usage reflects utilisation level of a server and it is computed as follows [30]:

$$Server\ Usage = \frac{Activity\ of\ the\ CPU}{Maximum\ ability\ in\ the\ highest\ frequency\ state} = [\emptyset] \quad \text{Eq. 2}$$

This approach really evaluates the ratio of utilisation of the CPU at the Server level and it matches with the CPU usage indicator that desktop computers, laptops and also servers provide as direct measurement. However it must not be confused with the CPU Usage metric, which corresponds in to “Activity of the CPU”. Server Usage is to be considered as “normalized” CPU Usage, which is normalized by considering maximum ability in the highest frequency state.

3) Network Usage

Defined by The Green Grid, it measures the bandwidth used relative to the bandwidth capacity [30].

$$\text{Network Usage} = \frac{\text{Network bandwidth used [Mbps]}}{\text{Total bandwidth capacity [Mbps]}} = [\emptyset] \quad \text{Eq. 3}$$

The Network Usage is obtained as a direct measurement from desktop computers, laptops and also servers.

4) Memory Usage

The Memory Usage is the ratio of the average size of the portion of memory used by the process to the total amount of memory available [30].

$$\text{Memory Usage} = \frac{\text{Amount of used memory [Gb]}}{\text{Total amount of memory [Gb]}} = [\emptyset] \quad \text{Eq. 4}$$

The requirement of high memory naturally drives to consume more energy [30]. The Memory Usage is a good indicator of electronic energy waste even if it is not a direct indicator of efficiency. Thus less Memory Usage for the same host would improve metrics based on ecological impact without having an impact on performance. The Memory Usage is obtained as a direct measurement from desktop computers, laptops and also servers.

5) Storage Usage

The Storage Usage is the ratio of the disk space used by a process with respect to the total disk space available for the application [30]:

$$\text{Storage Usage} = \frac{\text{Storage used [Gb]}}{\text{Total storage capacity of data centre [Gb]}} = [\emptyset] \quad \text{Eq. 5}$$

An application using high amount of disk space intends to consume more energy [30]. With the Storage Utilisation, it happens the same than with Memory Utilisation, thereby even it is not a direct indicator of efficiency, it would improve other metrics based on ecological impact without performance impact. The Green Grid also uses this metric and it defines it in the same way [30]. The Storage Usage is obtained as a direct measurement from desktop computers, laptops and also servers

6) I/O Device Usage

It describes the percentage of occupation of the corresponding I/O device for communications and the number of messages transferred by an application over a set of system components [26].

$$I/O \text{ Usage} = \frac{\text{Number of I/O operations}}{\text{Total capacity of I/O operations}} = [\emptyset] \quad \text{Eq. 6}$$

The number of I/O operations is an accumulative quantity, thereby this metric must be addressed to a particular period of time where it has been identified maximum and average time of jobs or batched jobs completion and time of response of interactive applications.

4.1.2 Power-based metrics

Defining the following concepts is required to a full understating of Power-based metrics in the Node.

Power used by the Node (P_{node}) is the electrical power drawn by the Node. As the Node is composed by several components as described in previous Sections, and being possible to measure power drawn individually per each component it is suitable to estimate the power usage by summing the power usage of all components in the Node.

Rated power of the Node ($P_{node,rated}$) is the rated electrical power drawn by the Node according manufacturer's specifications.

1) Node Power Usage

It is highlighted that in the literature [27] appears utilisation metrics for all components, all of them defined above, included in IT equipment and in this case, in the Node. But also, it is observed the necessity of a global utilisation metric including all components in the Node, rather a Node usage metric. This can be defined as the ratio of the power used by the Node and the rated power usage of the Node.

$$\text{Node - Power - Usage} = \frac{P_{node} [W]}{P_{node,rated} [W]} = [\emptyset] \quad \text{Eq. 7}$$

2) MHz / Watt

Indicator of how efficiently power is being used by a CPU or processor [31] [26].

$$\frac{\text{MHz}}{\text{Watt}} = \frac{Y_{CPU} [\text{MHz}]}{P_{CPU} [W]} = \left[\frac{\text{MHz}}{W} \right] \quad \text{Eq. 8}$$

Where,

Y_{CPU} is the performance of the CPU, [MHz].

P_{CPU} is the electrical power drawn by the CPU, [W].

3) Bandwidth / Watt

It indicates how much data is moved or accessed per second or time interval per unit of power. This is often associated with capacity per watt [31] [26].

$$\frac{Bandwidth}{Watt} = \frac{\varphi_{network} [bps]}{P_{network} [W]} = \left[\frac{bps}{W} \right] \quad \text{Eq. 9}$$

Where,

$\varphi_{network}$ is the data transfer rate by the network measured in bits per second, [bps].

$P_{network}$ is the electrical power drawn by the network, [W].

4) Capacity / Watt

This metric refers to how much power is used by the storage facility [31]. For inactive data or off-line and archive data, the capacity per watt can be an effective measurement gauge however for active workloads and applications activity per watt also needs to be considered in order to get a representative indicator of how power is being used [26].

$$\frac{Capacity}{Watt} = \frac{C_{storage} [b]}{P_{storage} [W]} = \left[\frac{b}{W} \right] \quad \text{Eq. 10}$$

Where,

$C_{storage}$ is the capacity of the Storage measured in bytes, [b].

$P_{storage}$ is the electrical power drawn by the Storage, [W].

5) IOPS / Watt

Indicator of how efficiently power is being used to perform a given amount of work [31]. The work could be I/O's transactions, throughput or other indicator of IT equipment activity [26].

$$\frac{IOPS}{Watt} = \frac{IOP_i [IOPS]}{P_i [W]} = \left[\frac{IOPS}{W} \right] \quad \text{Eq. 11}$$

Where,

$IOPS_i$ is the number of I/O operations or transactions per second made by an I/O device in the Node, [IOPS].

P_i is the electrical power drawn by an I/O device in the Node, [W].

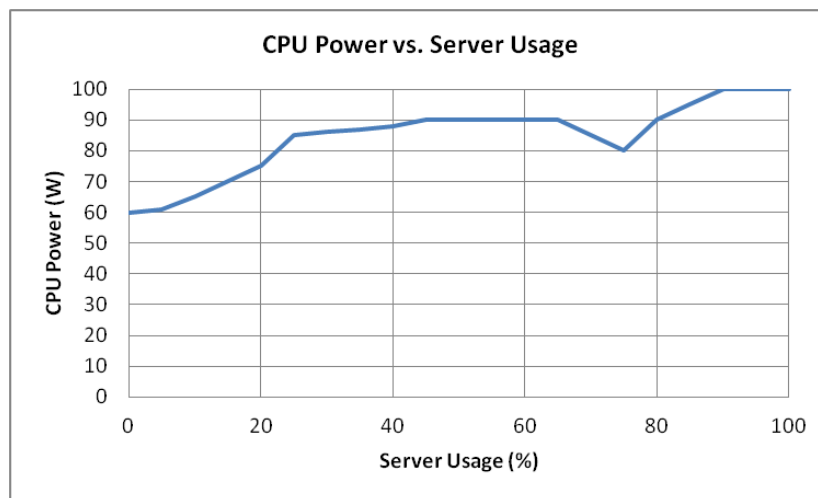
5) Power usage depending on the ratio of utilisation

This metric will help designers to size Cooling and Power supporting devices because it allows knowing the profile of behaviour of the Node comparing the

power usage of the Node and any Resource Usage metric defined in Section 4.1.1.

It must also be taken into account other factors that will determine this metric. Those are, the particular workload and the environmental conditions, being the inlet air temperature and relative humidity. Its evaluation can be done by drawing a graph with the power usage (Watt) at Y-axis and the usage ratio (%) at X-axis. Thus, it will be obtained a single graph for each set of environmental conditions and the particular workload running on the Node. All components in the Node are susceptible to be affected by environmental conditions modifying its global performance, however the more affected are the CPU (the main heat producer) and the fans (the active heat removing device), being the key environmental magnitude the server air inlet temperature [32].

Figure 4-1 CPU Power vs Server Usage: Source IREC



As usage metrics it is recommended to use all described in Section 4.1.1, which are addressed to specific components and also to the whole Node. Possible combinations are:

- CPU Power vs. Server Usage
- Memory Power vs. Memory Usage
- Storage Power vs. Storage Usage
- Network Power vs. Network Usage
- I/O Device Power vs. I/O Device Usage

4.1.3 Energy-based metrics

Specific metrics about productivity at the Node are not present in the literature, due to the fact that they are all defined at the Data Centre. Nevertheless it is made a new approach according CoolEmAll's requirements already described.

Defining the following concepts is required to a full understating of Energy-based metrics in the Node.

Energy consumed by the Node (E_{node}) is the electrical energy consumption of the Node during a given period of time. Being the Node composed by several components as described before, and being possible to measure the energy consumption individually per each component it is suitable to estimate it by summing them.

Useful work produced by the Node (W_{node}) is the quantity of useful work produced in the Node according the services provided. In this way and as is defined in Section 3.2.2, CoolEmAll focuses on HPC environments [FLOP], Cloud [Number of service invocations] and General-purpose services [number of transactions].

1) Node Productivity

The productivity according the type of service provided can be calculated as the ratio of the measurable produced work and the energy consumed by the Node during a given period of time.

$$Productivity_{node} = \frac{W_{node} [units\ of\ useful\ work]}{E_{node} [Wh]} = \left[\frac{units\ of\ useful\ work}{Wh} \right] \quad Eq. 12$$

Alternatively, a unit of watt hour [Wh] can be converted to Watt second [Ws] that is equal to Joule [J]. Furthermore, [second] in denominator can be shifted as reciprocal to nominator (while keeping its mathematical meaning). In that way, a unit of useful work i.e. [FLOP] (in HPC) per [Ws] can be converted to FLOP per seconds [FLOPS] per [W] as shown:

$$\left[\frac{FLOP}{Ws} \right] = \left[\frac{FLOPS}{W} \right]$$

4.1.4 Heat-aware metrics

1) Node Cooling Index

Classical use of temperature at the scale of a Data Centre is for problem detection. In current Data Centres, alert events are started once a temperature of a node rises over a certain threshold. In this case the exact value of temperature is often discarded, and only events of overheating are kept. At the scale of nodes, there is a feedback between temperature and cooling, usually provided by fans and sometime by rack-level cooling. Fans are usually impacted by maximum

temperature of the elements they are linked to and rack-level cooling is usually impacted by the mean temperature of its rack.

Therefore, the correct assessment about the health of the CPU would come from the study of the ratio of compliance of the temperature of the CPU taking in account the thresholds declared by the manufacturer of the CPU. In a study signed by Haywood et al. [33], it was used the Dell's OMSA (Open Manage System Administrator) software which indicated that processors can operate between 10°C and 120°C, and the maximum temperature possible is 125°C.

$$NCI_{node,LO} = \frac{T_{CPU}}{T_{CPU,min-all}} = [\emptyset] \quad \text{Eq. 13}$$

$$NCI_{node,HI} = \frac{T_{CPU}}{T_{CPU,max-all}} = [\emptyset] \quad \text{Eq. 14}$$

Where,

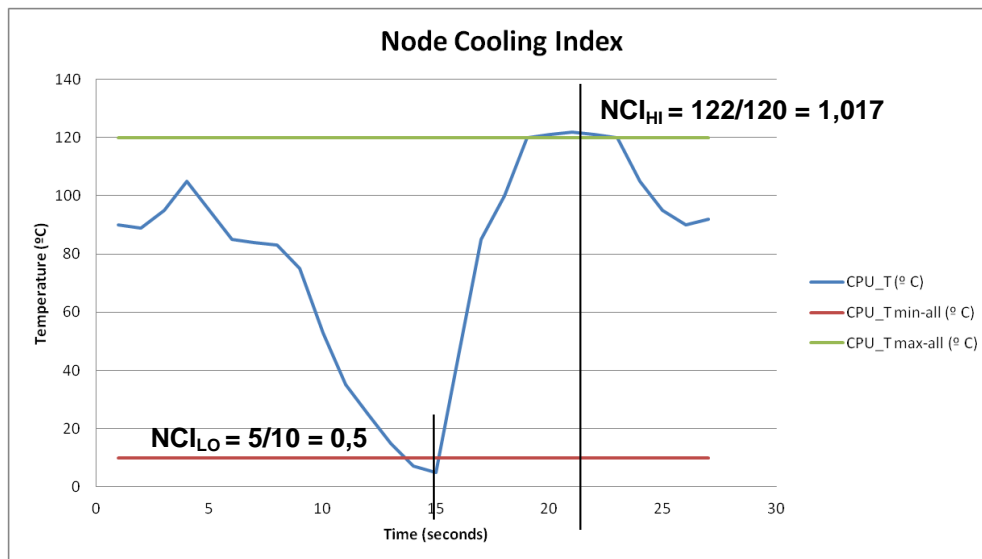
T_{CPU} is the temperature of the CPU.

$T_{CPU,min-all}$ is the CPU minimum allowable temperature according manufacturer specifications.

$T_{CPU,max-all}$ is the CPU maximum allowable temperature according manufacturer specifications.

An example is shown in Figure 4-2. In case of the temperature of the CPU is over the maximum threshold, NCI_{HI} is above one. In case the temperature of the CPU is under the minimum threshold, NCI_{LO} is less than one.

Figure 4-2 Example of use of NCI: Source IREC



2) Maximum and average heat dissipation

Heat dissipation is not directly measurable but is directly linked with temperature, cooling system, air-flow volume, in- and out-bound temperature. Measure is in J/s or Watt and its expression depends on the exact physical architecture.

The heat dissipation can be calculated using the expression in **Eq. 15**. It must be taken in account that the designing practices of infrastructures approximate the heat dissipated by the IT hardware with the electrical power drawn in a ratio of 1:1.

$$Q_{node} = \dot{m}_{node} \cdot C_p \cdot \Delta T_{node} \sim P_{node} \quad \text{Eq. 15}$$

Where,

Q_{node} is the heat dissipated by the Node, [W].

\dot{m}_{node} is the mass air flow rate through the Node, [kg/s].

C_p is the specific heat of the air used to cool the Node, [J/kg·K]

ΔT_{node} is the difference between the air inlet temperature and the air outlet temperature.

P_{node} is the electrical power drawn by the Node, [W].

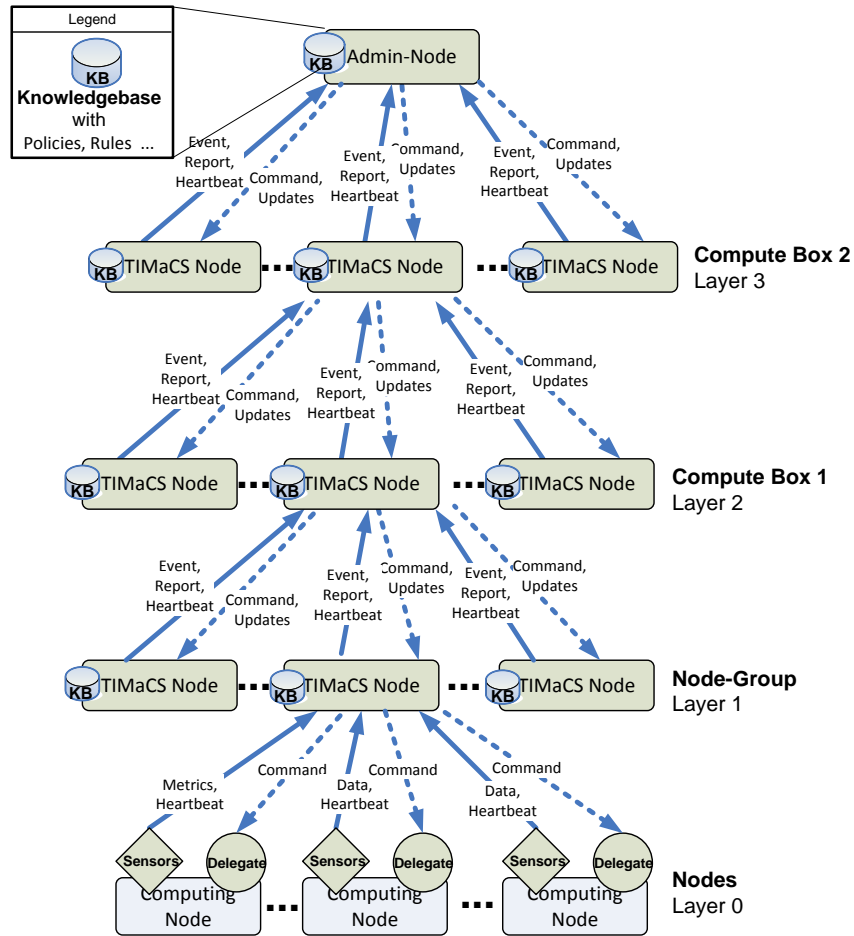
4.2 Node-Group Level

The Node-Group Level is the aggregation of several Nodes including potentially the PSU as well and it is also coincident with the Node-Group Level defined in DEBBs conception [29]. Therefore the components identified in this level are a fixed quantity of Nodes and the PSU.

With some exception, specific metrics at this level are not present in the literature, due to they are all defined at the data centre level. Therefore metrics at this level must come from the aggregation of the same kind of metrics defined in Node Level (Section 4.1) and calculating the averaged value.

Some deployments having a common platform are able to give averaged values for all servers they support. Examples are found in RECS developed by Christmann and explained in deliverable D3.1 [29] and Blade solution developed by almost all IT hardware manufacturers. This is shown in Figure 4-3 where hierarchy and interrelations between the different levels of granularity concerning the monitoring system TIMaCS are indicated.

Figure 4-3 DEBBs hierarchy according the monitoring system TIMaCS [29]



4.2.1 Resource Usage

1) Aggregation of metrics

The Resource Usage metrics defined in the Node level are suitable to be used in Node-Group by aggregation and averaging. Here two possible approaches are possible taking into account the homogeneity of the Nodes involved. Thus the metrics about Node-Groups with homogenous Nodes, thereby all with the same capacity, can be calculated using the general formulation in Eq. 16.

$$Resource\ Usage_{NG} = \frac{\sum_i^N \gamma_i}{\sum_i^N c_i} = \frac{1}{N} \sum_i^N Resource\ Usage_i \quad \text{Eq. 16}$$

Where,

y_i is the performance of the studied component of the Node (e.g. Storage).

c_i is the capacity of the studied component of the Node (e.g. Storage).

N is the quantity of Nodes in the Node-Group.

Resource Usage_i is the Resource Usage metric calculated for each Node in the Node-Group (e.g. Storage Usage).

Contrary in case of heterogeneous Nodes it will be obtained from a weighted average as expressed in **Eq. 17**.

$$Resource\ Usage_{NG} = \sum_i^N Resource\ Usage_i \cdot w_i \quad \text{Eq. 17}$$

The weighting factor is obtained from **Eq. 18**.

$$w_i = \frac{c_i}{C_{NG}} ; C_{NG} = \sum_i^N c_i \quad \text{Eq. 18}$$

It can be observed in the example of Figure 4-4 that both methods are equal when the study is about heterogeneous Nodes as it used to be. In this example it is calculated the Server Usage at the Node-Group.

Figure 4-4 Aggregation methods for Server Usage metrics from Node to Node-Group level: Source IREC

CASE 1				CASE 2	
Node_i	CPU Activity_i	CPU Capacity_i	Server Usage_i	weight_i	Server Usage_i*weight_i
#1	50	100	0,50	0,056	0,028
#2	75	110	0,68	0,061	0,042
#3	35	50	0,70	0,028	0,020
#4	45	85	0,53	0,047	0,025
#5	60	135	0,44	0,075	0,033
#6	75	100	0,75	0,056	0,042
#7	69	70	0,99	0,039	0,038
#8	73	80	0,91	0,045	0,041
#9	35	150	0,23	0,084	0,020
#10	53	95	0,56	0,053	0,030
#11	28	65	0,43	0,036	0,016
#12	38	100	0,38	0,056	0,021
#13	95	100	0,95	0,056	0,053
#14	48	83	0,58	0,046	0,027
#15	78	85	0,92	0,047	0,044
#16	86	100	0,86	0,056	0,048
#17	35	62	0,56	0,035	0,020
#18	66	82	0,80	0,046	0,037
#19	32	50	0,64	0,028	0,018
#20	72	91	0,79	0,051	0,040
SUM	1148,00	1793,00			0,640
		Server Usage_NG	0,640	Server Usage_NG	0,640

2) DH-UR: Deployed Hardware Utilisation Ratio

The DH-UR reflects in what degree hardware is used during “normal” period of time [26].

$$DH - UR = \frac{N_{node-useful}}{N} = [\emptyset] \quad \text{Eq. 19}$$

Where,

$N_{node-useful}$ is the quantity of Nodes in the Node-Group that are running applications producing useful work.

N is the total quantity of Nodes deployed in the Node-Group.

