



HAL
open science

CoolEmAll D5.6 Final metrics and benchmarks

Laura Siso, Jaume Salom, Eduard Oro, Georges da Costa, Thomas Zilio

► **To cite this version:**

Laura Siso, Jaume Salom, Eduard Oro, Georges da Costa, Thomas Zilio. CoolEmAll D5.6 Final metrics and benchmarks. [Research Report] IRIT-Institut de recherche en informatique de Toulouse. 2014. hal-01818070

HAL Id: hal-01818070

<https://hal.science/hal-01818070>

Submitted on 9 Jul 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Project acronym: **CoolEmAll**

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



D5.6 Final metrics and benchmarks

Author: Laura Sisó (IREC), Jaume Salom (IREC), Eduard Oro (IREC), Georges Da Costa (IRIT), Thomas Zilio (IRIT)

Version: 1.0

Date: 31/03/2014

Deliverable Number:	D5.6
Contractual Date of Delivery:	31/03/2014
Actual Date of Delivery:	31/03/2014
Title of Deliverable:	Final metrics and benchmarks
Dissemination Level:	Public
WP contributing to the Deliverable:	WP5
Author:	Laura Sisó (IREC), Jaume Salom (IREC), Georges Da Costa (IRIT), Thomas Zilio (IRIT)
Co-Authors:	Enric Pere Pages Montanera (ATOS)

History			
Version	Date	Author	Comments
0.1	22/07/2013	Laura Sisó (IREC)	Draft version
0.2	26/07/2013	Laura Sisó (IREC)	Draft version
0.3	10/01/2014	Laura Sisó (IREC)	Draft version
0.4	31/01/2014	Laura Sisó (IREC)	Draft version. Annex about test of metrics from experiments results
0.5	03/03/2014	Laura Sisó (IREC)	Version with metrics inputs refined
0.6	12/03/2014	Georges Da Costa (IRIT), Thomas Zilio (IRIT)	Version with benchmarks and global review
0.7	14/03/2014	Laura Sisó (IREC) Eduard Oró (IREC)	Revision of list of abbreviations Extension of references Improvement about benchmark for metrics Changes in OPEX, CAPEX and Carbon Emissions description
0.8	19/03/2014	Georges Da Costa (IRIT), Thomas Zilio (IRIT)	Version with abstract and minor changes
0.9	27/03/2014	Laura Sisó (IREC)	Version with changes suggested in

Version: 1.0



Authors: Sisó, L. & Da Costa, G.

Date: 31/03/2014

Page 2 / 96

			QR addressed
1.0	29/03/2014	Georges Da Costa (IRIT), Thomas Zilio (IRIT)	Merging contributions and integrating suggested changes

Approval		
Date	Name	Signature
25/03/2014	Philip Inglesant (451)	
31/03/2014	Ariel Oleksiak (PSNC)	

Abstract

The CoolEmAll framework can be used by designers to compare several Data Centre designs, or can be used to tune an existing Data Centre for an operator, or can be even used by scientists to investigate new optimization strategies for Data Centres. In order to assess their results and to compare different solutions, two elements are needed: 1) a set of standard benchmarks to make a comparison point and 2) metrics to allow comparison of differences in a sensible way.

This deliverable describes the ten most important metrics concerning Data Centres with a particular focus on the three metrics proposed by the project CoolEmAll: PUE4 (Power Usage Effectiveness level 4), EWR (Energy Wasted Ratio) and RCI (Rack Cooling Index). Along with those metrics, a set of seven standard benchmarks allow users to test a Data Centre using various Energy- Thermal- and Power-stimulations, in this way completing the classical Performance evaluation.

Keywords

Metrics, Benchmarks, Thermal aware Heat-aware, PUE, Rack Cooling Index, Carbon Emissions, OPEX, CAPEX

Table of Contents

1	Executive summary	11
2	Introduction.....	12
3	Final metrics selected for CoolEmAll.....	14
3.1	Node level.....	14
3.2	Node group level.....	18
3.3	Rack level	22
3.4	Data centre level.....	24
4	Classification of metrics in CoolEmAll SVD toolkit	32
5	Final benchmarks selected for CoolEmAll.....	38
5.1	HPC benchmarks.....	38
5.2	Cloud benchmarks.....	49
5.3	Selection of benchmarks	52
6	Conclusion.....	55
7	Annex 1. Other metrics not included in D5.6.....	56
8	Annex 2. Carbon Emission Factor and Price of Electricity	61
9	Annex 3. Test of metrics performance based on Experiments results	64
9.1	Description of experiments	64
9.2	Analysis of metrics.....	66
10	Annex 4. List of available tests in Cloud Benchmark test-sui	90
	References.....	94

Table of Tables

Table 3-1.	Advantages and disadvantages of Imbalance of CPU temperature ..	21
Table 3-2.	Thermal guidelines. ASHRAE (°C)	23
Table 3-3.	Thermal guidelines. ETSI (°C)	23
Table 4.	Cost of data centre per unit of IT power installed. Average values from market survey 2012 [451, 2012]	29

Table 4-1. Presentation of metrics in SVD CoolEmAll toolkit for test-bed experiments (I) 33

Table 4-2. Presentation of metrics in SVD CoolEmAll toolkit for test-bed experiments (II) 34

Table 4-3. Presentation of metrics in SVD CoolEmAll toolkit for simulation experiments (I) 35

Table 4-4. Presentation of metrics in SVD CoolEmAll toolkit for simulation experiments (II) 36

Table 4-5. Presentation of metrics in SVD CoolEmAll toolkit for CFD (COVISE) simulation experiments 37