Knowing the quantity of Nodes running live applications from the total number of deployed Nodes is an indicator for the energy consumption of the main computing equipment from the IT equipment in “normal” periods of time [26]. For instance if 50% of the Nodes are sufficient to handle average load and are running all the time, then the rest could be shut-down to save energy [26]. Efficient deployments would intend to have DH-UR as close to 1 as possible.

3) DH-UR_{CPU}: Deployment Hardware Utilisation Ratio considering CPU

The DH-UR_{CPU} metric reflects the utilisation ratio of CPUs (comparing to allocated CPUs) that are used within the allocated CPUs of the Node-Group.

$$DH - UR_{CPU} = \frac{N_{CPU-used}}{N} = [\emptyset] \quad \text{Eq. 20}$$

Where,

$N_{CPU-used}$ is the quantity of CPUs in use within the Node-Group.

N is the quantity of CPUs allocated in the Node-Group.

Efficient deployments would intend to have $DH - UR_{CPU}$ as close to 1 as possible.

4.2.2 Power-based metrics

Concepts used to define Power-based metrics in Node-Group level must be clarified after going through them. These are:

Power used by the component (P_{comp}) is the electrical power drawn by a particular type of component. The assessment in Node-Group level considers i.e. the summing of all the CPUs included in the Node-Group. Note this is completely different than the power used by the Node-Group (P_{NG}). Consequently it is calculated as in Eq. 21.

$$P_{comp} = \sum_i^N p_i \quad \text{Eq. 21}$$

Where,

N is the quantity of Nodes in the Node-Group.

p_i is the power drawn by the studied component of the Node-Group (e.g. Memory), but being really part of the Node, [W].

1) Aggregation of metrics

The Power-based metrics defined in Node level must be reformulated to be used in Node-Group level. These metrics are mainly referred to the performance of components in the Node-Group regarding power usage of that component. In consequence there is no a common point to measure all the same kind of components within the Node-Group and the metric can only be obtained as shown in Eq. 22.

$$Power_{NG} = \sum_i^N Power_i \cdot w_i ; w_i = \frac{p_i}{P_{comp}} \quad \text{Eq. 22}$$

Where,

$Power_i$ is the Power-based metric from each Node in the Node-Group (e.g. MHz/Watt).

2) SWaP: Space, Watts and Performance

In order to allow comparison of several IT server configurations, it is defined the SWaP indicator which takes space occupation, rated power usage and rated performance of a single server [26]. It is calculated as:

$$SWaP = \frac{W_{NG,rated} [\text{units of useful work}]}{H_{NG} [\text{number } U] * P_{NG,rated} [W]} = \left[\frac{\text{units of useful work}}{\text{number } U * W} \right] \quad \text{Eq. 23}$$

Where,

$W_{NG,rated}$ is the rated performance of the Node-Group, [units of useful work].

H_{NG} is the occupation of the Node-Group in the Rack, [number of U].

Therefore, it is not defined as a “living” indicator due to it is fixed for each server, but once assigned it can help data centre operators for servers’ collocation or reorganization [26].

4.2.3 Energy-based metrics

Defining the following concepts is required for a full understating of Energy-based metrics in the Node-Group.

Energy consumed by the Node-Group (E_{NG}) is the electrical energy consumption of the Node-Group during a given period of time. Because of the inclusion of the PSU, to obtain it, it must be measured just at the input of the PSU. Otherwise it would not include the PSU consumption due to its inefficiencies converting AC to DC.

Useful work produced by the Node-Group (W_{NG}) is the quantity of useful work produced in the Node-Group according the services provided. In this way and as is defined in Section 3.2.2, CoolEmAll focuses on HPC environments [FLOP], Cloud [Number of service invocations] and General-purpose services [number of transactions]. Due to it is implicitly measured in the Node it must be calculated by summing the useful work produced by all Nodes in the Node-Group.

$$W_{NG} = \sum_i^N W_{node,i} \quad \text{Eq. 24}$$

Where N is the number of Nodes in the Node-Group.

1) Node-Group Productivity

It is defined in the same way than the Node Productivity (Eq. 12) but applied to the Node-Group.

$$Productivity_{NG} = \frac{W_{NG} [\text{units of useful work}]}{E_{NG} [Wh]} = \left[\frac{\text{units of useful work}}{Wh} \right] \quad \text{Eq. 25}$$

4.2.4 Heat-aware metrics

1) Node-Group Cooling Index

It is defined in the same way than RCI (Eq. 42 and Eq. 43) but applied in the Node-Group level. Therefore is reformulated as shown in Eq. 26 and Eq. 27.

$$CI_{NG,HI} = \left[1 - \frac{\sum (T_{NG,x} - T_{max-rec})_{T_{NG,x} > T_{max-rec}}}{(T_{max-all} - T_{max-rec}) * n} \right] * 100 = [\%] \quad \text{Eq. 26}$$

$$CI_{NG,LO} = \left[1 - \frac{\sum (T_{min-rec} - T_{NG,x})_{T_{NG,x} < T_{min-rec}}}{(T_{min-rec} - T_{min-all}) * n} \right] * 100 = [\%] \quad \text{Eq. 27}$$

Where,

$T_{NG,x}$ is the average temperature at Node-Group air intake in a given period of time.

n is the total number of air intakes.

$T_{max-rec}$ is the maximum recommended air temperature per some guideline or standard.

$T_{max-all}$ is the maximum allowed air temperature per some guideline or standard.

$T_{min-rec}$ is the minimum recommended air temperature per some guideline or standard.

$T_{min-all}$ is the minimum allowed air temperature per some guideline or standard.

The interpretation is the following:

- $CI_{NG,HI} = 100\%$ All intake temperatures \leq max. recommended temperature.
- $CI_{NG,HI} < 100\%$ At least one intake temperatures $>$ max. recommended temperature.
- $CI_{NG,LO} = 100\%$ All intake temperatures \geq min. recommended temperature.
- $CI_{NG,LO} < 100\%$ At least one intake temperatures $<$ min. recommended temperature.

2) Node-Group Humidity Index

In addition to the temperature, different standards and guidelines also give recommended and allowable ranges for the relative humidity. Thereby it makes sense to define metrics in that way and following the same philosophy than Eq. 26 and Eq. 27.

$$HI_{NG,HI} = \left[1 - \frac{\sum (RH_{NG,x} - RH_{max-rec})_{RH_{NG,x} > RH_{max-rec}}}{(RH_{max-all} - RH_{max-rec}) * n} \right] * 100 = [\%] \quad \text{Eq. 28}$$

$$HI_{NG,LO} = \left[1 - \frac{\sum (RH_{min-rec} - RH_{NG,x})_{RH_{NG,x} < RH_{min-rec}}}{(RH_{min-rec} - RH_{min-all}) * n} \right] * 100 = [\%] \quad \text{Eq. 29}$$

Where,

$RH_{NG,x}$ is the average relative humidity at Node-Group air intake in a given period of time.

n is the total number of air intakes.

$RH_{max-rec}$ is the maximum recommended air relative humidity per some guideline or standard.

$RH_{max-all}$ is the maximum allowed air relative humidity per some guideline or standard.

$RH_{min-rec}$ is the minimum recommended air relative humidity per some guideline or standard.

$RH_{min-all}$ is the minimum allowed air relative humidity per some guideline or standard.

3) Imbalance of temperature of CPU

First it allows evaluating the quality of cooling. A good cooling for a Node-Group would lead to a constant temperature for each type of elements of nodes. Usually the temperature measured is the one of processors, thus this metric represent the imbalance of temperature of CPU. It is measured as the difference between the maximum and the minimum of average values of CPU temperature divided by the average over a timescale. $Im_{NG,temp}$ value close to 0 indicate good temperature balance.

$$Im_{NG,temp} = \frac{T_{CPU,max} - T_{CPU,min}}{T_{CPU,avg}} * 100 = [\%]; T_{CPU,avg} = \frac{1}{N} \sum_i^N T_{CPU,i} \quad \text{Eq. 30}$$

Where,

$T_{CPU,,i}$ is the temperature of each i CPU in the Node-Group.

N is the quantity of CPUs in the Node-Group.

$T_{CPU,max}$ is the maximum temperature reached by the CPUs in the Node-Group during a given period of time.

$T_{CPU,min}$ is the minimum temperature of the CPUs in the Node-Group during a given period of time.

$T_{CPU,avg}$ is the average temperature of the CPUs in the Node-Group during a given period of time.

4) Imbalance of heat generation

Heat generation imbalance shows problems at the scheduling level. If a node of a Node-Group has a largely higher heat generation than other nodes, it means the scheduler mainly allocate jobs on it, and thus create problems for the cooling infrastructure. Heat generated imbalance is computed in the same way as temperature imbalance. $Im_{NG,Heat}$ values close to 0 indicate good heat generation balance.

$$Im_{NG,Heat} = \frac{Q_{node,max} - Q_{node,min}}{Q_{node,avg}} * 100 = [\%]; \quad Q_{node,avg} = \frac{1}{N} \sum_i^N Q_{node,i} \quad \text{Eq. 31}$$

Where,

$Q_{node,i}$ is the heat generated by each i Node in the Node-Group, [W].

N is the quantity of Nodes in the Node-Group.

$Q_{node,max}$ is the maximum thermal heat generated by the Nodes in the Node-Group, [W].

$Q_{node,min}$ is the minimum thermal heat generated by the Nodes in the Node-Group, [W].

$Q_{node,avg}$ is the averaged thermal heat generated by the Nodes in the Node-Group, [W].

4.3 Rack Level

The Rack Level is the aggregation of several Server-Groups and it is coincident with the ComputeBox1 defined as one of the DEBBs [29]. The identified components within this boundary are: Several Group-Nodes with all its elements, UPS (Optionally) and a side heat exchanger (Optionally).

4.3.1 Resource Usage

1) Aggregation of metrics

The Resource Usage metrics in Node-Group level can be used on the Rack level by aggregation. As explained in Section 4.2.1, two approaches are possible depending on the homogeneity of the Nodes. Formulation for homogenous Nodes is presented in Eq. 32 and for heterogeneous Nodes in Eq. 33.

$$Resource\ Usage_{rack} = \frac{\sum_i^N \gamma_{NG,i}}{\sum_i^N c_{NG,i}} = \frac{1}{N} \sum_i^N Resource\ Usage_{NG,i} \quad \text{Eq. 32}$$

$$Resource\ Usage_{rack} = \sum_i^N Resource\ Usage_{NG,i} \cdot w_i \quad \text{Eq. 33}$$

$$c_{NG} = \sum_i^J c_i ; \gamma_{NG} = \sum_i^J \gamma_i ; w_i = \frac{c_{NG,i}}{c_{rack}} ; c_{rack} = \sum_i^N c_{NG,i} \quad \text{Eq. 34}$$

Where,

$Resource\ Usage_{NG,i}$ is the Resource Usage metric obtained for each Node-Group in the Rack as defined in Section 4.2.1.

J is the quantity of Nodes in the studied Node-Group.

N is the quantity of Node-Groups in the Rack.

4.3.2 Power-based metrics

A concept used to define Power-based metrics in Rack level can be clarified after going through them. This is:

Power used by the component (P_{comp}) is the electrical power drawn by a particular type of component. The assessment in Rack level considers i.e. the summing of power of all CPUs included in the Rack. Note this is completely different than the power used by the Rack (P_{rack}). Consequently it is calculated as in Eq. 35.

$$P_{comp} = \sum_i^N p_i \quad \text{Eq. 35}$$

Where,

N is the quantity of Node-Groups in the Rack.

p_i is the power drawn by the studied component of the Rack (e.g. Storage), but being really part of the Node, [W].

1) Aggregation of metrics

It is followed the same method explained in Section 4.2.2, to obtain Power-based metrics in the Rack level by aggregation and averaging of the same kind of metrics in Node-Group level.

$$Power_{rack} = \sum_i^N Power_{NG,i} \cdot w_i ; w_i = \frac{p_i}{P_{comp}} \quad \text{Eq. 36}$$

Where $Power_{NG,i}$ is the Power-based metric from each Node-Group in the Rack.

2) UPS Usage

The utilisation of the UPS is defined as the total apparent power measured downstream the UPS, also called the inverter apparent power, and the rated capacity of the UPS.

$$UPS\ Usage = \frac{S_{UPS} [VA]}{S_{UPS,rated} [VA]} * 100 = [\%] \quad \text{Eq. 37}$$

Where,

S_{UPS} is the apparent power supplied by the UPS measured at the output, [VA].

$S_{UPS,rated}$ is the rated apparent power of the UPS according to manufacturer specifications, [VA].

The UPSes are specified by the downstream apparent power they are able to handle under standard conditions, thereby a 500 kVA UPS is able to handle 500 kVA as maximum. This metric is obtained directly from the UPS as measurement having different communication protocols depending on the manufacturer (e.g. Modbus, SNMP, etc).

3) Heat exchanger Usage

The utilisation of the heat exchanger is defined as the heat removed by the rated capacity of the heat exchanger.

$$Heat\ exchanger\ Usage = \frac{Q_{coil} [W]}{C_{coil} [W]} * 100 = [\%] \quad \text{Eq. 38}$$

Where,

Q_{coil} is the heat removed by the heat exchanger, [W].

C_{coil} is the maximum capacity of heat removing of the heat exchanger, [W].

A general formulation to calculate the heat transportation is presented in Eq. 15.

4.3.3 Energy-based metrics

Defining the following concepts is required to a full understating of Energy-based metrics at Rack level.

Energy consumed by the Rack (E_{rack}) is the electrical energy consumption of the Rack during a given period of time. In order to calculate it two methods are possible. One measures the energy consumption in an electrical common point as the energy feed to the Rack or at the output of the PDU. In case this is not possible it must be obtained from the summing of all its components as expressed in Eq. 39.

$$E_{rack} = \sum_i^N e_{NG,i} + \sum_j^J e_{UPS,j} + \sum_k^K e_{cooling,k} + \sum_l^L e_{aux,l} \quad \text{Eq. 39}$$

Where,

$e_{NG,i}$ is the energy consumption of a Node-Group during a given period of time, [Wh]

$e_{UPS,j}$ is the energy consumption of a UPS in the Rack during a given period of time and measured at the input of the UPS, [Wh].

$e_{cooling,k}$ is the electrical energy consumption of the heat removers (fans, control devices, etc.) in the Rack during a given period of time, [Wh]

$e_{aux,l}$ is the electrical energy consumption of the auxiliary devices in the Rack during a given period of time, [Wh]

Useful work produced by the Rack (W_{rack}) is the quantity of useful work produced in the Rack according the services provided. In this way and as is defined in Section 3.2.2, CoolEmAll focuses on HPC environments [FLOP], Cloud [Number of service invocations] and General-purpose services [number of transactions]. The useful work produced in the Node-Group (W_{NG}) is calculated as per Eq. 24.

$$W_{rack} = \sum_i^N W_{NG,i} \quad \text{Eq. 40}$$

Where N is the number of Node-Groups in the Rack.

1) Rack Productivity

It is defined in the same way than the Node Productivity (Eq. 12) and the Node-Group Productivity (Eq. 25) but applied to the Rack.

$$Productivity_{rack} = \frac{W_{rack} [\text{units of useful work}]}{E_{rack} [Wh]} = \left[\frac{\text{units of useful work}}{Wh} \right] \quad \text{Eq. 41}$$

4.3.4 Heat-aware metrics

1) RCI: Rack Cooling Index

It was proposed by Herrlin as an indicator of how effectively the racks are cooled within industrial thermal standards or guidelines [18]. It is focused to be used in CFD results analysis, due to the problem to get conclusions from the great amount of data produced by a CFD simulation. Because of standards and guidelines have two thresholds (minimum and maximum), there are defined two RCI index, the low and the high.

Additional indications about how calculate and interpretate it have been presented in Section 4.1.4 and 4.2.4.

$$RCI_{HI} = \left[1 - \frac{\sum(T_{rack,x} - T_{max-rec})_{T_{rack,x} > T_{max-rec}}}{(T_{max-all} - T_{max-rec}) * n} \right] * 100 = [\%] \quad \text{Eq. 42}$$

$$RCI_{LO} = \left[1 - \frac{\sum(T_{min-rec} - T_{rack,x})_{T_{rack,x} < T_{min-rec}}}{(T_{min-rec} - T_{min-all}) * n} \right] * 100 = [\%] \quad \text{Eq. 43}$$

Where $T_{rack,x}$ is the average temperature at Rack air intake in a given period of time.

2) RHI: Rack Humidity Index

This metric is defined in the Node-Group level and transported to the Rack level to show fulfilment of the relative humidity in the server air inlet regarding guidelines and standards.

$$RHI_{HI} = \left[1 - \frac{\sum(RH_{rack,x} - RH_{max-rec})_{RH_{rack,x} > RH_{max-rec}}}{(RH_{max-all} - RH_{max-rec}) * n} \right] * 100 = [\%] \quad \text{Eq. 44}$$

$$RHI_{LO} = \left[1 - \frac{\sum(RH_{min-rec} - RH_{rack,x})_{RH_{rack,x} < RH_{min-rec}}}{(RH_{min-rec} - RH_{min-all}) * n} \right] * 100 = [\%] \quad \text{Eq. 45}$$

Where RH_x is the average relative humidity at Rack air intake in a given period of time.

3) Imbalance of Node-Group temperature

The imbalance of temperature of Node-Groups in the Rack can help on the identification of hotspots and air recirculation problems within the Rack.

$$Im_{rack,temp} = \frac{T_{NG,max} - T_{NG,min}}{T_{NG,avg}} * 100 = [\%]; T_{NG,avg} = \frac{1}{N} \sum_i^N T_{NG,i} \quad \text{Eq. 46}$$

Where,

$T_{NG,i}$ is the temperature of each Node-Group in the Rack.

N is the quantity of Node-Groups in the Rack.

$T_{NG,max}$ is the maximum temperature reached by the Node-Group during a given period of time.

$T_{NG,min}$ is the minimum temperature of the Node-Group during a given period of time.

4) Imbalance of heat generation of Node-Groups

Consequent with the assessment given by the imbalance of the temperature of the Node-Groups in the Rack (Eq. 46), the imbalance of heat generation can be calculated according Eq. 57.

$$Im_{rack,Heat} = \frac{Q_{NG,max} - Q_{NG,min}}{Q_{NG,avg}} * 100 = [\%]; Q_{NG,avg} = \frac{1}{N} \sum_i^N Q_{NG,i} \quad \text{Eq. 47}$$

Where,

$Q_{NG,i}$ is the heat generated by each Node-Group in the Rack, [W].

N is the quantity of Node-Groups in the Rack.

$Q_{NG,max}$ is the maximum thermal heat produced by the Node-Groups in the Rack, [W].

$Q_{NG,min}$ is the minimum thermal heat produced by the Node-Groups in the Rack, [W].

4.4 Data Centre Level

The Data Centre Level integrates several Racks as defined in Section 3.3.3, all supporting infrastructures and all components. Then physically it is the highest level of granularity and it is coincident with ComputeBox2 defined in DEBBs conception [29].

As it is introduced in Section 3.3.3 and shown in Figure 3-5 a data centre is a system that absorbs and exports energy through its boundary to produce a benefit or a useful work as defined in Section 3.2.2. In fact the energy exportation always occurs and, if it is not reused, it is named the losses of the data centre. Then conventional data centres will take electrical energy from the Utility and use it to produce the useful work where the wasting heat produced is rejected to the environment. Other typologies, for instance, are able to export the wasting heat to heat near offices.

The energy carriers entering the data centre can be electricity, gas, oil or also chilled water from a district system. Nevertheless the nomenclature only refers to power. The Global Metrics Harmonization Task Force states that the energy streams should be reported in energy terms [5] [24]. Those documents mention the conversion in source energy, necessary when dealing with different energy carriers. Nevertheless, being the electricity the typical energy carrier used in data centre, the source energy factors of the carriers used in a data centre are normalized with respect to electricity².

Also the Data Centre Metrics Coordination Task Force (U.S. Regional Task Force) supports the same idea but the factors are slightly different from the previous ones [21]. This association have taken the factors published by the EPA Energy Star Program in U.S.

² The weighting factors in Table 4-1 vary country by country [21]. In Europe, mean references values are listed in the standard EN 15603.

Table 4-1 Weighting factors for different energy sources

Energy Type	Global source energy weighting factor [5]	U.S. source energy weighting factor U.S. [21]
Electricity	1.00	1.00
Natural gas	0.35	0.31
Fuel oil	0.35	0.30
Other fuels	0.35	0.30
District chilled water	0.40	0.31
District hot water	0.40	0.40
District steam	0.40	0.43
Condenser water	-	0.03

The EN 15603:2008 [34] standard establishes the source energy weighting factors for other kind of buildings than data centres. An agreement in factors between this standard and the proposal of the Global Task Force would be required in order to have the same criteria about benefits of energy efficiency and RES in spite of kind of building or industrial/commercial activity.