Table 5-1 Benchmark resources usage 52

Table 5-2 Benchmark power-consumption 53

Table 8-1 Main Emissions Power Generation 62

Table of Figures

Figure 3-1. Example of use of node cooling index 18

Figure 2. TCO according distribution of a data centre 30

Figure 5-1 Profile of the OpenSSL speed benchmark 39

Figure 5-2 Profile of the C-ray benchark (AMD Fusion CPU) 40

Figure 5-3 Profile of the Pybench benchmark 41

Figure 5-4 Profile of the MPI ep.C.4 benchmark 42

Figure 5-5 Profile of the MemLoop benchmark 43

Figure 5-6 Profile of the ABINIT benchmark 44

Figure 5-7 Profile of the FFT-test3d benchmark (AMD Fusion CPU) 45

Figure 5-8 Profile of the Linpack 1GB benchmark (Intel i7 CPU) 46

Figure 5-9 Profile of the Linpack 3GB benchmark (Intel i7 CPU) 47

Figure 5-10 Profile of the Linpack tiny benchmark (Intel Atom CPU) 48

Figure 5-11 Profile of the TAR benchmark 49

Figure 5-12: CRAY - profile when running on INTEL with 8 cores VM 50

Figure 7-1. Node scheme. Frontal view 56

Figure 7-2. Node scheme. Top view. Black dots indicate physical sensors in testbed from which data is recorded in data-base. 57

Figure 9-1. Relation Power vs Temperature of CPU. Consolidated 50 % 66

Figure 9-2. Relation Power vs Temperature of CPU. Balancing 50 % 67

Figure 9-3. Relation Power vs Temperature of CPU. CRAY in RECS1 and in RECS 3 67

Figure 9-4. Relation Power vs Temperature of CPU. OpenSSL in RECS1 and in RECS 3 67

Figure 9-5. Relation Power vs ΔT . Consolidated 50 % 68

Figure 9-6. Relation Relation Power vs ΔT . Consolidated 50 % (detail of recs 2 and recs 3) 69

Figure 9-7. Relation Power vs ΔT . Balancing 50 % 70

Figure 9-8. Relation Power vs ΔT . Balancing 50 % (detail of RECS 2 and RECS 3) 70

Figure 9-9. Relation Power vs ΔT depending on time of operation. Consolidated 50 % in recs 1 71

Figure 9-10. Relation Power vs ΔT depending on time of operation. Balancing 50 % in recs 1. 72

Figure 9-11. IoT vs ΔT . Consolidated 50 % 73

Figure 9-12. IoT and ΔT on time. Consolidated 50 % 74

Figure 9-13. IoT referred to 100°C vs ΔT . Consolidated 50 % 75

Figure 9-14. IoT referred to 100°C and ΔT on time. Consolidated 50 % 75

Figure 9-15. IoT referred to 100°C vs ΔT . Balancing 50 % 76

Figure 9-16. IoT referred to 100°C and ΔT on time. Balancing 50 % 76

Figure 9-17. Power divided by output-input air temperatures difference. Consolidated 50 % 77

Figure 9-18. Power divided by output-input air temperatures difference. Balancing 50% 78

Figure 9-19. CPU Temperature and power executing C-ray on recs 1. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3 79

Figure 9-20. CPU Temperature and power executing C-ray on recs 2. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3 80

Figure 9-21. CPU Temperature and power executing C-ray on recs 3. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3 81

Figure 9-22. Imbalance of Temperature or CPU C-ray on recs 1 (a) recs 2 (b) recs 3 (c) and Imbalance of Temperature of CPU referred to 100 °C (d) recs 1 (e) recs 2 (f) recs 3 82

Figure 9-23. CPU Temperature and power executing Open SSL on recs 1. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3 83

Figure 9-24. CPU Temperature and power executing Open SSL on recs 2. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3 84

Figure 9-25. CPU Temperature and power executing Open SSL on recs 3. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3 85

Figure 9-26. Imbalance of Temperature or CPU Open SSL on recs 1 (a) recs 2 (b) recs 3 (c) and Imbalance of Temperature of CPU referred to 100 °C (d) recs 1 (e) recs 2 (f) recs 3..... 86

Figure 9-27. Temperature of CPU of (a) C-ray, (b) OpenSSL, (c) Netloopback and (d) StressCPU on Cloud 88

Figure 9-28. Imbalance of Temperature of CPU (a) OpenSSL and Netloopback, (b) C-ray and StressCPU on Cloud. Imbalance of Temperature of CPU referred to 100°C (c) OpenSSL and Netloopback, (d) C-ray and StressCPU on Cloud ... 89

List of abbreviations

ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
CAPEX	Capital Expenditure
CEF	Carbon Emission Factor
CFD	Computational Fluid Dynamics
COVISE	Collaborative Visualisation and Simulation Environment
CPU	Central Processing Unit
CRAC	Computer Room Air Conditioner
CRAH	Computer Room Handler
CUE	Carbon Usage Effectiveness
DC	Data Centre
DCiE	Data Centre infrastructure Efficiency
DEBB	Data centre Efficiency Building Block
DH-UR	Deployed Hardware Utilisation Ratio
EER	Energy Efficiency Ratio. Relation between cold produced and power consumed in vapor compression chiller
EP	Embarrassingly Parallel (benchmark)
FLOPS	Floating-point Operations per Second
FVER	Fixed to Variable Energy Ratio
GUI	Graphical User Interface
HPC	High Performance Computing