Therefore it is identified an energy balance through data centre outer boundaries taking in account delivered energy and feeding energy coming from different energy sources and shown in Figure 4-5 and formulated in Eq. 48.

$$\sum_i f_i \cdot w_{f,i} - \sum_i d_i \cdot w_{d,i} = F_{DC} - D_{DC} \geq 0 \quad \text{Eq. 48}$$

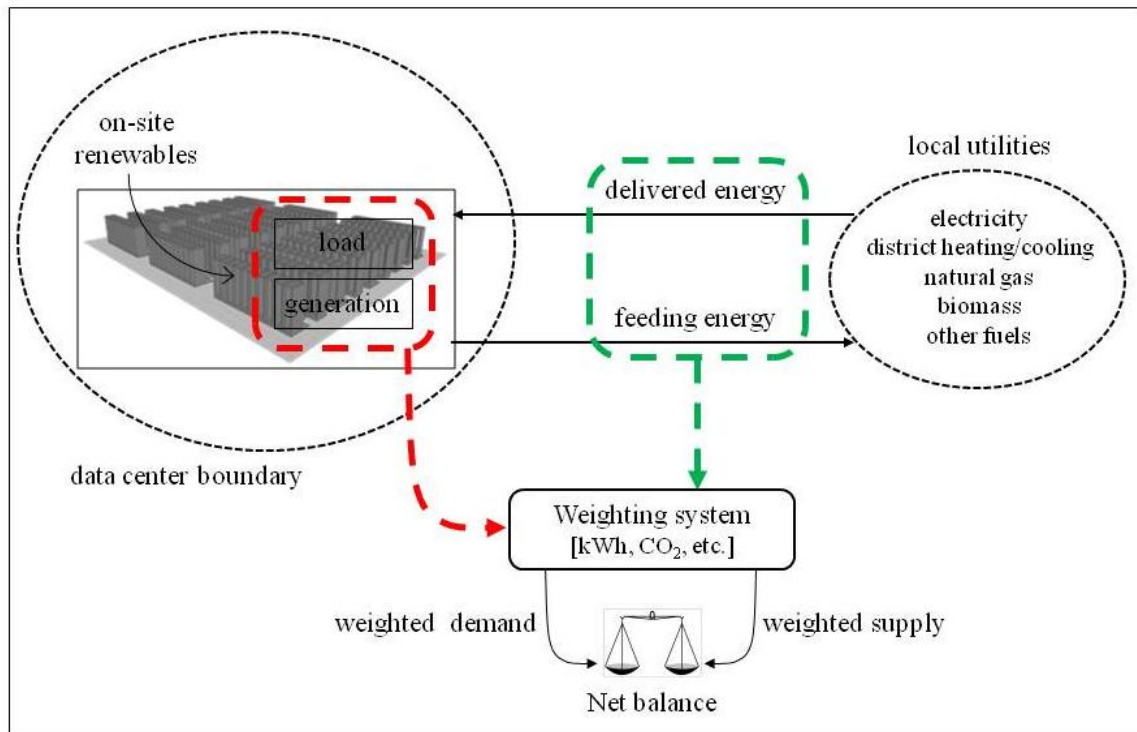
Where,

f_i is the feeding energy.

d_i is the delivered energy.

w_i is the corresponding weighting factor depending of the chosen weighting system. An example is in Table 4-1.

Figure 4-5 Weighted energy balance in data centres: Source IREC



From the general formulation in Eq. 48 it is deduced metrics that will assess about energy impact of the data centre. It is remarked that the Global Metrics Harmonization Task Force only considers RES outside of the data centre boundary [5] [24]. Such an approach is not in line with all the policies about energy efficiencies, where RES are considered as one of the primary energy efficiency measures..

Integration of energy efficiency measures and integration of renewable energy sources is a common strategy in the building sector and has led to the Zero Energy Building (ZEB) concept. The topic of Zero Energy Buildings (ZEBs) has received increasing attention in recent years, until becoming part of the energy policy in several countries. In the recast of the EU Directive on Energy Performance of Buildings (EPBD) it is specified that by the end of 2020 all new buildings shall be “nearly zero energy buildings” [35]. However, despite the emphasis on the goals the definitions remains in most cases generic and are not yet standardized. Relevant work can be found in literature on existing and proposed definitions [36] and survey and comparison of existing case studies. Furthermore, an international effort on the subject is ongoing in the International Energy Agency (IEA) joint Solar Heating and Cooling (SHC) Task40 and Energy Conservation in Buildings and Community systems (ECBCS) Annex52 titled “Towards Net Zero Energy Solar Buildings” [37]. It emerges from these analyses that little agreement exists on a common definition that is based on scientific analysis.

The wording ‘Net’ underlines the fact that there is a balance between energy taken from and supplied back to the energy infrastructures (electrical grids or district heating and cooling networks) over a period of time. As discussed in [38] and [39] Net ZEBs should be designed – to the extent that is in the control of the designers – to work in synergy with the grids and not to put additional stress on their functioning. In [40] a formal, comprehensive and consistent framework that considers all the relevant aspects characterizing Net ZEBs is described. This framework allows each country to define a consistent (and comparable with others) Net ZEB definition in accordance with the country’s political targets and specific conditions.

4.4.1 Resource Usage

1) Aggregation of metrics

The Resource Usage metrics in Rack level can be used on the Data centre by aggregation and averaging. Two approaches are possible depending on the homogeneity of the Nodes. Formulation for homogenous Nodes is presented in Eq. 49 and for heterogeneous Nodes in Eq. 50.

$$Resource\ Usage_{DC} = \frac{\sum_i^N \gamma_{rack,i}}{\sum_i^N c_{rack,i}} = \frac{1}{N} \sum_i^N Resource\ Usage_{rack,i} \quad \text{Eq. 49}$$

$$Resource\ Usage_{DC} = \sum_i^N Resource\ Usage_{rack,i} \cdot w_i \quad \text{Eq. 50}$$

$$c_{rack} = \sum_i^J c_{NG,i} ; \gamma_{rack} = \sum_i^J \gamma_{NG,i} ; w_i = \frac{c_{rack,i}}{C_{DC}} ; C_{DC} = \sum_i^N c_{rack,i} \quad \text{Eq. 51}$$

Where,

Resource Usage_{rack,i} is the Resource Usage metric obtained for each Rack in the Data Centre as defined in Section 4.3.1.

J is the quantity of Node-Groups in the studied Rack.

N is the quantity of Racks in the Data Centre.

4.4.2 Power-based metrics

Herein some concrete definitions are given to go through a consistent formulation of the different metrics in Data Centre level.

Power used by the IT Equipment (*P_{IT}*) is the electrical power drawn in Watts by all the IT equipment in the Data Centre (servers, storage, network, etc.). It can be calculated by measuring in a common electrical feeding point for all IT equipment or by summing all electrical feeding points dedicated to IT Equipment. It is remarkable that calculate it by summing power usage of all Racks would not be

correct in conventional data centres because in CoolEmAll's approach the Rack can include non-IT elements (UPS and heat exchangers).

Power used by the Data Centre (P_{DC}) is the electrical power drawn by the Data Centre from the Utilities. Best practices state that it must be measured at the Utility or what is the same at the A point in Figure 3-1.

Power at the UPS output (P_{UPS}) is the electrical power in Watts measured at the output of the UPS that only supports the IT equipment.

Power used by the component (P_{comp}) is the electrical power drawn by a particular type of component. The assessment in Data Centre level considers i.e. the summing of all the Storage devices included in the Data Centre. Note this is completely different than the power used by the Data Centre (P_{DC}). Consequently it is calculated as in Eq. 52.

$$P_{comp} = \sum_i^N p_i \quad \text{Eq. 52}$$

Where,

N is the quantity of Racks in the Data Centre.

p_i is the power drawn by the studied component of the Data Centre (e.g. Storage), but being really part of the Node, [W]

1) Aggregation of metrics

Aggregated metrics will be calculated as indicated in Eq. 53.

$$Power_{DC} = \sum_i^N Power_{rack,i} \cdot w_i ; w_i = \frac{p_i}{P_{comp}} \quad \text{Eq. 53}$$

Where $Power_{rack,i}$ is the Power-based metric from each Rack in the Data Centre.

2) UPS Usage

The data centres used to have more than one UPS to obtain the desired reliability of the power infrastructure. Therefore the redundant components must not be taken into account to measure the UPS Usage. Nevertheless some data centres have many UPS just to cover the design demand and from different manufactures and capacities. The UPS Usage must be calculated by the weighted average.

$$UPS Usage_{DC} = \sum_i^N UPS Usage_i \cdot w_i \quad \text{Eq. 54}$$

$$w_i = \frac{S_i}{C_{UPS}} ; C_{UPS} = \sum_i^N c_{UPS,i} \quad \text{Eq. 55}$$

Where,

$UPS Usage_i$ is the utilisation ratio of each UPS as defined in Eq. 37.

S_i is the apparent power drawn by the UPS measured at its input, [VA].

$C_{UPS,i}$ is the rated apparent power of the UPS according to manufacturer specifications, [VA].

3) DCU: Data Centre Utilisation

It was defined by The Green Grid as the amount of power drawn by the IT equipment relative to the actual capacity of the data centre [30].

$$DCU = \frac{P_{IT} [W]}{P_{IT, rated} [W]} = [\emptyset] \quad \text{Eq. 56}$$

Where, $P_{IT, rated}$ is the rated power capacity to hold the IT equipment in the Data Centre, [W].

4) PUE: Power Usage Effectiveness

Introduced by Malone in 2006 [4], was lately supported by The Green Grid [41] together with the DCiE and largely adopted to evaluate and compare data centres. It consists in comparing the power used by the Data Centre and the power used by the IT equipment.

$$PUE = \frac{P_{DC} [W]}{P_{IT} [W]} = [\emptyset] \quad \text{Eq. 57}$$

The PUE has been largely adopted since even if with different measurement methodologies. In fact measurements could be carried out in different points of the infrastructure: for instance IT equipment power was monitored at the UPS or PDU or at the IT hardware directly.

Even the PUE was initially defined as an instantaneous value, obtained from power measurements, it can be calculated with the nominal capacities or average values in a year or under different IT operation conditions. Because of that, the PUE based comparisons between different data centre could be unreliable and thus, this performance metric is converted to productivity assessment metric.

To solve inconsistencies, a group of global leaders has been meeting regularly to agree on standard approaches and reporting conventions for key energy efficiency metrics [5]. In consequence of that, four categories of PUE have been defined, PUE_0 being the current category for the first PUE definition. In fact, PUE_0

is still a demand based calculation representing the peak load during a 12-month measurement period [21].

$$PUE_0 = \frac{P_{DC} [W]}{P_{UPS} [W]} = [\emptyset] \quad \text{Eq. 58}$$

The IT power is represented by the demand reading of the UPS system output or sum of outputs if more than one UPS system is installed, as measured during peak IT equipment utilisation.

The most recent activities of The Green Grid about metrics focus the nomenclature of PUE on the point of measurement, data measurement frequency and averaging period [28]. The PUE_0 , that corresponds to a power-based metrics, an instantaneous measurement on UPS point without averaging value, should be named as $PUE_{L1,-}$.

5) PUE Scalability

This concept has been recently developed by The Green Grid association [28]. This is not a simple metric if not a complete statistical analysis of PUE values recorded in a certain period of time.

The main objective of PUE Scalability is to provide information about how the total load of a data centre can be adapted to variations of IT load. In an optimally designed data centre the infrastructure should (ideally) proportionally scale total power with changes in IT power loads.

The metric is defined as:

$$PUE \text{ Scalability} = \frac{m_{actual}}{m_{PUE}} = [\emptyset] \quad \text{Eq. 59}$$

The slope of proportional PUE Scalability is calculated as:

$$m_{PUE} = \frac{mean(P_{DC})}{mean(P_{IT})} \quad \text{Eq. 60}$$

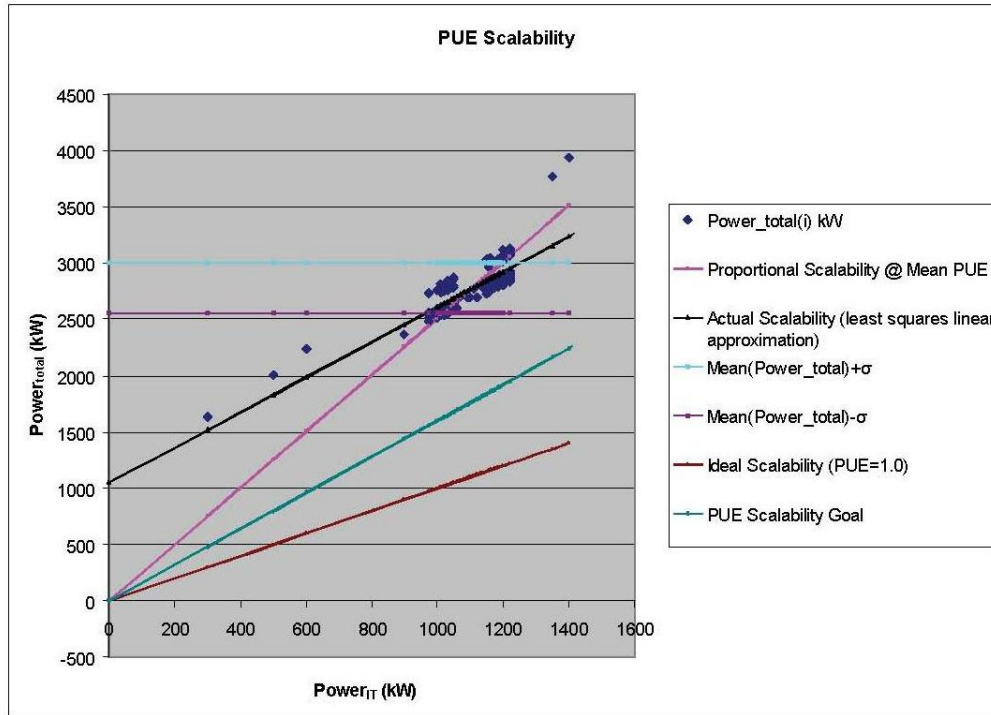
The slope of actual PUE Scalability is calculated as:

$$m_{actual} = \frac{(N \cdot \sum_{i=1}^N (P_{IT}(i) \cdot P_{DC}(i))) - ((\sum_{i=1}^N P_{IT}(i)) \cdot (\sum_{i=1}^N P_{DC}(i)))}{(N \cdot \sum_{i=1}^N (P_{IT}(i))^2) - (\sum_{i=1}^N P_{IT}(i))^2} = [\emptyset] \quad \text{Eq. 61}$$

The maximum value of PUE Scalability (ideal data centre) is 100 %.

The next figure illustrates an example of a data centre that do not scales the power of its infrastructure according the fluctuation on IT load.

Figure 4-6 Total power variation versus IT load variations: Source [28]



6) DCiE: Data Centre Infrastructure Efficiency

Being introduced in 2006 by Malone [4] as DCE (Data Centre Efficiency), it was later redefined by The Green Grid as DCiE Data Centre infrastructure Efficiency because of the general feeling of misconception of the meaning of data centre efficiency [41], even if from the behavior of the DCiE is much similar to the one of a generic efficiency as shown in Figure 4-7.

$$DCiE = \frac{P_{IT} [W]}{P_{DC} [W]} * 100 = [\%] \quad \text{Eq. 62}$$

Figure 4-7 Comparisson between DCiE and PUE: Source APC

	DCiE	PUE
Worst value	0%	Infinity
Best value	100%	1
Direction of improvement	Higher is better	Lower is better
Relation to other metric	1 / PUE	1 / DCiE
Meets metric requirement established by EPA report?	Yes	No

The two ratios present the same qualitative result but in a different way. The PUE informs on the power to be delivered to the overall facility in order to run the present IT equipment; the DCiE informs on the percentage of the total power used for IT equipment. The DCiE is more similar to an “energy efficiency” metric but actually it is not. If the general meaning of efficiency is the ratio of useful work performed to the total energy expended, the numerator should consider the work carried out by the IT equipment. Nevertheless, such work is not easy to be defined and measured, because it depends on the specific equipment used. Thereby the numerator of the DCiE is actually the power need for the IT equipment to provide users with services. From this point of view the Data Centre Productivity is much similar to an “energy efficiency” metric than the PUE and the DCiE.

In the reference [42] it is shown how to measure and calculate DCiE in-depth.

7) DCD: Data Centre Density

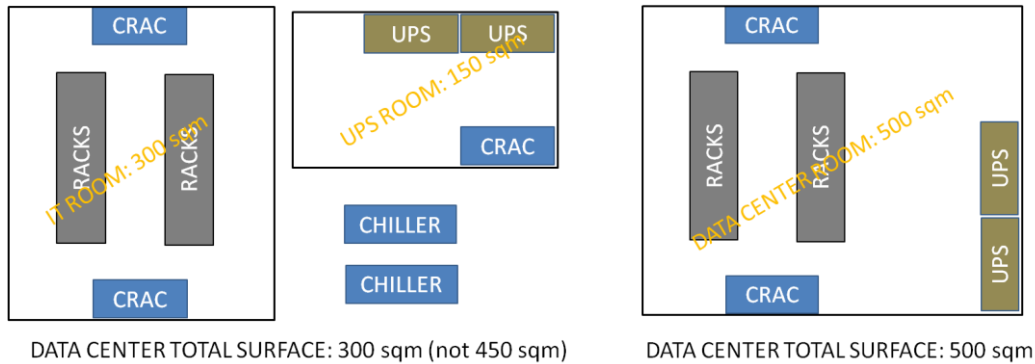
It was introduced by The Green Grid to quantify the data centre space efficiency. It is calculated as a ratio between the maximum power consumed by the Data Centre and the Data Centre space area. The data centre efficiency is provided in units of kilowatts per square meter.

$$DCD = \frac{P_{DC} [W]}{A_{IT} [m^2]} = \left[\frac{W}{m^2} \right] \quad \text{Eq. 63}$$

Where A_{IT} is the area of each *IT* room where the IT equipment is allocated, [m²].

It is proposed a more accurate definition of total data centre surface by considering only the rooms where the IT equipment is allocated. It will be accepted as total data centre surface that some facilities equipment as CRAC/CRAH or UPS are included within the same room than IT equipment, but it will not in case facilities are placed in other rooms (as it used to be).

Figure 4-8 Different cases of data centre total surface calculation: Source IREC



8) EER: Energy Efficiency Ratio

The EER is the cooling capacity divided by the power usage of the cooling system [43]. This indicator is provided by cooling machines manufacturers under standard conditions. However optimization of cooling facilities in data centres often makes them work far away of the standard conditions, therefore the periodical observation of the obtained EER gives a continuous assessment of the energy efficiency of the cooling system.

$$EER = \frac{Q_{cooling} [W_{th}]}{P_{cooling} [W_{el}]} = [\phi] \quad \text{Eq. 64}$$

Where,

$Q_{cooling}$ is the heat removed by the cooling system, $[W_{th}]$.

$P_{cooling}$ is the electrical power used by the cooling system, $[W_{el}]$.

4.4.3 Energy-based metrics

Some concrete definitions are given to solve inconsistencies. These are:

Energy consumed by the IT Equipment (E_{IT}) is the electrical energy consumed in Watts-hour by all the IT equipment in the Data Centre (servers, storage, network, etc.). It is the result of integrating the P_{IT} (Section 4.4.2) in a given period of time.

$$E_{IT} = \int_{t_1}^{t_2} P_{IT}(t) \cdot dt = [Wh] \quad \text{Eq. 65}$$

Energy consumed by the Data Centre (E_{DC}) is the energy consumed by the Data Centre from the Utilities. It is the result of integrating the P_{DC} (Section 4.4.2) in a given period of time.

$$E_{DC} = \int_{t_1}^{t_2} P_{DC}(t) \cdot dt = [Wh] \quad \text{Eq. 66}$$

Energy consumption at UPS output (E_{UPS}) is the energy consumption measured at the output of the UPS that only supports the IT equipment.

Energy consumption at PDU (E_{PDU}) is the energy consumption measured at the lines of the PDU only supporting the IT equipment.

Energy reused (ER_{out-DC}) is the energy losses in the data centre that can be reused outside of it.

Green energy (GE_{DC}) is the energy that comes from renewable sources in the data centre

Useful work produced by the Data Centre (W_{DC}) is the quantity of useful work produced in the Data Centre according the services provided. In this way and as is defined in Section 3.2.2, CoolEmAll focuses on HPC environments [FLOP], Cloud [Number of service invocations] and General-purpose services [number of transactions]. Similar approaches are developed by The Green Grid to measure the useful work in Data Centres and compare it with the energy consumption as indicator of productivity [20]. Particular cases not covered by CoolEmAll's case studies must investigate on these cited methods.

$$W_{DC} = \sum_i^N W_{rack,i} \quad \text{Eq. 67}$$

Where N is the number of Racks in the Data Centre.

1) Data Centre Productivity

It is defined in the same way as the Node Productivity (Eq. 12), the Node-Group Productivity (Eq. 25) and the Rack Productivity (Eq. 41) but applied to the Data Centre.

$$Productivity_{DC} = \frac{W_{DC} [\text{units of useful work}]}{E_{DC} [Wh]} = \left[\frac{\text{units of useful work}}{Wh} \right] \quad \text{Eq. 68}$$

2) PUE: Power Usage Effectiveness

Being the PUE initially introduced as instantaneous value based on power measurements, some efforts were done by the Data Centre Efficiency Task Force to extend PUE to energy usage effectiveness in data centre facilities by defining PUE_{1-3} depending on the measurement point and respectively at the UPS, PDU and single IT equipment [21]. The methodologies for calculating the PUE are in the cited paper.

$$PUE_1 = \frac{E_{DC}[Wh]}{E_{UPS}[Wh]} = [\emptyset] \quad \text{Eq. 69}$$

$$PUE_2 = \frac{E_{DC}[Wh]}{E_{PDU}[Wh]} = [\emptyset] \quad \text{Eq. 70}$$

$$PUE_3 = \frac{E_{DC}[Wh]}{E_{IT}[Wh]} = [\emptyset] \quad \text{Eq. 71}$$

According with the present activities of The Green Grid [28] referred on 4.4.2 (PUE section) the nomenclature of the formula above should correspond to PUE_{L1} , PUE_{L2} and PDU_{L3} , respectively.

As has been stated in this deliverable, PUE can be reported as power metric or as energy metric. The Green Grid endorses the use of PUE as energy metric instead of a power metric due to the most accurate information that provide. The use of energy when calculating PUE has also been supported by other industry groups, including the 7x24 Exchange, ASHRAE, Silicon Valley Leadership Group, U.S. Department of Energy, U.S. Environmental Protection Agency, U.S. Green Building Council, Uptime Institute, European Commission Joint Research Centre Data Centre Code of Conduct, Japan Ministry of Economy, Trade and Industry, and Japan's Green IT Promotion Council [28].

The recent discussions about PUE [24], [28] agree on the concept of *Source Energy Factor* (see Table 4-1) in order to have a comprehensive assessment of different kind of energy that can be considered as total data centre energy consumption (electricity, chilled water, natural gas, etc.).

3) pPUE: Partial Power Usage Effectiveness

The partial PUE is defined as the quotient between the energy consumed inside a certain boundary or zone of the total facility of the data centre, and the IT load inside this zone.

$$pPUE = \frac{E_{zone-DC}[Wh]}{E_{zone-IT}[Wh]} = [\emptyset] \quad \text{Eq. 72}$$

This metric is useful when a data centre is contained inside a zone, but part of the facilities is outside this zone. As PUE reports only the quotient between the total energy consumed in the zone divided by the IT load, the energy consumed by the facilities outside will be wrongly neglected. Values of PUE close to 1.0 can be observed in this situation. Then partial PUE provides more consistent information about the data centre efficiency. Partial Power Usage Effectiveness

is more appropriate for management of data centres than for comparing with other ones.

4) FVER: Fixed to Variable Energy Ratio

Developed by the BCS (British Computer Society), it provides information about how much energy is directly related to the useful work produced in a data centre on how much could be eliminated [44].

It is a fact that even a data centre is not producing any useful work it can consume around 80% of the peak energy consumption showing a flat behaviour during all data centre operation time. This evidences that a lot of energy can be saved during the idle periods.

As it is affirmed in the cited paper, despite all efforts trying to measure the useful work in a data centre, no method of measuring provides values which can be compared between different data centres due to the subjectivity of the methodology, being the principle obstacle for a wide adoption [44].

The FVER avoids this by using the subjective evaluation of useful work to find the energy consumption of the data centre at the time the useful work is zero, which is defined as the fixed energy consumption of the data centre, and normalizing the values obtained. Thus, FVER is calculated by comparing the fixed and the variable energy consumption:

$$FVER = 1 + \frac{\text{Fixed Energy [Wh]}}{\text{Variable Energy [Wh]}}$$

These energy values must be found by normalization of the useful work and the related normalized energy consumption. The fixed energy is the value obtained when the useful work is zero and the rest is the variable part. Normalization allows comparison between different Data Centres.

Higher FVER values indicate poor variability, whereas lower FVER values (close to 1) indicate high variability, as shown in Figure 4-9.



Figure 4-9: FVER Values [44].

Data Centre Fixed to Variable Energy Ratio metric ($FVER_{DC}$) measures what proportion of data centre energy consumption is variable. IT Fixed to Variable Energy Ratio metric ($FVER_{IT}$) measures what proportion of IT energy consumption is variable.

$$FVER_{DC} = 1 + \frac{E_{DC, fixed} [Wh]}{E_{DC, variable} [Wh]} = [\phi] \quad \text{Eq. 73}$$

$$FVER_{IT} = 1 + \frac{E_{IT, fixed} [Wh]}{E_{IT, variable} [Wh]} = [\phi] \quad \text{Eq. 74}$$

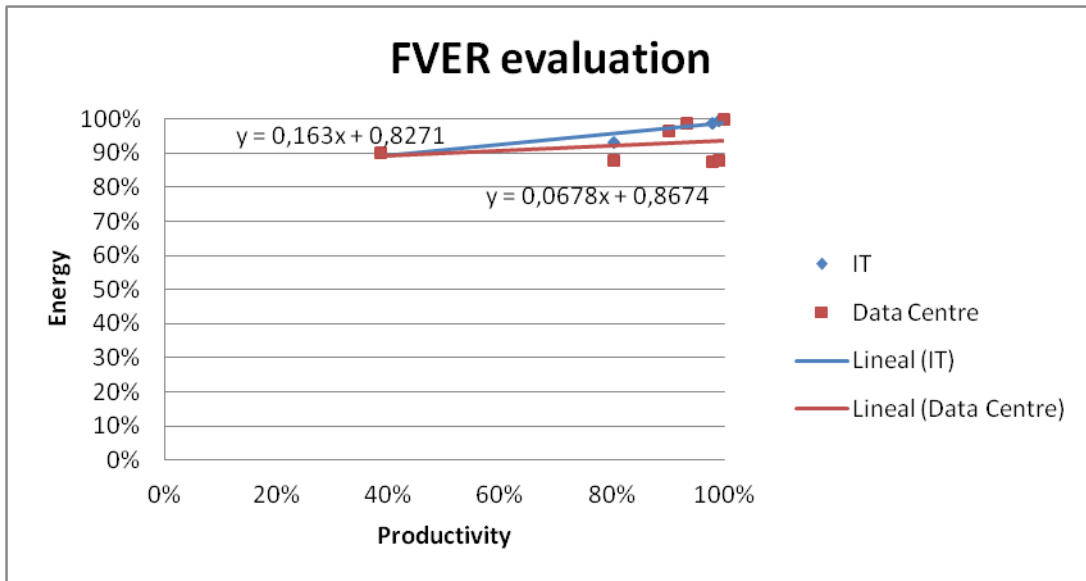
Making a simple example of a Data centre full oriented to Cloud services, the evaluation of the useful work would be the number of service invocations. In case using more magnitudes to quantify it, weighting factors must be applied according owner preferences. The collected values are shown in the Table 4-2.

Note the energy and the useful work are both accumulative quantities, and then being strict from hour to hour they should be increasing. Nevertheless the values shown correspond to the total amount during a specific hour. Normalizing them respect the peak values allows conversion to percentages as shown in Figure 4-10.

Table 4-2 Example of energy and productivity values

Hour	Productivity (# of service invocations)	IT Energy (kWh)	Data Centre Energy (kWh)
9:00	31.450	250	425
10:00	79.530	275	412,5
11:00	75.800	274	465,8
12:00	81.340	278	472,6
13:00	80.520	277	415,5
14:00	73.220	268	455,6
15:00	65.260	259	414,4
MAX	81.340	278	472,6

Figure 4-10 FVER evaluation example: Source IREC



Following this example, FVER values are calculated in Eq. 75 and Eq. 76 given respective linear regressions. Note that $FVER_{DC}$ will be always poorer than $FVER_{IT}$ because the former includes the latter.

$$FVER_{DC} = 1 + \frac{Intercept_{DC}}{Slope_{DC}} = 1 + \frac{0,8674}{0,0678} = 13,79 \quad \text{Eq. 75}$$

$$FVER_{IT} = 1 + \frac{Intercept_{IT}}{Slope_{IT}} = 1 + \frac{0,8271}{0,163} = 6,07 \quad \text{Eq. 76}$$

How much fixed energy consumes the Data Centre or the IT can be find out with the interception value and the peak value before normalization. In this example, these are calculated in Eq. 78 and Eq. 77.

$$E_{IT, fixed} = Incercept_{IT} \cdot \max[E_{IT}] = 0,8271 \cdot 278 \text{ kWh} = 229,93 \text{ kWh} \quad \text{Eq. 77}$$

$$\begin{aligned} E_{facilities, fixed} &= Incercept_{DC} \cdot \max[E_{DC}] - E_{IT, fixed} \\ &= 0,8674 \cdot 472,6 \text{ kWh} - 229,93 \text{ kWh} = 180 \text{ kWh} \end{aligned} \quad \text{Eq. 78}$$

As conclusion 82,71% of the energy consumed by the IT is fixed, thereby it is susceptible to be removed. The 64,75% of the energy dedicated to the supporting technical systems (excluding the IT) is susceptible to be saved. Therefore the efforts should be focused to optimize the IT equipment.

5) SEER: Seasonal Energy Efficiency Ratio

The SEER is the cooling energy output during the typical season when cooling is required and divided by the energy consumption of the cooling system during the

same period. Taking in account that data centres require cooling all the year, SEER in data centres can be defined as:

$$SEER = \frac{Q_{cooling,year} [Wh_{th}]}{E_{cooling,year} [Wh_{el}]} = [\emptyset] \quad \text{Eq. 79}$$

$$Q_{cooling,year} = \int_0^Y q_{cooling}(t) \cdot dt = [Wh_{th}] \quad \text{Eq. 80}$$

Where,

$E_{cooling,year}$ is the energy consumed by the cooling system of the Data centre during a whole year, [Wh_{el}].

Y is one year.

$q_{cooling}$ is the instant heat removed by the cooling system of the Data centre, [Wh_{th}].

4.4.4 Heat-aware metrics

1) Imbalance of Racks temperature

The imbalance of temperature of Racks in the Data centre can help on the identification of hotspots and air recirculation problems.

$$Im_{DC,temp} = \frac{T_{rack,max} - T_{rack,min}}{T_{rack,avg}} * 100 = [\%]; T_{rack,avg} = \frac{1}{N} \sum_i^N T_{rack,i} \quad \text{Eq. 81}$$

Where,

$T_{rack,i}$ is the temperature of each Rack in the Data centre.

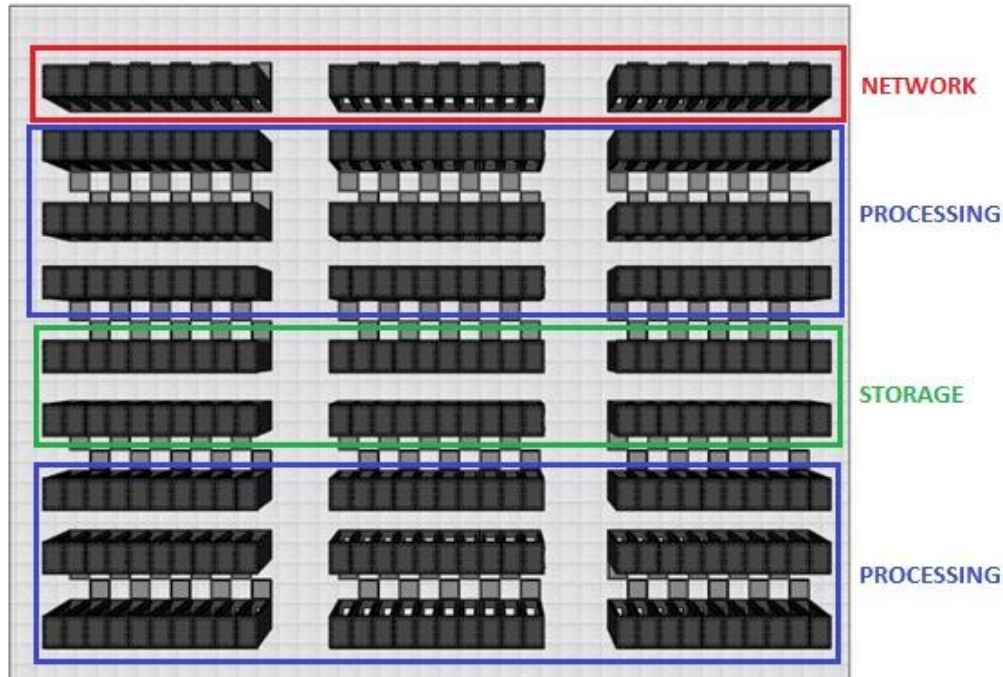
N is the quantity of Racks in the Data centre.

$T_{rack,max}$ is the maximum temperature reached by the Racks during a given period of time.

$T_{rack,min}$ is the minimum temperature of the Racks during a given period of time.

Even studying imbalance of all Racks in a Data centre provides useful assessment, make local studies about particular groups of Racks placed together in the Data centre will provide also useful information about the heat distribution. This is the case of many Data centres where racks are grouped according the kind of the IT equipment installed (e.g. processing, storage, network, legacy, etc.). An example is shown in Figure 4-11.

Figure 4-11 Example of racks grouping: Source IREC



However mixed-proposal racks can also be grouped according other reasons as nearness to the CRAC machines, particular air obstructions in the raised floor, etc.

2) Imbalance of Racks heat generation

Consequent with the assessment given by the imbalance of the temperature of the Racks in the Data centre (Eq. 81), the imbalance of heat generation can be calculated according Eq. 82.

$$Im_{DC,Heat} = \frac{Q_{rack,max} - Q_{rack,min}}{Q_{rack,avg}} * 100 = [\%]; \quad Q_{rack,avg} = \frac{1}{N} \sum_i^N Q_{rack,i} \quad \text{Eq. 82}$$

Where,

$Q_{rack,i}$ is the heat generated by each Rack in the Data centre, [W].

N is the quantity of Racks in the Data centre.

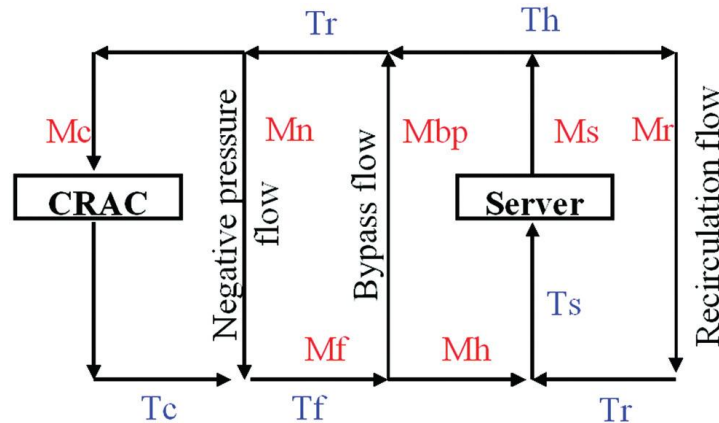
$Q_{rack,max}$ is the maximum heat produced by the Racks in the Data centre, [W].

$Q_{rack,min}$ is the minimum heat produced by the Racks in the Data centre, [W].

3) Air management indicators

In data centres, the cooling systems performance depends in a high way from air management performance [45]. Then the logical way is by quantifying the factors of the effectiveness decrease of data centre air cooling. These factors and the air mass transfers are shown in Figure 4-12.

Figure 4-12 Data centre air mass flows [45]



Temperatures definition is:

T_r is the return air temperature to CRAC

T_c is the discharge air temperature from CRAC.

T_f is the air temperature under the floor after room air is drawn in, very close to T_c .

T_s is the server inlet air temperature.

T_h is the server outlet air temperature.

The air management inefficiencies come from three different phenomena: negative pressure ratios (NP), bypass air flow (BP) and recirculation air flow (R) largely affect the heat removal efficiency of ventilation. In the mentioned paper is defined some metrics to assess on the evaluation of these phenomena.

Negative pressure ratio (NP): Caused by the high speed air and due to Venturi effect, the static pressure becomes negative and results in the air will circulate into the floor from the volume above in some points. This happens near CRAC/CRAH machines where the air velocities are high.

$$NP = \frac{m_{np}}{m_c} = \frac{T_f - T_c}{T_r - T_f} = [\phi] \quad \text{Eq. 83}$$

Bypass ratio (BP): It is caused by the air that leaves the CRAC/CRAH and returns to it directly without cooling anything.

$$BP = \frac{m_{bp}}{m_f} = \frac{T_h - T_r}{T_h - T_f} = [\phi] \quad \text{Eq. 84}$$

Recirculation ratio (R): Caused by air that is not sucked by CRAC/CRAH machine and mixes with air for cooling IT equipment.

$$R = \frac{m_r}{m_s} = \frac{T_s - T_f}{T_h - T_f} = [\emptyset] \quad \text{Eq. 85}$$

It is defined also the **Balance ratio (BAL)**, between the air mass flow through CRAC/CRAH machines and the servers.

$$BAL = \frac{m_c}{m_s} = \frac{T_h - T_s}{T_r - T_c} = [\emptyset] \quad \text{Eq. 86}$$

The interpretation of BAL is:

- BAL=1: Target.
- BAL<1: IT is receiving more air mass flow than the provided by CRAC/CRAH.
- BAL>1: IT is receiving less air mass flow than the provided by CRAC/CRAH.

In another paper signed by Tozer and Flucker the approach of the air-management indicators is very focused to performance by defining three indicators [46]. These are:

Flow performance: Defines directly how much cooled air is really being used by the IT equipment.

$$\eta_{flow} = \frac{m_f}{m_c} = \frac{T_r - T_c}{T_h - T_c} = [\emptyset] \quad \text{Eq. 87}$$

Thermal performance: Defines directly how much of the air used by IT equipment really comes from CRAC/CRAH.

$$\eta_{thermal} = \frac{m_f}{m_s} = \frac{T_h - T_s}{T_h - T_c} = [\emptyset] \quad \text{Eq. 88}$$

9) Cooling system response capacity

The concern about how much time needs the cooling system in a data centre to evacuate a concrete amount of heat or what is the same reducing the servers' inlet temperature to safe values is in mind of all data centre operators. Very energy efficient cooling could need too long time of response, which would not be problematic in human comfort applications, but could be catastrophic in a data centre. Therefore time response capacity in cooling systems must be analysed and taken in account to establish data centre management policies.

A paper signed by Kummert et al. [47] analyses a data centre cooling system under fault conditions concluding that having the redundant chillers in standby will possibly drive to high temperatures at servers' air inlet in case some of the

active chillers fails. Then an energy saving policy can drive easily to IT equipment failure, which finally will be much more expensive, because the time of response of the cooling system depends highly on the starting scenario.

This analysis concerning the behaviour of the cooling system depends on environmental factors, the starting scenario and the event. The environmental factors refer to the outdoors temperature, outdoors relative humidity, Node inlet air temperature and Node inlet relative humidity. The starting scenario is defined by the concrete workload and the state of the cooling system given generally by the state of the equipment (% of utilisation) and the temperatures of the water loop. The event is defined by some changing on the starting scenario such as switching off of some cooling component or sectioning the water loop, or on the environmental conditions or on the workload.

Thus a useful analysis will be realized by observing and registering the time of response of the cooling system in order to predict the behaviour of the system when a particular management policy is applied or when a failure occurs.

4.4.5 Green metrics

Several approaches are present in the literature defining greenness of a data centre. Bitterlin admits that a data centre is basically green because allows a sort of carbon emission reduction to the atmosphere [48]. Some examples make that evident such as taking a video conference or sending an email. Nevertheless Bitterlin also says that the data centre cannot be green because they take electrical energy turn into heat and reject it as waste to the atmosphere. Another approach is found in the definition of GPIs by GAMES project, which is more generalist than simply assessing about the environment impact of data centres [26]. Even though estimating the environmental impact implies a wide study of several factors, CoolEmAll project focuses on carbon emissions and non-renewable resources consumption during operation and exploitation of data centres. This kind of metrics takes special advantage of the energy concepts explained in Sections 3.3.3 and 4.4, but another concept must be defined to clarify the energy exportation.