I/O	Input / Output
kW	kilowatt (capacity unit)
kWh	kilowatt hour (energy unit, 1kW for 1 hour)
OPEX	Operating Expenditure
PDU	Power Distribution Unit
PSU	Power Supply Unit
PUE	Power Usage Effectiveness
RECS	Resource Efficient Cluster Server
RCI	Rack Cooling Index
ROI	Return Of Investment
SVD	Simulation Visualisation and Decision support toolkit
SWaP	Space, Watts and Performance
UPS	Uninterruptable Power System
W	Watt

1 Executive summary

The CoolEmAll framework can be used by designers to compare several Data Center designs, or can be used to tune an existing Data Center by an operator or by scientists to investigate new optimization strategies for Data Centers. In order to assess the results and to compare different solutions, two elements are needed: 1) a set of standard benchmarks to make a comparison point and 2) metrics to allow comparison of differences in a sensible way.

The following list collects **the 10 most relevant key metrics** used in the CoolEmAll SVD toolkit to assess energy efficiency in data centres and reduction in carbon emissions. In bold are the three new metrics proposed in the framework of CoolEmAll.

1. E_{DC}	Total Energy Consumption
2. PUE_3	<i>Power Usage Effectiveness – level 3</i>
3. PUE_4	<i>Power Usage Effectiveness – level 4</i>
4. EWR	<i>Energy Wasted Ratio</i>
5. $Prod$	<i>Productivity</i>
6. $RCI_{LO,HI}$	<i>Rack Cooling Index (in CFD visualization)</i>
7. IoT	<i>Imbalance of CPU temperature (in test-bed experiments)</i>
8. $CAPEX$	<i>Capital Expenditure</i>
9. $OPEX$	<i>Operation Expenditure or Electricity Costs</i>
10. CO_2	<i>Carbon Emissions (embedded and power consumption)</i>

The associated benchmarks are the following:

1. EP
2. $CpuBurn$
3. IS
4. $LoopMemory$
5. tar
6. $test3d$
7. CG

These benchmarks present a different profile of resource consumption while having the same power- or thermal-impact or present different resource consumption profiles while having different power- or thermal-impact in order to guarantee a maximum coverage. All resources (CPU, Network, Memory, Cache, Disk) are also stressed in a maximum number of combinations to achieve a maximum coverage also from the point of view of resources.

2 Introduction

This deliverable provides the description of selected metrics and benchmarks to assess the energy efficiency of IT infrastructures with the CoolEmAll SVD toolkit.

A detailed analysis of metrics literature has been already done in deliverable D5.1 of CoolEmAll Project [D5.1]. Also in this former report a classification of metrics was defined under two different approaches:

- a) Level of granularity of IT infrastructures
- b) Physical concepts assessed

Depending of the level of granularity of IT infrastructures the metrics are defined for:

- **Node unit:** the smallest element of a data centre to be modelled. This unit reflects a single computing node, e.g. a single blade CPU module with its integrated cooling device.
- **Node group:** reflects an assembled unit of node units, e.g. a complete blade centre or a rack unit consisting of 18 server nodes.
- **Rack level:** reflects the well-known element within an IT service centre, including blocks of node groups and power supply units.
- **Data centre** is considered as assembled units of rack level, e.g. reflecting a container filled with racks or even complete compute rooms, with the corresponding CRAC/CRAH (Compute Room Air Conditioner or Air-Handling Unit), chiller, power distribution units, lighting and other auxiliary facilities.

Depending of physical concepts assessed the metrics are defined according the following list:

- **Resource usage metrics:** it refers to the ratio of utilisation as the consumption of a particular resource divided by the total amount of that resource concerning a component or set of components.
- **Energy metrics:** includes metrics addressed to the energy impact of IT use.
 - **Capacity-based metrics:** metrics related to peak conditions
 - **Energy-based metrics:** metrics related to power along a period of time
 - **Heat-aware metrics:** metrics related with temperature and heat-dissipation impact.

- **Green metrics:** these describe the impact of the operation of a data centre in the natural environment.
- **Financial metrics:** these describe the economic impact of the operation of a data centre in a business organisation.

The final selection of metrics for CoolEmAll has been based on the assessment of several metrics initially selected with experiments on test-bed and simulations.

Concerning benchmarks, a first evaluation of several benchmarks was done in D5.5 (Energy- and Heat-aware benchmarks) based on the classification and monitoring techniques described in D5.4 (White paper on Energy- and Heat-aware classification of application). In order to evaluate the metrics in a reproducible way, a standard set of benchmarks is needed. Using all the classical benchmark and profiling their resource consumption lead us to select seven of them (EP, CpuBurn, IS, LoopMemory, tar, test3d and CG) as a minimalistic set. Those benchmark have been selected to provide a wide coverage of:

- **Resource consumption:** such as CPU, network, memory, disk
- **Power consumption:** Similar application can consume different amount of power
- **Thermal impact:** Using the profile of power consumption over the lifetime of a benchmark, it is possible to assess its thermal impact.

The final selection of benchmarks for CoolEmAll has been the result of runs of a large variety of benchmarks on the testbed and has fed the simulation by providing not only a set of benchmarks but also the profile of those benchmarks.

Section 1 contains an Executive Summary with most relevant achievements on metrics and benchmark of IT reached in CoolEmAll. Section 3 contains a detailed description of selected metrics. Section 4 is focused in the presentation of metrics for an end-user of SVD CoolEmAll toolkit on Web-GUI. In Section 5 the selected benchmarks are explained. Finally some conclusions about the work carried out are presented.

3 Final metrics selected for CoolEmAll

In this section useful metrics implemented in CoolEmAll are described and classified according the criteria previously described.

3.1 Node level

This chapter collects the metrics related to the smallest element of DC that is modelled. This unit reflects a single computing node, e.g. a single blade CPU module with its integrated cooling device.

3.1.1 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. It is measured by evaluating how much CPU allocated to a process is used by a process over a given time interval.

The metric definition is based on [JIANG,2010].

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

Metric	Typical	Maximum from real cases	Maximum
CPU Usage	0.10-0.15 0.20-0.30 (cloud)	0.50	1.0

Reference for the benchmark of CPU usage has been obtained from [VASAN, 2009] and [McMILLAN, 2014]

2) Server Usage / Load

Server Usage reflects utilisation level of a server and it is computed as follows:

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

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.

In the simulations experiments carried out with SVD CoolEmAll toolkit, this metric is named Load. It has to be noted that for an overloaded server, load can be over 1.

The definition is based on [TGG,2008]. The next table shows a benchmarking of this metric according the mentioned reference.

Metric	Theoretical	Target	Average
Server Usage	1.0	0.80	0.15

3) Network Usage

Network Usage measures the bandwidth used relative to the bandwidth capacity.

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

It is obtained as a direct measurement from desktop computers, laptops and also servers.

The definition is based on [TGG,2008]. The next table shows a benchmarking of this metric according the mentioned reference.

Metric	Theoretical	Target	Average
Network Usage	1.0	0.80	0.10

4) Memory Usage

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.

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

Memory Usage is a good indicator of electronic energy usage even if it is not a direct indicator of efficiency. The Memory Usage is obtained as a direct measurement from desktop computers, laptops and also servers.

The definition is based on [TGG,2008]. The next table shows a benchmarking of this metric according the mentioned reference.

Metric	Theoretical	Target	Average
Memory Usage	1.0	0.70	0.35

3.1.2 Capacity-based metrics

1) Node Power Usage

This metric can be defined as the ratio of the power used by the node and the rated power usage of the Node.

$$NodePowerUsage = \frac{P_{node} [W]}{P_{node,maximum} [W]} = [\emptyset] \quad \text{Eq. 5}$$

Where,

P_{node} corresponds to power (electricity) consumed by a certain node

$P_{node,rated}$ is the rated power (electricity) consumed by the node according to the manufacturer's specifications.

3.1.3 Energy-based metrics

1) Node Energy

E_{node} is the power consumed by the node during a given period of time.

$$E_{node} = P_{node} \cdot time = [Wh] \quad \text{Eq. 6}$$

2) Node Productivity

Productivity can be calculated as the ratio of the measurable produced work over the energy consumed by the node, aggregated in a given period of time. The units of useful work depend on the type of service provided.

$$Productivity_{node} = \frac{W_{node}}{E_{node}} = \left[\frac{\text{units of useful work}}{Wh} \right] \quad \text{Eq. 7}$$

Where,

E_{node} is the power consumed by the node during a given period of time.

W_{node} is the useful work produced by the node; its value depends of the services provided for instance, on HPC environments is measured in FLOPS and in the Cloud is measured in number of service invocations and in general-purpose services is measured in number of transactions.

3.1.4 Heat-aware metrics

1) Node Cooling Index

Node Cooling Index are two metrics that aim to assess the appropriate performance of the CPU considering the ratio of compliance of the temperature of the CPU taking into account the thresholds declared by the manufacturer of the CPU. This is defined by the following formula:

$$NCI_{node,LO} = \frac{T_{CPU}}{T_{CPU,min-all}} = [\emptyset] \quad \text{Eq. 8}$$

$$NCI_{node,HI} = \frac{T_{CPU}}{T_{CPU,max-all}} = [\emptyset] \quad \text{Eq. 9}$$

Where,

T_{CPU} is the temperature of the CPU. In test bed of CoolEall there are four cores sensors; this can be calculated as the average of those sensors.

$T_{CPU,min-all}$ 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 3-1. In case 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. The interest of the metrics is on detecting these points ($NCI_{HI} > 1$; $NCI_{LO} < 1$) in a certain time-stamps of the whole period of time.