Green energy generated onsite ($G_{DC,onsite}$) is the renewable energy generated onsite of the Data centre, usually electricity. Commonly Data centres have diesel motor generators to support the facilities in case of power outage, furthermore Uptime Institute considers the motor generators as the main power source at Tier levels higher than II [49]. Nevertheless the energy coming from a diesel motor generator must not considered renewable energy in any case. By definition it excludes the green energy purchased from the Utilities.

Green energy purchased to the Utilities (G_{DC}) is the renewable energy purchased to the Utilities to cover totally or partially the Data centre energy demand. This is a relatively common practice made by data centre operators who prefer purchasing green energy to the energy suppliers instead of generated it onsite.

1) Primary energy balance

The primary energy balance in the Data centre is established in Eq. 89. Through this balance the impact of the Data centre regarding any parameter under study is possibly by choosing the corresponding weighting systems (see Figure 4-5).

$$\sum_i f_i \cdot w_{f,i} - \sum_i d_i \cdot w_{d,i} = F_{DC} - D_{DC} \geq 0 \quad \text{Eq. 89}$$

Where,

f_i is the feeding energy.

d_i is the delivered energy.

w_i is the corresponding weighting factor depending of the chosen weighting system. An example is in Table 4-1 (p. 53).

2) GEC: Green Energy Coefficient

It was introduced to promote the use of green energy from a point of view of power consumption reduction [50]. It represents how much renewable energy is generated in the data centre or purchased from the Grid.

$$GEC = \frac{GE_{DC,onsite} [Wh]}{E_{DC} [Wh]} = [\phi] \quad \text{Eq. 90}$$

The meaning of the metric is based on the legal ownership of the rights corresponding to the Green Energy Certificates provided by a recognized organism.

The maximum value of GEC is 1.0. The amount of energy considered in numerator of the metric is not related by the on-site generation and consumption of renewable energy but also with the property of environmental rights. The way to obtain these rights might be purchasing it or generating on-site green electricity, in spite of the renewable electricity is consumed on data centre or exported to the network. The relevant issue is to keep the Green Energy Certificates, with a maximum value of GEC of 1.0 [24].

3) ERE: Energy Reuse Effectiveness and ERF: Energy Reuse Factor

The ERE was introduced to provide greater visibility into energy efficiency in data centres that make beneficial use of any recovered energy from the data centre, for example to provide heating to some human being occupied areas from IT equipment heat recovering [25].

$$ERE = \frac{E_{DC} - ER_{out-DC}}{E_{IT}} = [\phi] \quad \text{Eq. 91}$$

It can be noted that in case there is no energy re-usage, it will correspond exactly with the PUE_3 (Eq. 71). The value of PUE_3 might be the same in case the energy is reused in the same data centre.

The reused energy corresponds to energy losses of data centre that can be used outside of it. In case the energy is used inside the data centre, ER_{DC} equals zero and the benefit is contained within a lower PUE value. Therefore, both metrics are complementary.

The Global Taskforce in Harmonizing Global Metrics for Data Centre Energy Efficiency recommends the use of Energy Reuse Factor [24], defined as:

$$ERF = \frac{ER_{out-DC}}{E_{DC}} = [\emptyset] \quad \text{Eq. 92}$$

The calculation of ERF requires the clear definition of boundaries of data centre. The concept developed in 3.3.3 can contribute to define it. The Global Taskforce states that the different kind of energies (electricity, chilled water, etc) reused from data centre should be unified using the factors of Table 4-1.

4) CUE: Carbon Usage Effectiveness

Defined by The Green Grid [51], this indicator is used to address carbon emissions associated with data centres which used together with other metrics as PUE can quickly assess the sustainability of a data centres, compare the results, and determine if any energy efficiency and/or sustainability improvements need to be made. It is calculated as the total CO_2 emissions caused by the Data centre energy consumption by the IT equipment energy consumption in a given time period. It could be estimated with Eq. 93.

$$CUE = CEF \cdot PUE_3 = \left[\frac{kg \ CO_2 eq.}{Wh} \right] \quad \text{Eq. 93}$$

Where,

CEF is the Carbon Emission Factor of the energy supplying to the data centre, [kg CO_2 eq./Wh].

PUE_3 is defined in Eq. 71.

With the simultaneous use of different energy sources than electricity, the CUE can be calculated using the expression in Eq. 94.

$$CUE = \frac{\sum_i w_{d,i} \cdot d_i}{E_{IT}} = \frac{\sum_i CEF_{d,i} \cdot d_i}{E_{IT}} = \left[\frac{kg \ CO_2 eq.}{Wh} \right] \quad \text{Eq. 94}$$

The values of CEF vary depending on country or region.

The Global Taskforce in its last report [24] states that in case of renewable energy produced on site, then the emissions of this energy depend on whether or not the data centre owns the rights to the green energy certificate or renewable

energy certificate, as defined by a local/regional authority. If these rights have been sold, then the emissions of this energy are equivalent to what the emissions would be with a conventional utility purchase (e.g. grid-electric purchase). If the rights have not been sold, then the emissions for the renewable source are equal to zero. It can be noticed that the value is not depending about if the energy is locally consumed or not.

5) WUE: Water Usage Effectiveness

This metric provides assessment of the water used on-site for operation of the data centre. This includes water used for humidification and water evaporated on-site for energy production or cooling of the data centre and its supporting systems [52].

$$WUE = \frac{A_{DC}}{E_{IT}} = \left[\frac{\text{water liters}}{Wh} \right] \quad \text{Eq. 95}$$

Where, A_{DC} is the water consumed by the data centre during a given period of time, [liters].

6) Carbon emissions balance

Due to the operation of a data centre, it is generated a quantity of carbon dioxide that goes to the atmosphere depending on the kind energy sources used and the amount of non-renewable energy use. Thereby adjusting weights of the primary energy balance in Eq. 89, it is established a carbon emissions balance as formulated in Eq. 96.

$$\sum_i f_i \cdot CEF_{f,i} - \sum_i d_i \cdot CEF_{d,i} \geq 0 \quad \text{Eq. 96}$$

This metric is consistent with the Primary Energy Balance, metric in Eq. 89 and concept explained on Chapter 4.4.

7) Global KPI of Energy Efficiency

The Global KPI of Energy Efficiency is currently under discussion at ETSI. This KPI (Key Performance Indicator) is a combination of up to four “objective” KPIs: Energy Consumption (KPI_{EC}), Renewable Energy (KPI_{REN}), Energy Reuse (KPI_{REUSE}) and Task Efficiency (KPI_{TE}) and reflects energy impact. It shall contribute to [53]:

- reduced energy consumption (KPI_{EC}) - the total consumption of energy by an operational infrastructure
- improved task efficiency (KPI_{TE}) - a measure of the work done for a given amount of energy consumed

- re-use of energy (KPI_{REUSE}) - transfer or conversion of energy produced by the operational infrastructure to do other work
- use of renewable energy (KPI_{REN}) - produced from dedicated generation systems using resources that are naturally replenished

It is calculated as follow [54]:

$$KPI_{EE} = (KPI_{EC} - w_{REN} \cdot KPI_{REN} - w_{REUSE} \cdot KPI_{REUSE}) \cdot KPI_{TE} \quad \text{Eq. 97}$$

With:

- w_{REN} – weighting factor for renewable energy
- w_{REUSE} – weighting factor for energy – reuse

8) DPPE: Datacentre Performance Per Energy

Developed by the Green IT Promotion Council (GIPC) [55], [56] the DPPE, aims to integrate several energy efficiency parameters in one. It includes the assessment of facility efficiency using PUE, the CO₂ emissions associated to energy purchased using GEC, the efficiency features of IT equipment using ITEE and the IT equipment utilisation using ITEU.

$$DPPE = ITEU \cdot ITEE \cdot \frac{1}{PUE} \cdot \frac{1}{1 - GEC} \quad \text{Eq. 98}$$

A larger DPPE indicates higher energy efficiency with a maximum of 1.0.

The ITEU is named IT Equipment Utilisation and is defined as the actual energy consumption divided by the total rated energy (rated power by time of measurement), of IT equipment. The corresponding formula is in Eq. 99.

$$ITEU = \frac{E_{IT}}{E_{IT, rated}} \quad \text{Eq. 99}$$

This metric has relation with DCU (Eq. 56) although ITEU is referred to energy consumption and DCU to power capacity.

The ITEE is named IT Equipment Energy Efficiency. This metrics consist of the quotient between the total rated capacity of work of IT equipment and the total rated power of IT equipment. It is expressed in formula Eq. 100.

$$ITEE = \frac{W_{DC, rated} [units\ useful\ work]}{P_{DC, rated} [W]} \quad \text{Eq. 100}$$

This metric is similar to Data Centre Productivity (Eq. 68) although the difference is that, on one hand the ITEE is a static metric based on rated values; and on the other hand Data Centre Productivity refers to a dynamic values of real performance of the data centre.

4.4.6 Financial metrics

This category of metrics refers to the financial aspect of the data centre such as improvements investment as operation costs. These will be used by the IT managers to measure and evaluate organizational factors of the data centre. Because of the nature of these metrics, they are not specific for data centre facilities and they are widely used for business management.

1) CAPEX: Capital Expenditure

It is the amount of money used to acquire assets or improve the useful life of existing assets [57]. Even the CFO (Chief Financial Officer) of each company decides what is imputed to CAPEX or OPEX, in general terms, CAPEX would include server purchasing costs, construction costs of a new data centre and any investment realized to improve the data centre.

2) OPEX: Operating Expenditure

It is the ongoing cost for running a product, business or system. In a data centre it includes [58]: Electricity costs (or any energy source costs), License costs, Maintenance costs and Labour costs

The main efforts to reduce the OPEX in data centre are by reducing electricity costs improving the energy use of the data centre. As said by Brill the cost of servers purchase is dropping but the cost of powering and cooling them has increased 500% since 2000 [59].

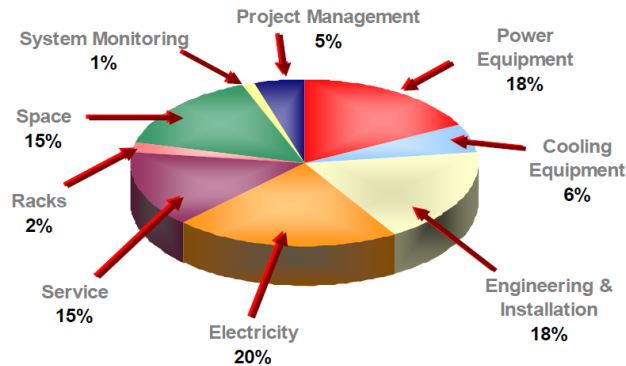
3) TCO: Total Cost of Ownership

Being popularized by Gartner, the TCO is the total expense including capital and operation costs related to a product, system or facility. Thus it can be understood as a way to quantify the financial impact of any capital investment regarding IT business. The TCO is used to assess the true total costs of building, owning, and operating their data centre physical facilities [60].

In a white paper signed by Rasmussen it is said that there are no recognized standards for measuring the TCO of the physical infrastructure of data centres [61]. However at the cited white paper it is proposed simple methods to evaluate the TCO by summing various capital and operating expense items (CAPEX and OPEX).

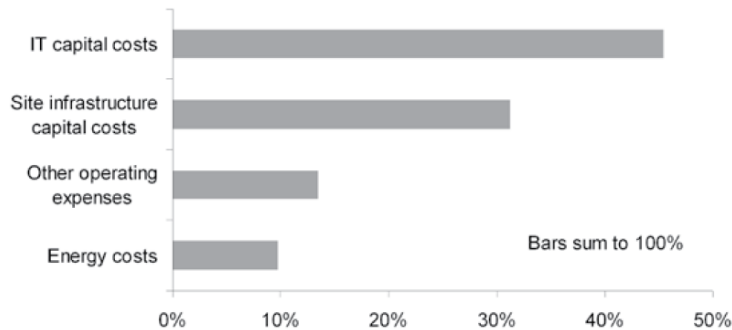
The TCO can be expressed under some points of view, for example on single rack basis and over the data centre lifetime. In this case, and it is assured in the cited white paper approximately half of the TCO per rack over data centre lifetime is capital expense (CAPEX) and the rest is operating expense (OPEX), as can be checked at Figure 4-14.

Figure 4-13 Breakdown of the TCO cost components for a typical rack in high availability 2N data centre [61]



The Uptime Institute also proposes simple model to determine the TCO for data centres [60], but instead of taking per-rack basis as [61] it is taking the whole data centre. The result reached (as shown in Figure 4-13) indicates that about one quarter of the total annualized costs are OPEX and three quarters are CAPEX. Nevertheless this study was made on 2008, and nowadays the parity CAPEX / OPEX has been reached as it was said by [59] and reflected at [61] white paper.

Figure 4-14 Annualized cost by component as a fraction of the total [60]



This information drives to opportunities to cost saving in various areas through investigation and investment. One of them is sizing well the data centre from the beginning or resizing it if the data centre already exists, because the utilisation of infrastructures or IT equipment is one of the factors that makes the TCO higher.

Some tools are available to estimate the TCO and some of them oriented by the manufacturers that have developed them for sales proposals. Here are collected some of them:

- Schneider Electric TCO Calculator: <http://www.apc.com/tools/isx/tco/>
- MySQL TCO Savings Calculator <http://mysql.com/tcosavings/>
- VMware TCO: www.vmware.com/go/calculator.

4) Payback Return

It is defined as the length of time needed for an investment's net cash receipts to cover completely the initial outlay expended in acquiring the investment [62].

$$\text{Payback Period} = \frac{\text{Total investment } [€]}{\text{Annual Cash Inflows } \left[\frac{€}{\text{year}}\right]} = [\text{year}] \quad \text{Eq. 101}$$

This indicator is widely used by IT managers to compare the performance of the investment of different energy efficiency improvement proposals, being one of the searched effects the reduction of OPEX mostly as electricity savings. It must be taken in account that it ignores:

- Any benefits that occur after the payback period and, therefore, does not measure profitability.
- The time value of money.

However, and because of that, it is easy to calculate it. Additionally it is useful to combine it with some data centre infrastructures as PUE to obtain a global vision of the investment benefits. On IT business, Payback Return is usually called ROI Payback or simply ROI, but ROI (Return of Investment) is a completely different indicator than Payback Return.

5) ROI: Return Of Investment

The ROI is the amount, expressed as a percentage that is earned on a company's total capital calculated by dividing the total capital into earnings before interest, taxes or dividends are paid [57].

6) Carbon credits

The offset credits that can be bought and sold to offset the CO₂ emissions [26]. This indicator is different applicable from one country to another in it works as follows.

In case a big company has allocated a number of CO₂ tone emissions and this company doesn't emit the specified number of CO₂ it can sell the difference. If case not, the company must buy the excess of CO₂ emissions from other companies from anywhere. Nevertheless, some environmental agencies as [63] declare that the carbon off-setting is doing nothing to prevent climate change because don't make the developed countries to cut their carbon emissions.

4.5 Application Level

The metrics on this level are named as Application Performance Factor (APF). The $APF_{power\#1}$ to $APF_{power\#7}$ are related to power usage of the Data Centre and the rest ($APF_{energy\#1}$ to $APF_{energy\#6}$) to the energy consumption. Definitions of the concepts involved in these metrics are defined in Sections 4.4.2 and 4.4.3).

4.5.1 Power-based metrics

1) $APF_{power\#1}$

It provides assessment about maximum Data Centre power usage within given period time. Given a fixed infrastructure and workload it allows comparing the whole software stack, from applications (linked to their efficiency) to middleware (how it uses energy savings techniques such as switching off nodes). The goal of this metric is help evaluate the best software stack given an infrastructure and its usage. As it is the maximum data centre power usage, it also is necessary when sizing the electrical infrastructure.

$$APF_{power\#1} = \max[P_{DC,i}] \quad \text{Eq. 102}$$

2) $APF_{power\#2}$

It gives information about maximum Data Centre power usage by a given application during its whole execution (for batch applications). This metric is heavily used by middleware when they are subject to limits of type power-budget. They use it to know the impact of their scheduling decision. It helps also to decide which application to use or buy depending on their power consumption.

$$APF_{power\#2} = \max[P_{DC,i}] \quad \text{Eq. 103}$$

3) $APF_{power\#3}$

Application performance assessment also requires knowing the maximum Data Centre power usage by a given application within given period. This metric is a more precise version of the previous one, allowing middleware to make more precise decision.

$$APF_{power\#3} = \max[P_{DC,i}] \quad \text{Eq. 104}$$

4) $APF_{power\#4}$

It provides assessment about maximum and mean completion time (for batch jobs) or response time (for interactive applications) subject to power usage limits. This metric is a more precise version of the previous one as it gives information

to the middleware on the impact of its decisions. This metric is aimed at an HPC environment.

$$APF_{power\#4_{MAX}} = \max[t_i] \quad \text{Eq. 105}$$

$$APF_{power\#4_{AVG}} = \frac{1}{N} \sum_i^N t_i \quad \text{Eq. 106}$$

Where,

t_i is the completion time for batch jobs for each batch job evaluated, [s].

N is the total number of batch jobs evaluated.

5) $APF_{power\#5}$

In consequence of the $APF_{power\#4}$ the same assessment is required to Cloud environments studying the maximum and mean latency (or number of missed deadlines / SLA violations) subject to power usage limits.

$$APF_{power\#5_{MAX}} = \max[l_i] \quad \text{Eq. 107}$$

$$APF_{power\#5_{AVG}} = \frac{1}{N} \sum_i^N l_i \quad \text{Eq. 108}$$

Where,

l_i is the latency obtained running a process [s], the number of missed deadlines or the number of SLA (Service Level Agreement) violations.

N is the total number of processes evaluated.

6) $APF_{power\#6}$

It provides information about maximum and mean power usage subject to performance guarantees as productivity specific for application types, max response time, deadlines, etc. This metric is heavily used by middleware when they are subject to limits of type performance or productivity objectives.

$$APF_{power\#6_{MAX}} = \max[P_{DC,i}] \quad \text{Eq. 109}$$

$$APF_{power\#6_{AVG}} = \frac{\max[P_{DC,i}] - \min[P_{DC,i}]}{2} = \text{avg}[P_{DC,i}] \quad \text{Eq. 110}$$

7) $APF_{power\#7}$

Application assessment requires using weighted aggregation of energy efficiency and performance metrics based on preferences of data centre operator. This metric is usually shown as an indicator of the global efficiency of an application. It

allows choosing the best application that fits the best a local policy which is neither an energy-budget one nor a performance-objective one.

Two main terms are involved in this metric: the average power usage of the Data Centre and any other factor resulting of running an application (response time, completion time, or latency). Application of weights according Data Centre operator preferences allows emphasizing importance of the power usage or the second factor. A general formulation is indicated in Eq. 111.

$$APF_{power\#7} = \frac{1}{N} \sum_i^N \text{avg}[P_{DC,i}] \cdot w_i \quad \text{Eq. 111}$$

Where,

N is the number of processes evaluated.

w_i is the weighting factor.

In case of emphasizing power usage the weighting factor would be as shown in Eq. 112.

$$w_i = \frac{\text{avg}[P_{DC,i}]}{\max[\text{avg}[P_{DC,j}]]} \quad \text{Eq. 112}$$

Contrary to that, in case of emphasizing completion time, response time or latency, it could be used the weighting factor in

$$w_i = \frac{t_i}{\max[t_i]} \quad \text{Eq. 113}$$

Where t_i is the completion time (for batch jobs) in [s], the response time (for interactive applications) in [s], the latency in [s], the number of missed deadlines or the number of SLA violations. Weighted w_i is dimensionless.

In Figure 4-15, it is shown an example of application of $APF_{power\#7}$ where two different management policies are compared concerning the average power usage of the Data Centre and the completion time both within the same external conditions. Policy#2 has higher average values concerning power usage and completion time, but the weighted mean regarding completion time is lower (then better) in Policy#2 than in Policy#1. As conclusion an operator interested obtaining better time results must choose Policy#2, but if the interest is on power usage because of limits on its power infrastructure it should select the Policy#1.