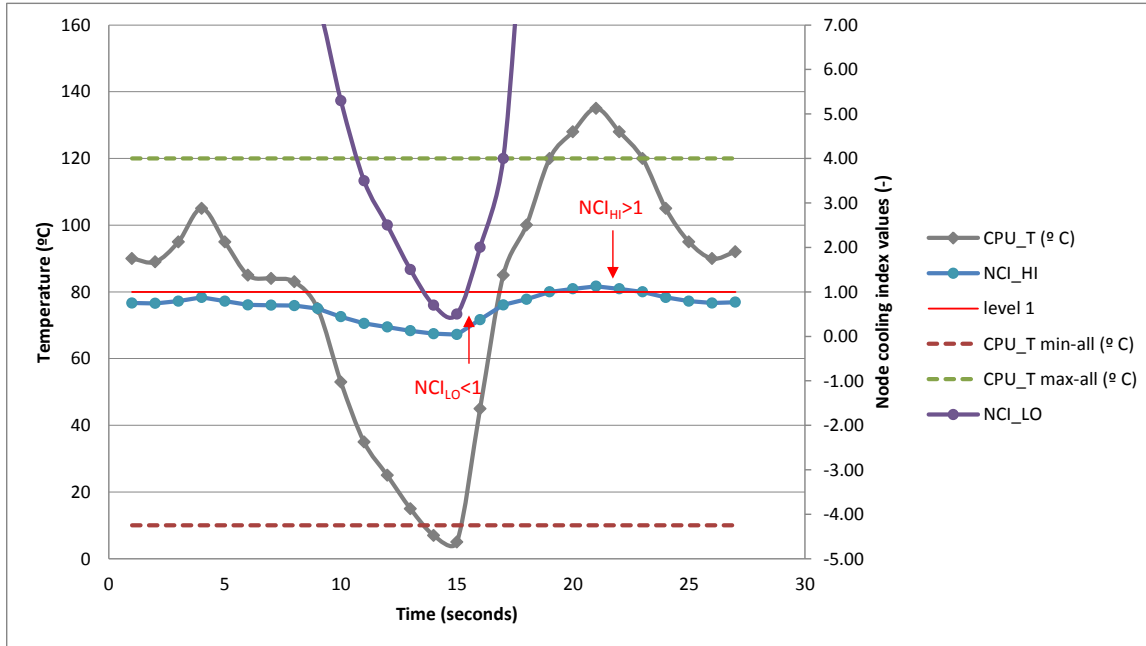


Figure 3-1. Example of use of node cooling index

The next table shows a benchmarking of this metric according the definition above.

Metric	Normal operation	Operation out of the limits
NCI _{HI}	<1	>1
NCI _{LO}	>1	<1

3.2 Node group level

The node group reflects an assembled unit of node units, e.g. a complete blade centre or a rack unit consisting of 18 server nodes. This section collects the metrics related to this level of analysis

3.2.1 Resource usage

1) DH-UR: Deployed Hardware Utilisation Ratio

This metric reflects in what degree hardware is used during a “normal” period of time.

$$DH - UR = \frac{N_{node-useful}}{N} = [\emptyset] \tag{Eq. 10}$$

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. 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. Efficient deployments would intend to have $DH-UR$ as close to 1 as possible.

The metric definition is based on [JIANG,2010].

3.2.2 Capacity-based metrics

1) SWaP: Space, Watts and Performance

In order to allow a comparison of several IT server configurations, the SWaP indicator was defined which takes space occupation, rated power usage and rated performance of a singles server into account. It is calculated as follows:

$$SWaP = \frac{W_{NG,rated}}{H_{NG} * P_{NG,rated}} = \left[\frac{\text{units of useful work}}{\text{number } U * W} \right] \quad \text{Eq. 11}$$

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 variable indicator due to it is fixed for each server, but once assigned it can help data centre operators for servers' collocation or reorganization.

The metric definition is based on [JIANG,2010].

3.2.3 Energy-based

1) Node-group Energy

E_{NG} is the power consumed by the rack during a given period of time.

$$E_{NG} = \int P_{NG} \cdot \delta t = [Wh] \quad \text{Eq. 12}$$

2) Node-group Productivity

Regarding the previous definition in Eq. 7 the Productivity metric extended to node-group will be depicted as follows:

$$Productivity_{NG} = \frac{W_{NG}}{E_{NG}} = \left[\frac{\text{units of useful work}}{Wh} \right] \quad \text{Eq. 13}$$

3.2.4 Heat-aware metrics

1) Imbalance of CPU temperature (node-group)

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. 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 of all the nodes in the same time-stamp. IoT_{NG} value close to 0 indicates good temperature balance.

$$IoT_{NG} = \frac{T_{CPU,max} - T_{CPU,min}}{T_{CPU,max\ ref}} * 100 = [\%]; T_{CPU,max\ ref} = 100\text{ }^{\circ}\text{C} \quad \text{Eq. 14}$$

Where,

$T_{CPU,i}$ is the temperature of each i CPU in the node-group in a certain time-stamp.

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 in a certain time-stamp.

$T_{CPU,min}$ is the minimum temperature of the CPUs in the node-group in a certain time-stamp.

T_{CPU,max_ref} is a value of reference for maximum acceptable temperature of CPU.

Maximum value accepted for CPU depends on type of components and is different for different manufacturers. [HAYWOOD, 2012] states that CPU can operate in a range of temperatures between 10 °C and 120 °C with a maximum of 125 °C, when failure occurs. The selection of 100 °C is based on the criteria of taking a value placed in the upper range that permits comparison between technologies, without knowing the specifications of each model.

The next table shows a first proposal for benchmarking of this metric according the definition of Eq. 14, suggested by authors of this report and based on available results of executed experiments. However, one must consider that extended test of this metric and comparison with metric applied to data centres in operation will contribute to have a more reliable benchmarking.

Metric	well- balanced	average balanced	highly unbalanced
--------	----------------	------------------	-------------------

IoT	0 %	20-30 %	80 – 120 %
-----	-----	---------	------------

Imbalance of CPU temperature is a new step in the approach of defining new figures to assess the energy efficiency in data centres and particularly to provide heat-aware metrics that permit to assess the effect on thermal performance of components. However, the assessment of the metric should be extended to provide a consistent benchmarking and to identify clearly what is the relation of the metric with heat distribution, possible risky hot-spots, and consequently with cooling requirements. The following table summarizes the advantages and disadvantages of this metric that have been identified during the CoolEmAll project realization.

Table 3-1. Advantages and disadvantages of Imbalance of CPU temperature

Advantages	Disadvantages
<ul style="list-style-type: none"> • Useful to detect hot-spots beforehand • Estimated relation with cooling requirements • Easy to measure in front of other measurements to provide cooling metric (air temperature or air flow) • Applicability with DCIM 	<ul style="list-style-type: none"> • First feedback from Standardization bodies: not suitable to be standardized • Focused on a such detailed level of granularity that is out of scope of data centre operators • Metric unsuitable for designing approach since information about CPU temperature is not available. • CPU temperature is not simulated in CoolEmAll.