Figure 4-15 Using of APF#7 comparing two management policies

	Evaluation	P_DC(i) [kW]	t(i) [s]	t(i)/Max_t(i)	P_DC(i)/Max_P_DC(i)	P_DC(i)*t(i)/Max_t(i)	P_DC(i)*P_DC(i)/Max_P_DC(i)
Policy#1	#1	100	3	0,27	1,00	27,27	100,00
	#2	50	10	0,91	0,53	45,45	26,32
	#3	30	11	1,00	0,32	30,00	9,47
	#4	95	5	0,81	1,00	77,03	95,00
	#5	60	4	0,65	0,60	38,92	36,00
	#6	45	4	0,44	0,45	20,00	20,25
	AVERAGE	63,33	6,17			39,78	47,84
Policy#2	#1	100	4	0,25	1,00	25,00	100,00
	#2	60	9	0,56	0,63	33,75	37,89
	#3	40	16	1,00	0,42	40,00	16,84
	#4	95	5	0,73	1,00	69,51	95,00
	#5	55	3	0,44	0,80	24,15	43,73
	#6	65	4	0,59	0,94	38,05	61,08
	AVERAGE	69,17	6,83			38,41	59,09
Comparisson Policy#1/Policy#2						1,04	0,81

4.5.2 Energy-based metrics

1) APF_{energy}#1

Given a fixed infrastructure and workload it allows to compare the whole software stack, from applications (linked to their efficiency) to middleware (how it use energy savings techniques such as switching off nodes), this time from the energy point of view which is the most global indicator. This is the energy version of APF_{power}#1

$$APF_{energy\#1} = [E_{DC}]_t \quad \text{Eq. 114}$$

2) APF_{energy}#2

The energy version of APF_{power}#2 is defined as the total Data Centre energy consumption by a given application during its whole execution (for batch applications). This metric helps to compare several applications in order to use or buy the greenest. It is usually linked with a particular field and a particular data-set in order to compare the applications. It is also used by middleware to deduce the heat dissipation impact of an application on a node.

$$APF_{energy\#2} = [E_{DC\ of\ applications}] \quad \text{Eq. 115}$$

3) APF_{energy}#3

The energy version of APF_{power}#3 is defined as the total Data Centre energy consumption by a given application within given period. This metric is a more precise version of the APF_{energy}#2.

$$APF_{energy\#3} = [E_{DC}]t \quad \text{Eq. 116}$$

4) $APF_{energy\#4}$

This is the energy version of $APF_{power\#4}$ and is defined as the maximum and mean completion time (for batch jobs) or response time (for interactive applications) subject to total energy consumption limits. This metric is used by middleware to make decision when subject to energy budget, usually due to cooling infrastructure constraints or cost constraints.

$$APC_{energy\#4_{MAX}} = \max[t_i] \quad \text{Eq. 117}$$

$$APC_{energy\#4_{AVG}} = \frac{1}{N} \sum_i^N t_i \quad \text{Eq. 118}$$

Where,

t_i is the completion time for batch jobs for each process evaluated, [s].

N is the total number of processes evaluated.

5) $APF_{energy\#5}$

This metric is the Cloud equivalent of the $APF_{energy\#4}$ and the energy version of $APF_{power\#5}$, thereby it is defined as the maximum and mean latency, number of missed deadlines or number of SLA violations subject to total energy consumption limits.

$$APF_{energy\#5_{MAX}} = \max[l_i] \quad \text{Eq. 119}$$

$$APF_{energy\#5_{AVG}} = \frac{1}{N} \sum_i^N l_i \quad \text{Eq. 120}$$

Where,

l_i is the latency obtained running a process [s], the number of missed deadlines or the number of SLA violations.

N is the total number of processes evaluated.

6) $APF_{energy\#6}$

This metric is the energy version of the $APF_{power\#7}$ the weighted productivity metrics are referred to the energy consumption of the Data Centre. The general formulation is indicated in Eq. 121.

$$APF_{energy\#6} = \frac{1}{N} \sum_i^N E_{DC,i} \cdot w_i \quad \text{Eq. 121}$$

The weighting factor depends on what is interesting to emphasize: the energy consumption or other factor that characterizes the application management policies. In case the importance falls on the energy consumption it must be applied the weighting factor in **Eq. 122**.

$$w_i = \frac{E_{DC,i}}{\max[E_{DC,i}]} \quad \text{Eq. 122}$$

Contrary, in case the interest is on the second factor the weighting factor is indicated in

$$w_i = \frac{t_i}{\max[t_i]} \quad \text{Eq. 123}$$

The same example in $APF_{power\#7}$ can help on the understanding of this metric.

5 Tendencies on metrics standardisation

The Power Usage Effectiveness (PUE) metric is set to become an ISO standard within the two years, according to The Green Grid [64]. This could be a first step to start the standardisation process of data centre metrics. As it is described below there are multiple initiatives to endorse metrics about energy efficiency of data centres.

Firstly, there are mentioned the most recent activities from the standard bodies.

ISO (International Organisation for Standardisation) and IEC (International Electrotechnical Commission) established Joint Technical Committees in several areas. One of them, named “Sustainability for and by Information Technology” focuses on standardization related to the intersection of resource efficiency and Information Technology. This committee supports sustainable development and, application, operation and management aspects are investigated. Based on discussions in November 2011 ISO/IEC JTC 1 Plenary, JTC 1/SC 39 established a Working Group on Resource Efficiency of Data Centres. One of the metrics supported by this standardization group is Global KPIs (Key Performance Indicators). Another one is Datacentre Performance per Energy (DPPE).

CEN-CENELEC (European Committee for Electrotechnical Standardization) proposes the EN 50600 standard series addressing the design of Data Centre facilities and infrastructures partly based on the criteria of Energy efficiency. The first version of the standard has been ratified (September 2012), but will not be available until end of 2012. It is expected that this standard will also manage with metrics for data centre.

ETSI (European Telecommunications Standards Institute) with the Specialist Task Force STF439 endorses Global KPIs for energy efficiency assessment of data centres.

The European Code of Conduct on Data Centres Energy Efficiency (EU CoC) will develop, adopt and publicize metrics, so that data centres can be compared and (eventually) given targets. As a start, it will use The Green Grid’s Datacentre Infrastructure Efficiency (DCiE) ratio.

Moreover of the standard bodies there are several industry groups and professional bodies that provides information to standardisation process.

One of the most active groups promoting metrics is The Green Grid. They endorse several metrics, not only PUE, but also DCiE, Carbon Usage Effectiveness (CUE), Water Usage Effectiveness (WUE) and Energy Reuse Effectiveness (ERE).

One of the metrics that are nowadays within discussion for standardization, the DPPE is endorsed by the Green IT Promotion Council.

The Uptime Institute recommends some metrics as for instance the Deployed Hardware Utilisation Ratio (DH-UR) [19].

The British Computer Society has a number of initiatives, particularly through its Data Centre Specialist Group (DCSG). They have developed a new metric that is Fixed to Variable Energy Ratio (FVER). Although there has been no indication of this, the EU could recommend the use of such metrics in a future iteration of the data centre Code of Conduct.

Also the EC Projects on data centre energy efficiency researches in-depth about the performance of existing metrics, its gaps and proposals of new ones.

Finally other groups providing potential input useful for CoolEmAll developments on metrics are ASHRAE, US Energy Star, IEEE, GHG Protocol, US Green Building Council, BRE Global.

Some industry players and government agencies, from US and Japan participate in a cooperative activity related with metrics through the Task Forces. The Data Centre Metrics Coordination Task Force (U.S. Regional Task Force) and the Global Harmonization of Data Centre Efficiency Metrics Task Force (Global Task Force) are the main of them and they endorses metric for measuring infrastructure energy efficiency in data centres and states the methodology and criteria for an appropriate calculation. These task forces agreed on using PUE as a standard metric [28] [24].

An extensive analysis about standardisation updated tendencies is being developed in-depth in the framework of CoolEmAll in Workpackage WP7. The first results, from which the information of this chapter has been extracted, can be found in deliverable D7.6.1 [65]

6 Gaps on existing metrics and new proposals from CoolEmAll

As previously mentioned PUE is one of the metrics preferred on industry and one that is close to become a standard. This is a useful metric for evaluating the energy usage and efficiency of the infrastructure equipment that supports the IT equipment within a data centre. However, it is relevant to notice some limitations of this metric [28].

- Reduction on IT load can generate an increasing of PUE if the facilities do not adapt its performance to this reduction.
- PUE requires to be calculated including total data centre consumptions to be significant and to provide a value comparable with other references.
- PUE do not reflect renewables usage or recovering waste heat. It is not a metric to identify the efficiency of electricity production. Instead of that, the PUE focus on the efficiency of using electricity inside the data centre.

The Green Grid states that issues such as cogeneration, waste heat reuse, and local generation of electricity should be considered in other metrics than PUE. The report [28] provides some guidelines to calculate a source conversion factor for IT energy in case of a cogeneration plant in a data centre. The last report of the Global Task Force endorses the integration on RES and cogeneration in PUE with the calculation of *Source Energy Factor* [24]. Therefore, the question about boundaries of data centre and criteria about homogenisation of source of energy is clearly nowadays under discussion.

In case of heat reuse outside the boundaries of data centre, if the amount of energy reused is counted in PUE, values below 1.0 can be obtained, that are not consistent with the physical definition of the metric.

Most proposed improvement to PUE still considers data centres as a whole. The repartition of thermal production is not taken into account while it has a major impact on the cooling infrastructure, and thus on cooling energy consumption. As the cooling system aims at preventing each and every physical element to reach a certain temperature, position of heat points, thermal imbalance, and thermal characteristics have an impact of operational behaviour.

Therefore, to provide additional information about energy efficiency that it is not included in the meaning of PUE some other metrics are considered relevant, as well in the framework of CoolEmAll.

- About the introduction of renewable or reuse of waste heat it is recommended to complement the PUE use with CUE, Primary Energy Balance or ERE (or ERF) and GEC that are affected by the origin of kind of energy provided to data centre.

- FEVER has the advantage of focusing on the performance of IT load. This could be a solution for the first remark about PUE's gaps.
- Global KPI or DPPE are metrics that consider aspects of environmental benefits in a data centre in a holistic way.
- This report has provided specific metrics for optimizing energy performance at the levels of node, node-group or rack. At these stages it is better to consider the metrics proposed instead of PUE, which is a metric referred to complete data centre.

Most data centre metric-based public analysis are based on mainly one metric: PUE. As this simplification helps clarification, it also reduces the possibilities to understand and improve the energy, heat and power behaviour of data centres. A complete analysis requires simultaneous information from several levels as stated in the previous sections, from application-level to data centre-level. One of the main difficulties is the lack of standardised or even widely used metrics at other levels than at the one of whole data centres.

One of the main objectives of CoolEmAll is to propose new metrics that contribute to improve energy efficiency of data centres. Besides the monitoring and benchmark analysis of some of the metrics that are nowadays on common use or discussion on standardisation bodies and industrial groups, CoolEmAll aims to improve the knowledge about some new metrics on dynamic performance and heat-aware based on the experience gained on developing the DEBBs, MOP and SVD tool. This is also important to focus the proposal of new metrics on the requirements of potential users of CoolEmAll results. In a first approach, the application on data centre of some the metrics that will be validated with CoolEmAll Project (see 0), related with heat dissipation and temperature on different levels of granularity of a data centre and dynamic performance, can be considered an improvement of the state of the art from the project.

However, this document is a first step on metrics activities within the project and the final selection will be based on the experience obtained developing CoolEmAll. This means monitoring test-bed, simulating virtual scenarios, developing a benchmark analysis, participating in dissemination activities and being in contact with industry and standardisation bodies will permit to obtain enough knowledge to endorse some of the results of CoolEmAll.

7 Selection of metrics for CoolEmAll

A set of metrics has been accurately analysed and selected from the literature to show the state of the art in analysing the energy efficiency on data centre. Based on this analysis, the most appropriate metrics to accomplish with CoolEmAll's expectations regarding characterisation of the energy and heat aware dynamic performance of data centre have been selected.

A summary of all the metrics is provided including a graphical explanation about the interrelation between metrics. Besides that, there is information about the sensors required to get the data for metrics calculation in CoolEmAll project. Finally, taking into account all this information as well as the requirements of Validation Scenarios in CoolEmAll-WP6 [66] the selected metrics are displayed.

Nevertheless, the limitations in the scope of the CoolEmAll project causes that not all the selected metrics will be properly used evaluated and validated within its framework. The knowledge about the metrics will rise developing the proposed tests in Validation Scenarios. Therefore better selection of metrics will be done at the end of this process.

7.1 Summary of metrics

The metrics collected in this White Paper are presented and organised in tables below according the classification system explained in Sections 3.3.3 and 3.4.

Table 7-1 Summary of metrics collected in the present report (node and node-group level)

Level	Resource Usage	Energy			Green metrics	Financial metrics
		Power-based metrics	Energy-based metrics	Heat-aware metrics		
Node	CPU Usage	Node Power Usage	Node Productivity	Node Cooling Index		
	Server Usage	MHz/Watt		Maximum -mean heat dissipation		
	Network Usage	Bandwidth/Watt				
	Memory Usage	Capacity/Watt				
	Storage Usage	IOPS/Watt				
	I/O Dev.Usage	Power vs. Utilzat				
Node - Group	Aggregation and averaging of previous level metrics	Aggregation and averaging of previous level metrics	Node-Group Productivity	Node-Group Cooling Index		
	CPU Usage	SWaP		Node-Group Humidity Index		
	DH-UR			Imbalance of temperature CPU		
	DH-UR _{CPU}			Imbalance of heat generation of Nodes		

Table 7-2 Summary of metrics collected in the present report (rack, data centre and application level)

Level	Resource Usage	Energy			Green metrics	Financial metrics
		Power-based metrics	Energy-based metrics	Heat-aware metrics		
Rack	Aggregation and averaging of previous level metrics	Aggregation and averaging of previous level metrics	Rack Productivity	Rack Cooling Index		
		UPS Usage		Rack Humidity Index		
		Heat exchanger Usage		Imbalance of temperature of Node-Groups		
				Imbalance of heat generation of Node-Groups		
Data Centre	Aggregation and averaging of previous level metrics	Aggregation and averaging of previous level metrics	Data Centre Productivity	Imbalance of temperature -rack	Primary Energy Balance	CAPEX
		UPS Usage	PUE (Energy)	Imbalance of heat generation -rack	GEC	OPEX
		DCU	pPUE	Air management indicators	ERE/ERF	TCO
		PUE (Power)	FVER	Cooling system response capacity	CUE	Payback Return
		PUE Scalability	SEER		WUE	ROI
		DCiE			KPI _{EE}	Carbon credits
		DCD			DPPE	
		EER			Carbon emissions balance	
Application		APF _{power} #1	APF _{energy} #8			
		APF _{power} #2	APF _{energy} #9			
		APF _{power} #3	APF _{energy} #10			
		APF _{power} #4	APF _{energy} #11			
		APF _{power} #5	APF _{energy} #12			
		APF _{power} #6	APF _{energy} #13			
		APF _{power} #7				

7.2 *Interrelation of metrics*

Following the example of GAMES, an interrelation scheme is presented in the following figures where the selected metrics are interrelated between them and with the data coming from the monitoring system to calculate them.

Some clarifications about these figures are herein presented. It can be noted that some measuring data have been joined in single blocks as:

- **Node Performance:** It represents any quantification of the job produced by a Node or its components. This is the reason why it is linked with the block of “Measurable produced work at Node”. Particular quantifiable parameters are:
 - Activity of the CPU
 - Network bandwidth used
 - Amount of used memory
 - Data per unit of time
- **Component Power:** It is the power used by any component of the Node. It is linked with the Node Power because the sum of all components power usage is the total power usage of the Node.
- **Node Capacity:** It is the maximum capacity or the ability of a component in the Node to hold a particular state excluding the power usage because is already assessment in “Node Power” and “Component Power” blocks. Some examples are:
 - Bandwidth maximum capacity
 - Total capacity of I/O operations (per second)
 - Computing capacity (FLOPS)
- **Air temperature at different Data Centre locations:** The locations where the air temperature must be measured to obtain the “Air management indicators” are specified in Section 4.4.4.

Another important point is the lack of direct interrelation between metrics in general. This has been accomplished by the selection process where redundant and not enough clear metrics were refused. Then each metric provides assessment on very particular aspect of the Data Centre and the applications running on it, avoiding for redundancies.

Looking at Figure 7-1 to Figure 7-6 it can be noticed how the metrics can be calculated. The blue globes are the measurements and the squares are the related metrics. Depending on the colour of the square, the different concepts of metrics (resource, power, energy, green, financial) are collected. Depending on the area of each figure, the level of granularity, as described in this document, can be identified.

For instance, in Figure 7-3, to calculate FVER, we can identify:

- This is energy metric (brown square).
- This metric need following measurements (blue globes): useful work, IT equipment energy and data centre energy.
- This metric correspond to data centre level of granularity.