Improvement of the metric along CoolEmAll research activity

The Imbalance of CPU Temperature definition has been proposed in the framework of CoolEmAll project as first time. The first approach of the metric refers the difference between maximum and minimum temperatures to the average. However, the formula has been re-defined to have a fixed reference value for the metric and to permit to define a benchmarking. The former formula for Imbalance of Temperature of CPU that was proposed in deliverable D5.1 of CoolEmAll [D5.1] is the following.

$$Im_{NG,temp} = \frac{T_{CPU,max} - T_{CPU,min}}{T_{CPU,avg}} * 100 = [\%]; T_{CPU,avg} = \frac{1}{N} \sum_i^N T_{CPU,i} \quad \text{Eq. 15}$$

Detailed analysis of this metric is provided in Annex 3 based on data recorded from test bed experiments.

3.3 Rack level

This section shows the metrics defined for analysis at rack level. This level reflects the well-known element within an IT service centre, including blocks of node groups and power supply units.

3.3.1 Resource usage

1) DH-UR: Deployed Hardware Utilisation Ratio

This metric is defined at rack level in the same way as it has been presented for node-group level (see Eq. 10).

3.3.2 Energy-based

1) Rack Energy

E_{rack} is the power consumed by the rack during a given period of time.

$$E_{rack} = \int P_{rack} \cdot \delta t = [Wh] \quad \text{Eq. 16}$$

2) Rack Productivity

It is defined in the same way than the Node Productivity (Eq. 7) but applied to the Rack.

$$Productivity_{rack} = \frac{W_{rack}}{E_{rack}} = \left[\frac{\text{units of useful work}}{Wh} \right] \quad \text{Eq. 17}$$

3.3.3 Heat-aware metrics

1) Node-Group Cooling Index

It is defined in the same way as the Rack Cooling Index (Eq. 27 and Eq. 28) but applied to a group of nodes. Therefore, it is reformulated as shown in Eq. 18 and Eq. 19.

$$CI_{NG,HI} = \left[1 - \frac{\sum (T_{NG,x} - T_{max-rec})_{T_{NG,x} > T_{max-rec}}}{(T_{max-all} - T_{max-rec}) * n} \right] * 100 = [\%] \quad \text{Eq. 18}$$

$$CI_{NG,LO} = \left[1 - \frac{\sum (T_{min-rec} - T_{NG,x})_{T_{NG,x} < T_{min-rec}}}{(T_{min-rec} - T_{min-all}) * n} \right] * 100 = [\%] \quad \text{Eq. 19}$$

Where,

$T_{NG,x}$ is the node temperature at node-group air intake in a certain time-stamp.

n is the total number of air intakes.

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

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

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

$T_{min-all}$ is the minimum allowed air temperature by 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. $CI_{NG,HI}$ can be negative.
- $CI_{NG,LO} = 100\%$ All intake temperatures \geq min. recommended temperature.
- $CI_{NG,LO} < 100\%$ At least one intake temperatures $<$ min. recommended temperature. $CI_{NG,LO}$ can be negative.

Some recommended and allowed values can be the following shown in Table 3-2 and Table 3-3 .

Table 3-2. Thermal guidelines. ASHRAE (°C)

class	definition	$T_{max-rec}$	$T_{min-rec}$	$T_{max-all}$	$T_{min-all}$
A1	Typically a data center with tightly controlled environmental parameters (dew point, temperature, and relative humidity) and mission critical operations; types of products typically designed for this environment are enterprise servers and storage products.	27	18	32	15
A2	Typically an information technology space with some control of environmental parameters (dew point, temperature, and RH); types of products typically designed for this environment are volume servers, storage products, personal computers and workstations. Among these 3 classes A2 has the narrowest temperature and moisture requirements and A4 has the widest environmental requirements.	27	18	35	10
A3		27	18	5	40
A4		27	18	5	45

Table 3-3. Thermal guidelines. ETSI (°C)

Version: 1.0		Authors: Sisó, L. & Da Costa, G.
Date: 31/03/2014		Page 23 / 96

class	definition	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
		continuous operation		Class 3.1 ≤10% of operational hours		Class 3.13 ≤1% of operational hours	
3.1	Telecommunication centers, data centers, and similar en-use locations.	35	10	40	5	45	-5
3.1e	Non-condensing environment, no risk of biological or animal contamination, normal levels of airborne pollutants, insignificant vibration and shock, and the equipment not situated near a major source of sand or dust.	35	10	40	5	45	-5

2) Imbalance of CPU temperature (rack)

The imbalance of temperature of node-groups in the rack can help with the identification of hotspots and air recirculation problems within the rack.

$$IoT_{rack} = \frac{T_{CPU-NG,max} - T_{CPU-NG,min}}{T_{CPU,maxref}} * 100 = [\%]; T_{CPU,maxref} = 100\text{ }^{\circ}\text{C} \quad \text{Eq. 20}$$

Where,

$T_{CPU-NG,i}$ is the temperature of each node-group in the rack, defined as the average temperature of the CPU of the node-group in a certain time-stamp.

N is the quantity of node-groups in the rack.

$T_{CPU-NG,max}$ is the maximum temperature reached by one of the node-groups' CPU ($T_{CPU-NG,i}$) in a certain time-stamp.

$T_{CPU-NG,min}$ is the minimum temperature reached by one of the node-group' CPU ($T_{CPU-NG,i}$) in a certain time-stamp.