Figure 7-1 Interrelation of Resource Usage metrics between layers: Source IREC

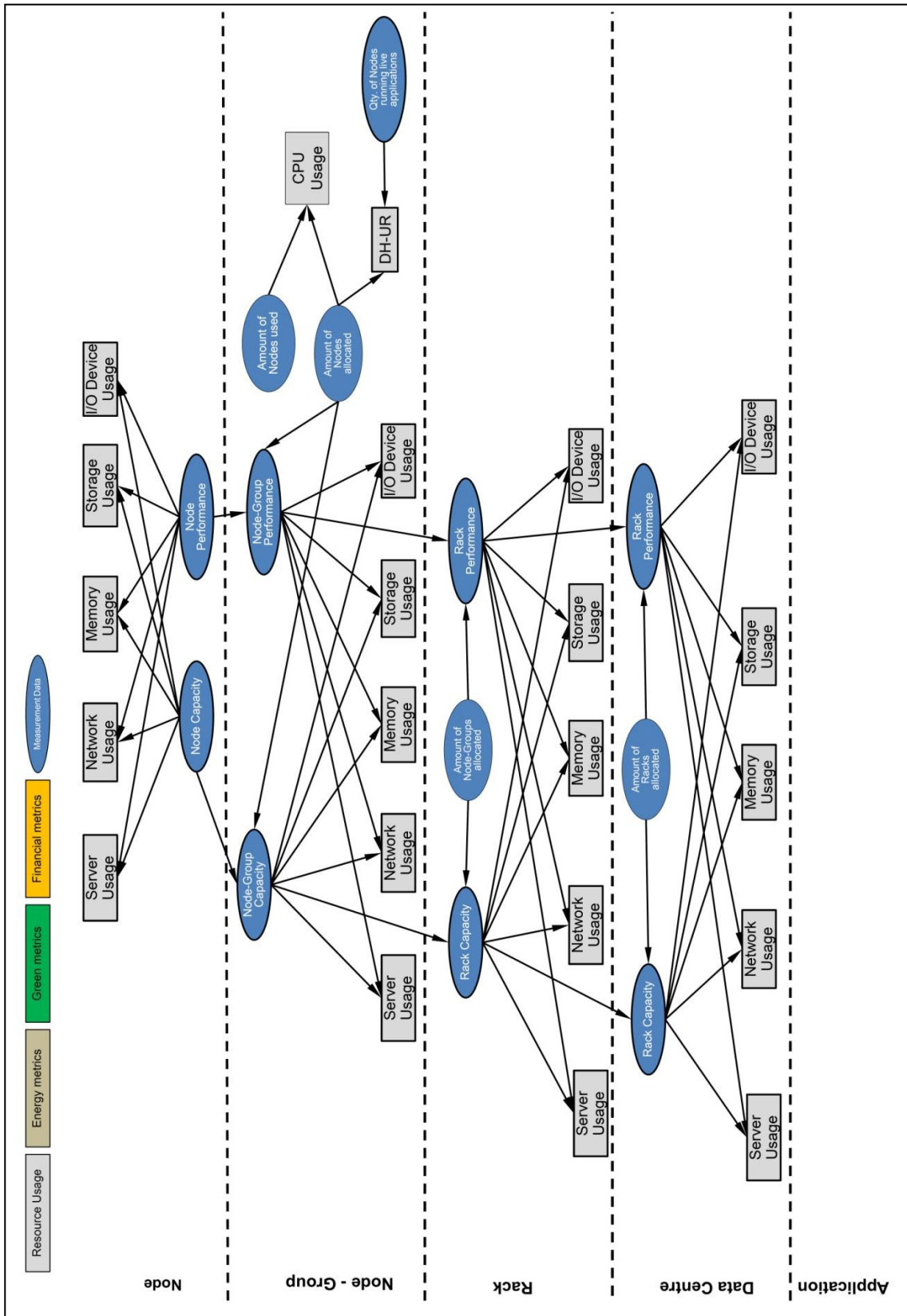


Figure 7-2 Interrelation of Power-based metrics between layers: Source IREC

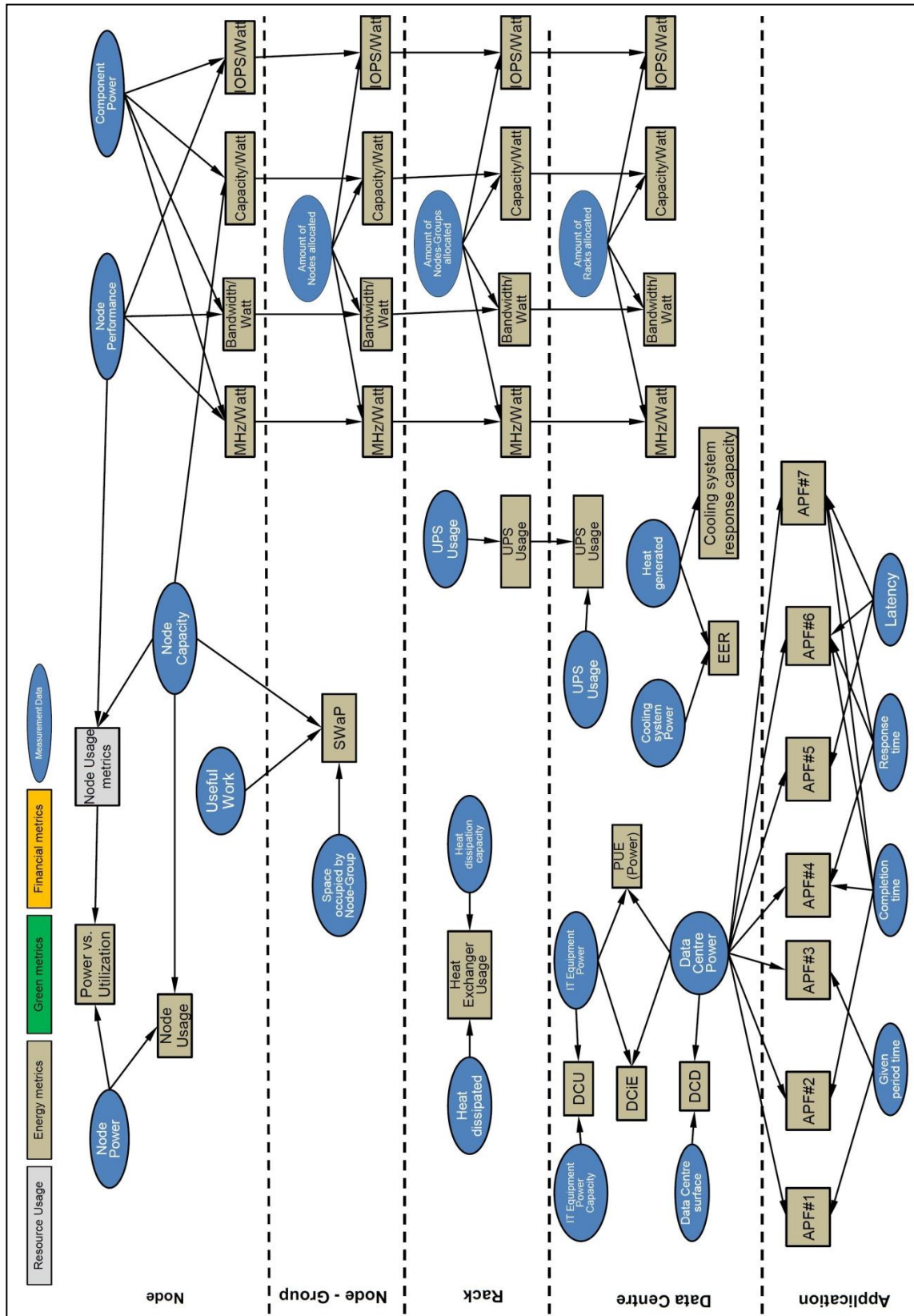


Figure 7-3 Interrelation of Energy-based metrics between layers: Source IREC

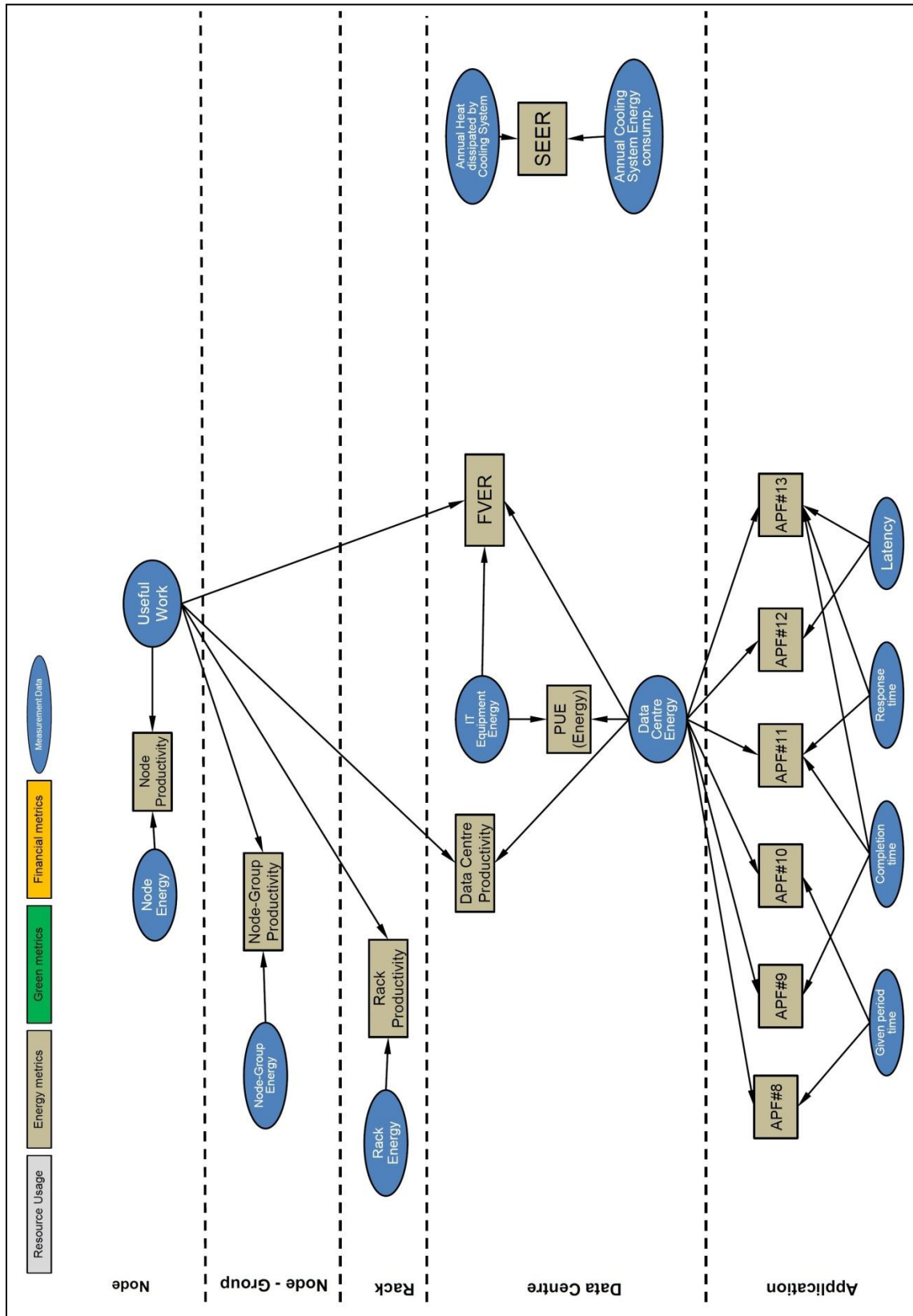


Figure 7-4 Interrelation of Heat-aware metrics between layers: Source IREC

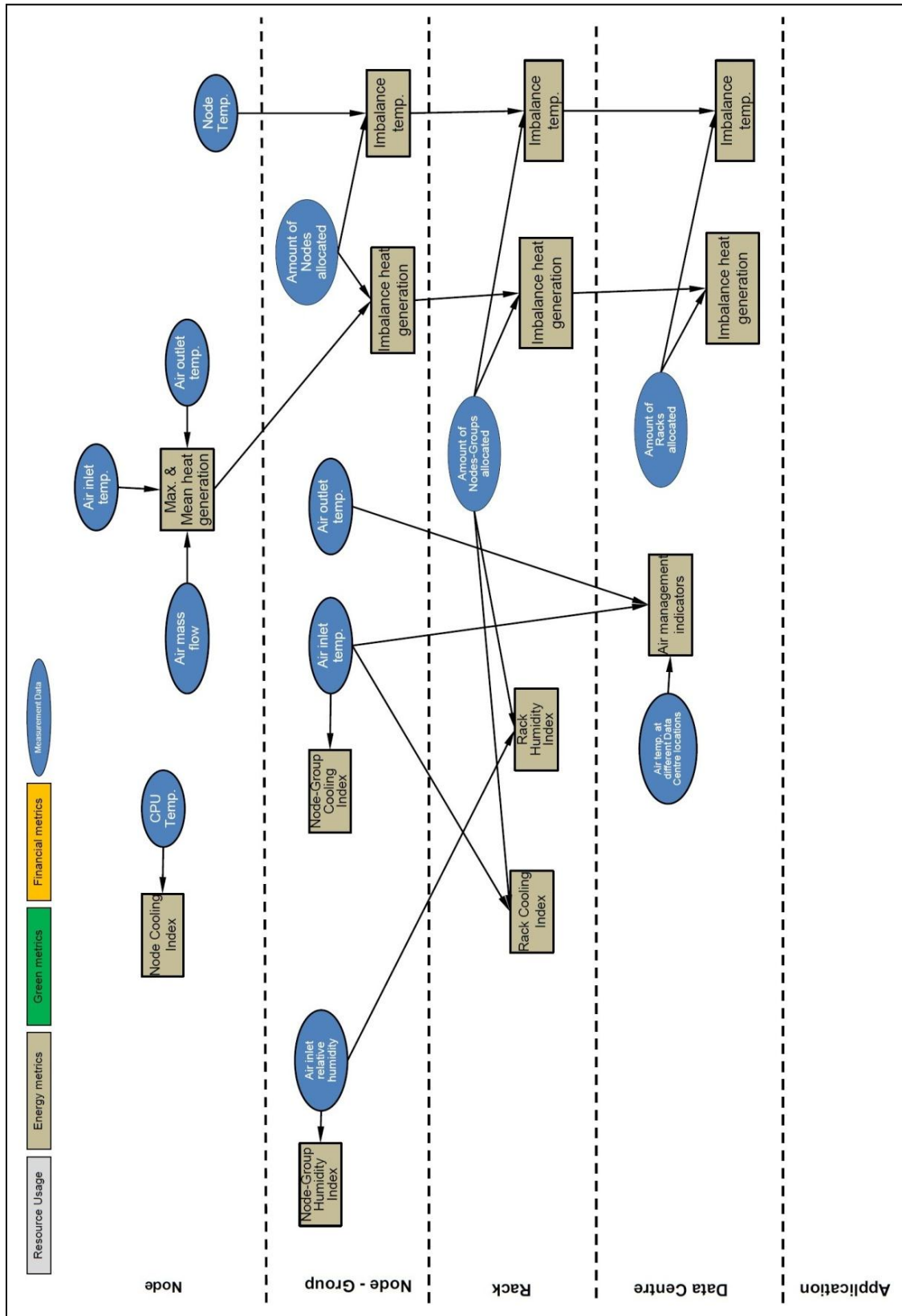


Figure 7-5 Interrelation of Green metrics between layers: Source IREC

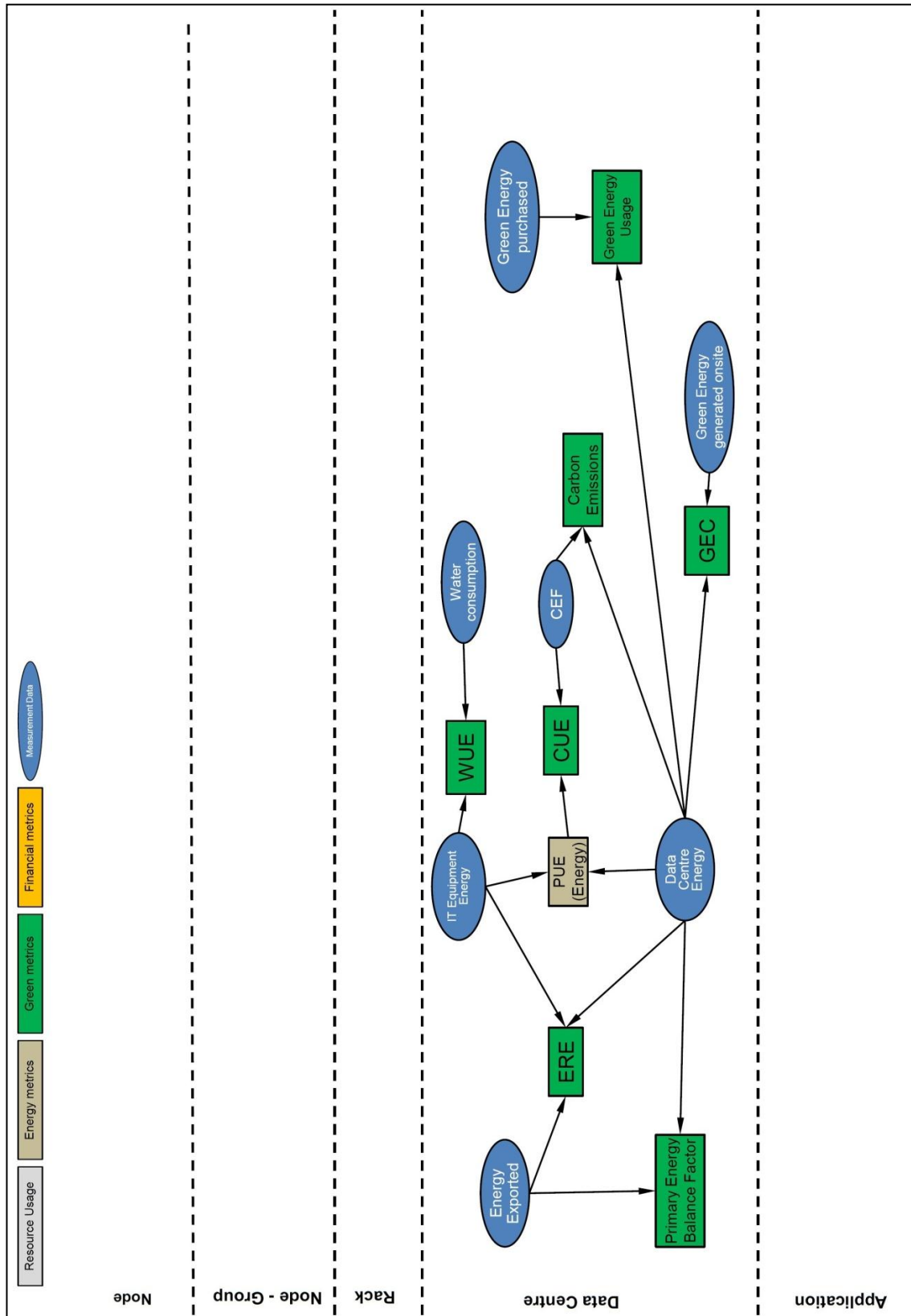
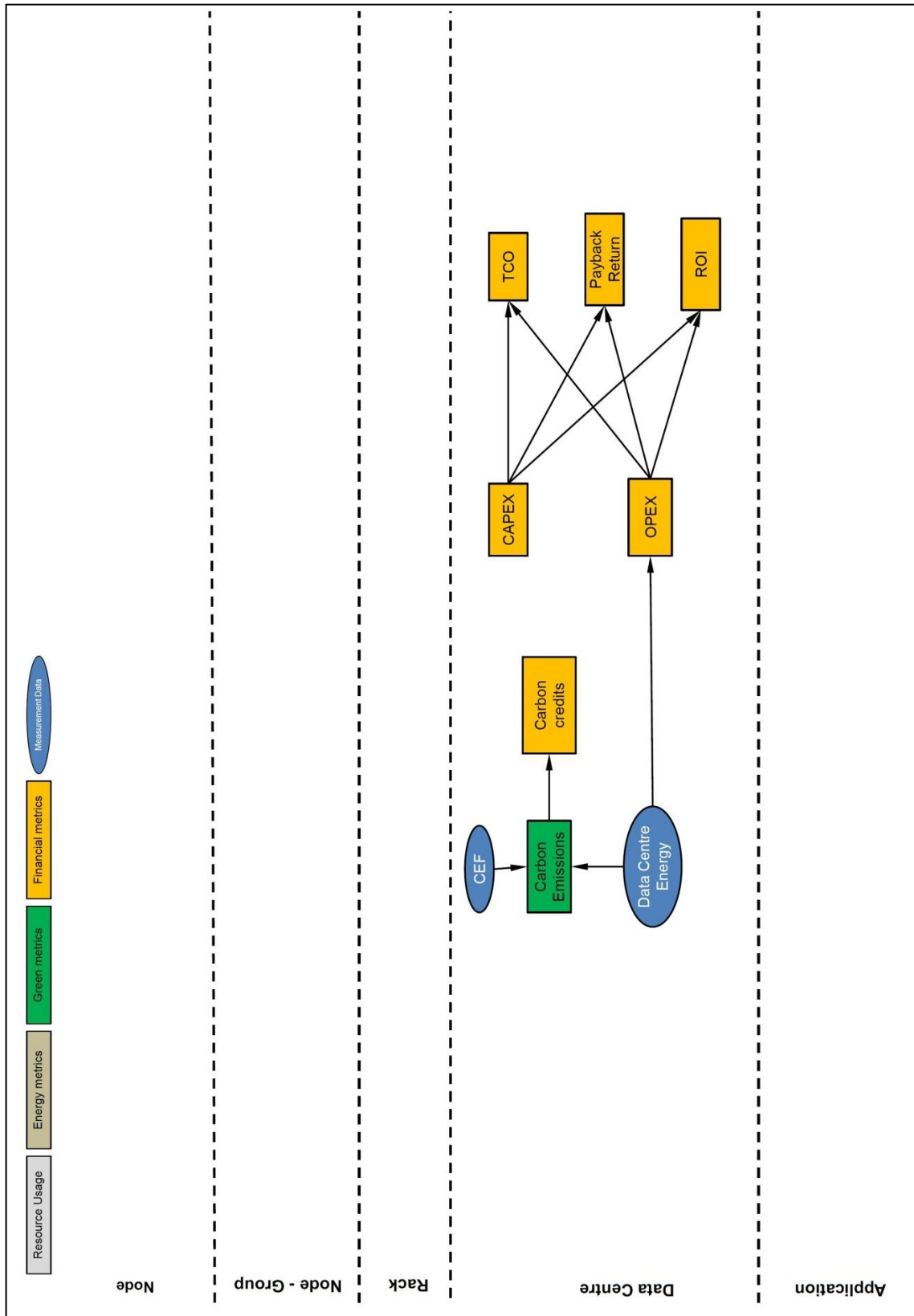


Figure 7-6 Interrelation of Financial metrics between layers: Source IREC



7.3 Measurement sensors

Following physical sensors are installed on the test bed and can be used to measure:

Table 7-3 Sensors on the test bed

Input Data	Level	Unit
Status of the Mainboard	node_recs	On/Off
Current used by the Mainboard	node_recs	Ampere
Voltage of the Power Supply	node_recs	Volt
Power consumption of the Mainboard	node_recs	Watt
Temperature of the Mainboard	node_recs	°C
Potential on the Mainboard	node_os	Volt
Temperature of the CPU	node_os	°C
Inlet air temperature	rack, node_recs	°C
Outlet air temperature	rack, node_recs	°C
Airflow speed	rack, node_recs	% of a given maximum
Relative humidity	rack, node_recs	%

The meaning of nomenclature used on level column is the following:

- node_os: The measurement can be determined on a node-level with the help of software that runs on the Operation System. This is e.g. the memory-usage or server-usage.
- node_recs: This measurement can be determined on the node-level of the RECS | Box. The RECS | Box management interface is able to provide this measurement.

Other measurements can be provided by applications or operating system (via monitoring tools):

Table 7-4 Measurements by applications

Input Data	Level	Unit
CPU frequency	node_os	Hz
CPU voltage	node_os	Volt
CPU utilisation	node_os	%
Total Memory	node_os	MB
Memory utilisation	node_os	MB
Active processes	node_os	[number]
Total processes	node_os	[number]
Time	all	seconds
Benchmark	node, recs, rack	Benchmark specific
Service	VM	Completion time

Following values can be provided by simulation:

Table 7-5 Simulated values

Input Data	Level	Unit	Component
Temperature history	All, determined in simulation	°C	CFD simulation
Power usage history	CPU, Node, Node-Group, Rack, Data Centre, Cooling Device	Watt	DCWoRMS
Air throughput history	CPU, Node, Node-Group, Rack, Data Centre	m ³ /minute	DCWoRMS
Energy consumption	CPU, Node, Node-Group, Rack, Data Centre, Cooling Device	Watt-hours	DCWoRMS
Resource utilisation	CPU, Node, Node-Group, Rack, Data Centre	%	DCWoRMS
Max power usage	Data Centre	Watt	DCWoRMS
Completion time	Application	seconds	DCWoRMS
Latency	Application	seconds	DCWoRMS
Power usage history	Application	Watt or %	DCWoRMS

According the report [28], the energy measurement guidance requirements proposed by The Green Grid and ASHRAE can be found on the reference [67].