3.4 Data centre level

Data centre level or Room level is considered as assembled units of rack level, e.g. reflecting a container filled with racks or even complete compute rooms, with the corresponding CRAC/CRAH (Compute Room Air Conditioner or Air-Handling Unit), chiller, power distribution units, lighting and other auxiliary facilities. This section shows the metrics selected at this level of assessment.

3.4.1 Resource usage

1) DH-UR: Deployed Hardware Utilisation Ratio

This metric is defined at data centre level in the same way as it has been presented for node-group level (Eq. 10).

3.4.2 Capacity-based metrics

1) EER: Energy Efficiency Ratio

The EER is the cooling capacity divided by the power usage of the cooling system [ASH, 2012]. This indicator is provided by manufacturers of cooling machines 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.

$$EER = \frac{Q_{cooling} [W_{th}]}{P_{cooling} [W_{el}]} = [\phi] \quad \text{Eq. 21}$$

Where,

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

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

3.4.3 Energy-based metrics

1) Data centre Energy

E_{DC} is the power consumed by the rack during a given period of time, defined in the way that it is defined for rack level but extending it to data centre level (Eq. 16).

2) Data centre Productivity

It is defined in the same way that is presented for rack level (Eq. 17) but applied to the data centre level.

3) Power usage effectiveness (Level 3)

This metric was defined by The Green Grid as the relation between the power used in the whole data centre and the power used by the IT components. In [TGG, 2012] it was defined different levels of measurement of the IT power. The one closest to the IT elements (excluding UPS and PDU consumption), proposed by now, is Level 3.

$$PUE_3 = \frac{E_{DC}[Wh]}{E_{IT}[Wh]} = [\phi] \quad \text{Eq. 22}$$

The next table shows a benchmarking of this metric according the reference [VanGEET, 2011]

Metric	better	good	standard
PUE_3	1.1	1.4	2.0

4) Power usage effectiveness (Level 4)

In the framework of CoolEmAll it is proposed a new level to measure the PUE, named Level 4. In this case, the consumption of fans inside the rack and the PSU are excluded from the energy consumption in denominator. This approach allows focusing on energy used directly to perform actual IT work. However, we are aware of the difficulties to measure this metric in a real data centre. Therefore, alternative approach to proposing new levels of PUE is a definition of separate metrics.

$$PUE_4 = \frac{E_{DC}[Wh]}{E_{IT} - E_{fan-rack} - E_{PSU}[Wh]} = [\phi] \quad \text{Eq. 23}$$

5) DCiE: Data Centre Infrastructure Efficiency

This metric is the inverse of PUE. It is usually used for instantaneous values considering capacity instead of energy. In the framework of CoolEmAll it is defined considering energy values.

$$DCiE = \frac{E_{IT} [Wh]}{E_{DC} [Wh]} * 100 = [\%] \quad \text{Eq. 24}$$

The next table shows a benchmarking of this metric according to the reference [VanGEET, 2011]

Metric	better	good	standard
$DCiE$	0.9	0.7	0.5

6) Energy Wasted Ratio

This is the third new metric proposed in the framework of CoolEmAll. This metric is based on the previous knowledge of Productivity and FVER (Fixed to Variable Energy Ratio). The metric proposed tries to overcome the problem of measure the useful work that depends on the features of data centre and on the kind of

job. Additionally, it concentrated on actual energy that can be saved rather than an artificial scale. In that sense, it only measures energy depending on the status of workload, that can be useful or not.

$$EWR = \frac{E_{DC\text{-related to useless workload}} [Wh]}{E_{DC} [Wh]} * 100 = [\%] \quad \text{Eq. 25}$$

The wasted energy is an integral of wasted power in the period in question. The wasted power is calculated as a difference between actual power and an “ideal” power proportional to the load. It is defined by the equation below.

$$E_{DC\text{-related to useless workload}} = \int_{t_0}^{t_1} (P(t) - load(t) * P_{max}) dt = [Wh] \quad \text{Eq. 26}$$

The theoretical optimum value for the metric is “0”.

3.4.4 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 [Herrlin, 2005]. 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 standards and guidelines have two thresholds (minimum and maximum), there are defined two RCI indices, the low and the high.

$$RCI_{HI} = \left[1 - \frac{\sum (T_{rack,x} - T_{max-rec})_{T_{rack,x} > T_{max-rec}}}{(T_{max-all} - T_{max-rec}) * n} \right] * 100 = [\%] \quad \text{Eq. 27}$$

$$RCI_{LO} = \left[1 - \frac{\sum (T_{min-rec} - T_{rack,x})_{T_{rack,x} < T_{min-rec}}}{(T_{min-rec} - T_{min-all}) * n} \right] * 100 = [\%] \quad \text{Eq. 28}$$

Where,

$T_{rack,x}$ is the average of a certain “x” node-group temperature air intake in a certain time-stamp.

n is the total number of node-groups.

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

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

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

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

The interpretation is the following:

- $RCI_{HI} = 100\%$ All intake temperatures \leq max recommended temperature.
- $RCI_{HI} < 100\%$ At least one intake temperatures $>$ max recommended temperature. RCI_{HI} can be negative.
- $RCI_{LO} = 100\%$ All intake temperatures \geq min. recommended temperature.
- $RCI_{LO} < 100\%$ At least one intake temperatures $<$ min. recommended temperature. RCI_{LO} can be negative.

Some recommended and allowed values can be seen in Table 3-2 and Table 3-3.