7.4 First selection of metrics for CoolEmAll

Finally some of the reported metrics are selected for the CoolEmAll purposes. These metrics will be tested and validated along the project. The present Chapter consists of a reference for the Consortium of CoolEmAll to know how to calculate the relevant metrics. However, some of the selected will not be possible to be checked due to the limitations of the project. As well, some of them will be refined on its definition and formulation. In that sense, the present deliverable will be updated at the end of the project to provide the experience acquired.

In the presented table there are indicated the metrics to be calculated in the different Validation Scenarios, defined in D6.1. The metrics marked with “P” the *Primary Metrics*, are used directly (without additional assumption) to assess the experiments / trials results, whereas those marked with “S” the *Secondary Metrics* are not the first focus of the experiment, for a certain Validation Scenario, but are which ones calculated making certain assumptions. The following subsections explain selection of metrics for the assessment of experiments within the scenarios defined in D6.1.

Table 7-6 Metrics selected at node, node-group and rack level

			Physical testbed scenarios						Optimization by simulation					Verification Scenarios				
			Configuration of the physical testbed	Configuration of the virtual testbed	Execution of applications/benchmarks on the selected physical computing nodes	Execution of applications/benchmarks on the selected virtual computing nodes	Virtual thermal camera	Historical data browsing	Application workload simulation	Capacity management	Optimization by CFD	Server room optimization by simulation with change of cooling	Free Cooling on server room	Simulation within a RECS	Real data vs simulation output comparison - verification of HPC models	Real data vs simulation output comparison - verification of Cloud models	Real data vs simulation output comparison - verification of HPC CFD	Real data vs simulation output comparison - verification of Cloud CFD
Node	Resource-Usage	CPU Usage			P	P	P	P	P					P				
		Server Usage			P	P	P	P	P					P				
		Network Usage			S	P	S	S	S	S				S				
		Memory Usage			S	P	S	S	S	S				S				
		Storage Usage			S	S	S	S	S	S				S				
		I/O Device Usage			S	S	S	S	S	S				S				
	Power-Based	Node Power Usage			P	P	P	P	P	P				P				
		MHz/Watt			S	S	S	S	S	S				S				
		Bandwidth/Watt			S	S	S	S	S	S				S				
		Capacity/Watt			S	S	S	S	S	S				S				
		IOPS/Watt			S	S	S	S	S	S				S				
	Energy-based	Power vs. Utilization			S	S	S	S	S	S				S				
		Node Productivity			P	P	P	P	P	P				P				
	Heat-aware	Node Cooling Index			P	P	P	P	P	P				P				
Max & mean heat dissipation				P	P	P	P	P	P				P					
Node-Group	Resource-Usage	Aggregation and averaging of previous level metrics																
		DH-UR			P	P	P	P	P	P				P	P	P	P	
		DH-UR _{CMU}			P	P	P	P	P	P				P	P	P	P	
	Power-Based	Aggregation and averaging of previous level metrics																
		SWaP			P	P	P	P	P	P				S	P	P	P	P
	Energy-based	Node-Group Productivity												S				
		Node-Group Cooling Index			P	P	P	P	P	P				P	P	P	P	P
	Heat-aware	Node-Group Humidity Index			S	S	S	S						S	S	S	S	S
Imbalance temperature of CPUs				P	P	P	P							P	P	P	P	
Imbalance of heat generation of Nodes				P	P	P	P						P	P	P	P	P	
Rack	Resource-Usage	Aggregation and averaging of previous level metrics											S					
		Aggregation and averaging of previous level metrics												S				
	Power-Based	UPS Usage								S	S			S				
		Heat exchanger Usage			P	P	P	P			S			S	P	P	P	P
	Energy-based	Rack Productivity			P	P	P	P			P	P	P	S	P		P	P
		Rack Cooling Index			P	P	P	P			P	P	P	S	P		P	P
		Rack Humidity Index			S		S	S			S	S	S	S		S	S	S
Heat-aware	Imbalance of temperature of Node-Groups			P		P	P			S	S	S		P	P	P	P	
	Imbalance of heat generation of Node-Groups			P		P	P			S	S	S		P	P	P	P	

Table 7-7 Metrics selected at data centre level

			Physical testbed scenarios					Optimization by simulation					Verification Scenarios						
			Configuration of the physical testbed	Configuration of the virtual testbed	Execution of applications/benchmarks on the selected physical computing nodes	Execution of applications/benchmarks on the selected virtual computing nodes	Virtual thermal camera	Historical data browsing	Application workload simulation	Capacity management	Optimization by CFD	Server room optimization by simulation with change of cooling	Free Cooling on server room	Simulation within a RECS	Real data vs simulation output comparison - verification of HPC models	Real data vs simulation output comparison - verification of Cloud models	Real data vs simulation output comparison - verification of HPC CFD	Real data vs simulation output comparison - verification of Cloud CFD	
Data Center	Resource-Usage	Aggregation and averaging of previous level metrics																	
	Power-Based	Aggregation and averaging of previous level metrics																	
		UPS Usage																	
		DCU							S	S									
		PUE (Power)							P	P	P	P	P						
		PUE Scalability							P	P	P	P	P						
		DCIE							P	P	P	P	P						
		DCD							S	S	S	S	S						
	EER																		
	Cooling system response capacity																		
	Energy-based	PUE (Energy)							P	P	S	S	S						
		pPUE							S	S									
		FVER							S	S	S	S	S						
		SEER																	
		Data Centre Productivity							P	P	S	S	S						
	Heat-aware	Imbalance of temperature of Racks										P	P	P					
		Imbalance of heat generation of Racks										P	P	P					
		Air management indicators										P	P	P					
	Green metrics	Primary Energy Balance																	
		GEC																	
		Green Energy Usage																	
		ERE																	
		CUE									S	S	S						
		WUE											P						
		KPI _{EE}																	
		DPPE																	
	Carbon emissions balance																		
	Financial	CAPEX																	
		OPEX																	
		TCO																	
		Payback Return																	
		ROI																	
			Carbon credits																

7.4.1 Selected metrics for the assessment of physical testbed scenarios

1) HPC Scenarios

The following set of validation and verification scenarios related to the physical project testbed for HPC has been defined:

- EX_HPC_2 - Execution of applications/benchmarks on the selected physical computing nodes,
- EX_Monitoring_1 - Virtual Thermal Camera - Real-time monitoring,
- EX_Monitoring_2 - Virtual Thermal Camera - Historical data browsing,
- VER_HPC_1 - Real data vs. simulation output comparison – verification of HPC models.

Metrics and measurements to be used in the aforementioned scenarios are listed below:

Server Usage metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The value is provided by OS and stored in the MOP DB.

Node usage metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The value of current power consumption of the node needed to calculate the metric is provided by Node Level RECS sensor and stored in MOP DB. The calculation of this metric is provided by the metrics calculator.

Node Productivity metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The energy consumption needed to calculate the metric is provided based on power consumption of the node measured by Node Level RECS sensors. The “units of useful work” factor will be specified and measured individually for every case (trial),

Node cooling index metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The temperature of CPU is provided by OS and stored in the MOP DB. The calculation of this metric is provided by the metrics calculator.

Maximum and mean heat dissipation metrics are used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. Based on the assumption that the heat dissipated by the IT hardware is equal to the power drawn, the node heat dissipation is provided by Node Level RECS power consumption sensor. The calculation of this metric is provided by the metrics calculator.

CPU Usage metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. For the HPC case the metric is defined as a ratio of used queueing system slots to the total number of slots. In the HPC environment the slot is usually assigned to single core. The calculation of this metric is provided by the queueing system and stored in the MOP DB.

DH-UR metric is used EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The value of the metric is provided by the queueing system based on the number of both used and total nodes. The metric is stored in the MOP DB.

Node-Group cooling index metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The temperature air intake is provided by external sensors and stored in the MOP DB. The calculation of this metric is provided by metrics calculator.

Imbalance of temperature of CPUs and Nodes metrics are used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. Temperatures of CPUs and Nodes are provided by OS and Node Level RECS sensors, respectively.

Rack Productivity metric is used in the EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The energy consumption needed to calculate the metric is measured by external meter. The “units of useful work” factor will be defined and measured individually for every case (trial).

Recs cooling index metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The required value of temperature is provided by the external thermometer and stored in the MOP DB. The calculation of this metric is proved by metrics calculator.

Imbalance of temperature of node-groups metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The required value of temperature is provided by the external thermometer and stored in the MOP DB. It is necessary to specify what exactly is the temperature of node-

group in context of RECS system. The calculation of this metric is proved by metrics calculator.

Imbalance of heat-generation of node-group metric is used in EX_HPC_2, EX_Monitoring_1, EX_Monitoring_2 and VER_HPC_1 scenarios. The required value of the consumed power which is equal to the dissipated heat is provided by RECS and stored in the MOP DB. The calculation of this metric is provided by the metrics calculator.

2) Cloud Scenarios

There are 6 scenarios identified within the scope of the execution of experiments on the physical testbed in Cloud environment.

- EX_CLOUD_2: Execution of applications/benchmarks on the selected virtual computing nodes
- EX_Monitoring_1: Virtual Thermal Camera - Real-time monitoring
- EX_Monitoring_2: Virtual Thermal Camera - Historical data browsing

Server Usage, server usage will be used in the physical scenarios to measure the CPU status when executing different workloads on the test bed. When talking about the cloud scenarios, the server usage metric will imply the migration of a service from one node to another due to the need of balance the server usage. This metric is specifically important for the scenarios EX_CLOUD_2, EX_Monitoring_1, EX_Monitoring_2.

Network Usage, might not be by itself a metric that would affect the heat or power increase, but it provides and indicator that the application workload changes, hence it is used to collect the application profile. The network usage metric is monitored in all the physical use cases.

Memory Usage is a metric used in the scenarios EX_CLOUD_2, EX_Monitoring_1, EX_Monitoring_2. This metric indicates the memory usage of a certain node providing information of the workload and used in the EX_CLOUD_2 as one of the KPIs to manage the cloud service and migrate among different nodes.

Node Usage, this metric is used to control the power usage of a certain node when executing a workload on it. Node usage will mainly be used in the EX_Monitoring_1 and EX_Monitoring_2.

Node Productivity is used in the EX_Monitoring_1 and EX_Monitoring_2 displaying the amount of effective energy used in one node when an application workload is being executed.

Node Cooling index provides information about the temperature relation of the CPU node along the time having into account the maximum and minimum

execution temperature. The metric will be displayed in the web interface in the scenarios EX_Monitoring_1 and EX_Monitoring_2.

Maximum & mean heat dissipation, this metric is calculated after measuring the upper ones and is used in the EX_Monitoring_2, offering a relationship on the heat dissipation and the workload of the node during a certain period of time.

7.4.2 Selected metrics for the assessment of workload simulation results

The workload simulations scenarios according to D6.1 deliverable will include 2 main scenarios:

- SIM_DC1: Application workload simulation
- SIM_DC2: Capacity management

Opposite to the physical testbed scenarios in which measurements are taken from real sensors, calculation of metrics in simulation scenarios will be based on simulated measurements. To perform SIM_DC1 and SIM_DC2 the Data Centre Workload and Resource Management Simulator (DCWoRMS) will be used. Therefore, measurements needed to calculate metrics will be based on approximated computational models without Computational Fluid Dynamics (CFD) computations. The measurements that can be simulated by DCWoRMS are summarized in Table 7-5.

The following metrics have been selected to be used in workload simulation scenarios:

Resource usage metrics (Server Usage, Network Usage, Memory Usage, Storage Usage, I/O Device Usage) will be used in both SIM_DC1 and SIM_DC2 scenarios to evaluate resource utilisation of hardware. Estimations of these values will come from DCWoRMS simulations of workloads with specific application profiles.

Node usage will provide information about power consumption of computing nodes in SIM_DC1 and SIM_DC2 scenarios. Power usage in time will be estimated by DCWoRMS based on power profiles of simulated hardware and given workloads.

Node, Rack, and Data Centre Productivity will allow evaluating the amount of useful work to consumed energy for a given hardware configuration in SIM_DC2. Energy will be calculated based on power usage history as said above for Node usage calculation. Useful work will be estimated using estimated performance indicators which will be selected in specific trials defined in D6.2. These indicators may include throughput, numbers of specific application iterations and others.

Heat-aware metrics (Node Cooling Index and Maximum and mean heat dissipation for Node; Node-Group Cooling Index, Imbalance of temperature of CPUs and Imbalance of heat generation of Nodes for Node-Group; Rack

Cooling Index for Racks) can assess heat processes for given hardware configurations caused by specific workloads and/or workload management policies in SIM_DC2. To estimate them without CFD use, DCWoRMS calculates dissipated heat based on power usage and temperatures using simplified thermodynamics models (built based on experiments on real hardware).

PUE and **DCiE** (defined in section 4.4.2) will be used in SIM_DC1 and SIM_DC2. In scope of CoolEmAll we simulate, in addition to IT infrastructure also power consumption of other devices such as HVAC, PDUs, UPS. DCWoRMS will be able to include estimations of power usage of these devices in a total DC power usage based on their description in DEBBs and simplified models (either constant or simple dependencies of heat dissipation and power – in the case of HVAC).

PUE-scalability and **FVER** will help to assess data centre's power usage in relation to its load (one of the key CoolEmAll goals). Measurements can be obtained in similar way as for PUE calculation taking power usage history for various workloads from DCWoRMS.

7.4.3 Selected metrics for the assessment of CFD simulation results:

In scope of definition of CFD based optimisation scenarios in D6.1, we defined 4 scenarios:

- SIM_CFD_1: Server room optimisation by simulation with rearrangement of ComputeBox1
- SIM_CFD_2: Server room optimisation by simulation with change of cooling
- SIM_CFD_3: Free cooling on server room
- SIM_CFD_4: Simulation within RECS

Selected Metrics and Measurements defined in Table 7-6 and Table 7-7 to be used in particular scenarios are explained below:

Rack Cooling Index (defined in section 4.3.4) is used by SIM_CFD1, SIM_CFD2 and SIM_CFD3 to indicate how effectively the racks are cooled. It uses average Temperature-values on inlets and outlets of each rack. These values are provided by CFD simulation and are stored in the Database. The calculation of this metric is proved by metrics calculator.

Node-Group Cooling (defined in section 4.2.4) is used by SIM_CFD4 to indicate how effectively Node-Group (RECS) is cooled. It uses average Temperature-values at Node-Group (RECS) intakes. These values are provide by CFD simulation and are stored in the Database. The calculation of this metric is proved by metrics calculator.

Imbalance of heat generation of Nodes (defined in section 4.2.4) is used by SIM_CFD4 to indicate problems (heat generation imbalance) at the scheduling level. It uses min, max and average power-usage-values for each/all Node(s) of a

RECS. These values are provided by DCWorms simulation and are stored in the Database. The calculation of this metric is provided by metrics calculator.

PUE (Power Usage Effectiveness) (defined in section 4.4.2) used by SIM_CFD1..3 is defined as a ratio between power-usage of entire data centre and power-usage of IT infrastructure. In scope of CoolEmAll we simulate, in addition to IT infrastructure (racks) also power consumption of HVAC, enabling to calculate the power-usage of the entire data centre as a sum of HVAC power-usage and power-usage of racks. The power-usage values are provided by DCWorms and are stored in the Database. The calculation of PUE is done by metrics calculator.

DCiE and PUE-scalability are calculated as defined in section 4.4.2, used by SIM_CFD1..3. The calculation of these metrics are based on IT-Power-usage and DC-Power-usage. Measurements can be obtained in similar way as for PUE calculation.

Imbalance of temperature of Racks (defined in section 4.4.4) used by SIM_CFD1..3 can help to identify hotspots and air recirculation problems. It uses min, max and average temperature-values on outlets of each rack - these values are provided by CFD simulation and are stored in the Database. The calculation of this metric is provided by metrics calculator.

Imbalance of heat generation of Racks (defined in section 4.4.4) used by SIM_CFD1..3 can help to identify reason for imbalance of the temperature of the Racks in the Data centre, i.e. result of bad scheduling policy. It uses min, max and actual heat/power-values generated by racks - these values are provided by DCWorms simulation and are stored in the Database. The calculation of this metric is provided by metrics calculator.

8 Conclusions

The present White Paper has provided an extensive overview of the existing metrics that are today present on literature and on industry practices. The report has intensified the efforts on metrics classification considering the boundaries of data centre and different levels of granularity inside it. Furthermore, an extensive explanation about how to calculate it with a clear definition of formula has been reported.

The levels of granularity treated are the following:

- Node level
- Node-group level
- Rack level
- Data centre level

The metrics have been classified according the following concepts:

- Resource Usage metrics
- Energy metrics
 - Power-based metrics
 - Energy-based metrics
 - Heat-aware metrics
- Green metrics
- Financial metrics

The present report has focused on three different objectives. For each one, the conclusions are summarized below.

a) Collecting existing metrics

In that sense, a widely analysis of literature and accurate analysis of existing metrics has been done, according the classification above mentioned. Selection of metrics has been carried out to provide metrics that are comprehensive, simple measurable, and suitable for comparison and representation. Also, redundancy between metrics has been avoided.

b) Useful metrics for CoolEmAll objectives

The CoolEmAll project is focussed in optimization of energy efficiency and heat-aware knowledge inside the minimum levels of them, node, node-groups or rack level. The project combines specific design of data centres with monitoring and simulation tools to reach optimal designs and performance. In

that sense, specific metrics for CoolEmAll objectives have been incorporated in this deliverable.

The contents of this White Paper will be used to reach the aim of CoolEmAll about quantification of heat-aware and energy efficiency of data centres, focused on the dynamic performance (energy approach instead of power approach) and of the knowledge about the influence of temperature and heat distribution inside data centre over the IT productivity and total energy consumption.

At the end of the project, based on experience acquired through the Validation Scenarios (experimental and simulated practices described on D6.1 of WP6 [66]) some of the proposed metrics will be tested and validated and some of them will be refined in definition and scope. Finally, the results in metrics knowledge through CoolEmAll development, could contribute with the present activities of standardization bodies and industry/research groups or associations.

- c) Analysis of metrics widely used by industry: analysis of existing gaps and state of metrics standardisation

The project has also attempted to consider the full range of different users (planners, operators, researchers), organisation types (enterprise, multi-tenant, HPC, cloud, research facility) and facilities designs (bespoke, pre-fabricated, container) encompassed by the term data centre. These various potential users and their requirements are explored more thoroughly in other Work Package deliverables (WP6 and WP7) of CoolEmAll but it is important to consider what these very different data centre types may require from existing and new metrics rather than to think in purely theoretical terms.

For instance, regarding to PUE, as a metric widely used in industry, this White Paper have developed an analysis of the effect of only using this metric in evaluating the energy efficiency of data centre and the related gaps. The combination with other metrics is proposed to get a more complete vision and to improve the existing gaps.

The metrics are subject to standardisation. To this objective, several groups are endorsing not only PUE but other metrics like Global KPI, DPPE, CUE, WUE, ERF or GEC as future standards. The paper has exposed the latest activities in this field and the most important agents in the development of the standards process.

Future CoolEmAll-WP5 deliverables will aim to integrate more closely with the use cases, market assessment and standardisation tasks in WP6 and WP7. The aim is to include existing metrics, and propose new metrics, for use in the project outcomes that are not only worthy from a research perspective but also commercially viable/acceptable.

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10 List of abbreviations

AC	Alternative Current
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
CAPEX	Capital Expenditure
CEF	Carbon Emission Factor
CEF	Carbon Intensity Factor
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
CPU	Central Processing Unit
CRAC	Computer Room Air Conditioner
CRAH	Computer Room Handler
CUE	Carbon Usage Effectiveness
DC	Direct Current
DCD	Data Centre Density
DCiE	Data Centre infrastructure Efficiency
DCU	Data Centre Utilisation
DEBB	Data centre Efficiency Building Block
DH-UR	Deployed Hardware Utilisation Ratio
EER	Energy Efficiency Ratio
ERE	Energy Reuse Effectiveness
FLOPS	Floating-point Operations per Second
FVER	Fixed to Variable Energy Ratio
GAMES	Green Active Management of Energy in IT Service centres
GEC	Green Energy Coefficient
GPI	Green Performance Indicators
HPC	High Performance Computing
HVAC	Heating, Ventilation and Air-Conditioning
I/O	Input / Output
IOPS	Input / Output operations per second

KPI	Key Performance Indicators
OPEX	Operating Expenditure
PDU	Power Distribution Unit
PSU	Power Supply Unit
PUE	Power Usage Effectiveness
PV	Photovoltaic
RCI	Rack Cooling Index
RES	Renewable Energy Source
ROI	Return Of Investment
SEER	Seasonal Energy Efficiency Ratio
SLA	Service Level Agreement
SWaP	Space, Watts and Performance
TCO	Total Cost of Ownership
UPS	Uninterruptable Power System
WP	Work Package
WUE	Water Usage Effectiveness