The next table shows a benchmarking of this metric according [Herrlin, 2008]:

Metric	ideal	good	acceptable	poor
RCI	100 %	$\geq 96\%$	91-95 %	$\leq 90 \%$

3.4.5 Green metrics

1) Carbon Emissions

This metric is the mathematical product of the Total Data Centre Energy consumed in the data centre by the Carbon Emission Factor (CEF).

$$\text{Carbon Emissions} = E_{DC} * CEF = [kg CO_2] \quad \text{Eq. 29}$$

In Annex 2 is depicted the reference value considered in CoolEmAll for CEF according different sources. The value proposed in the Methodology Study Eco-design of Energy-using Products MEEUP [MEEUP, 2005] is 0.34 kgCO₂/kWh.

Reference value of carbon emissions associated to energy consumption in data centre sector is about 0.2 % of world total emissions, with an impact of 80 tones CO₂ per year emitted globally [FORREST, 2008].

Nowadays, the metric under discussion in the standardization bodies is *CUE*, *Carbon Usage Effectiveness*. However, direct quantification of carbon emissions is more consistent with the detailed analysis about energy improvements provided by CoolEmAll. As stated in Chapter 3.4.3 PUE₄ shows benefits not indicated by the commonly used *PUE*. Due to *CUE* is equal to $CEF \times PUE$ it has been decided to have a unique metric related to carbon emissions which shows all kind of improvement achieved by energy efficiency strategies, particularly

capacity management of workload using appropriate applications. On the other hand, the *Carbon Emissions* metric is consistent with the Euro Eco-design Directive.

2) Embedded - Carbon Emissions

Another metric provided by the SVD CoolEmAll Toolkit is the Total Life Cycle Analysis Carbon Emissions.

The end-user provides the value of associated CO₂ emissions considered in the manufacturing, exploitation and recycling process of each component. The toolkit provides the aggregated value for a certain simulation experiment.

3.4.6 Financial metrics

Financial metrics are crucial to promote the energy efficiency strategies. In the point of view of stakeholders responsible to take decisions about actions to carry out in data centres, and particularly related with implementation of measures to improve the energy use, the economic feasibility must be included as one of the main indicators. In that sense, the CoolEmAll Consortium has been considered crucial to integrate the following ones in the metric calculator: CAPEX, OPEX and ROI have been implemented.

1) CAPEX: Capital Expenditure

This is the amount of money used to acquire assets or improve the useful life of existing assets. 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.

Market survey developed by 451 Research company [451, 2012] estimates the building costs (CAPEX) for a traditional data centre and for modular data centre. Table 4 shows the values presented in US\$ per unit of capacity power installed of IT (kW) and in € (conversion used according [ECB, 2011]).

Table 4. Cost of data centre per unit of IT power installed. Average values from market survey 2012 [451, 2012]

	3.4.6.1 traditional data centre	3.4.6.2 modular data centre
3.4.6.3 US\$/kW	15 000	9 000
3.4.6.4 €/kW	10 784	6 470

On the other hand, the following distribution of Total Costs of Ownership (TCO) (Figure 2) can be considered according the study done by Schneider Electric [RASMUSSEN-2, 2011]. TCO includes capital and operation expenditure. From

the figure can be identified that nearly 50 % corresponds to capital costs (dark colours) and 50 % to operation cost (light colours).

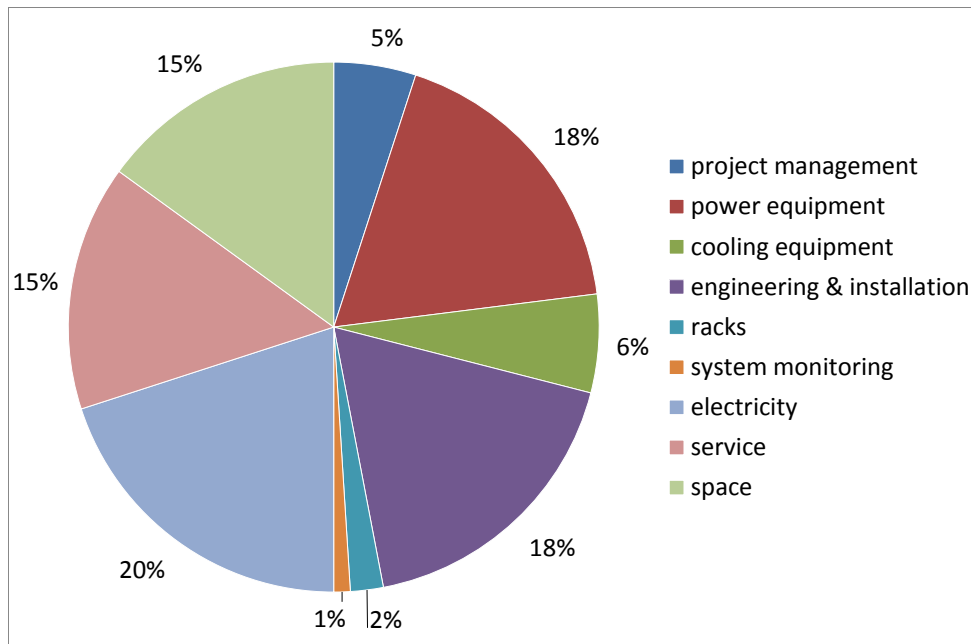


Figure 2. TCO according distribution of a data centre

2) OPEX: Operating Expenditure

OPEX or Operating Expenditure is the ongoing cost for running a product, business or system. In a data centre it includes [AT, 2010]:

- Electricity costs (or any energy source costs)
- License costs
- Maintenance costs
- Labour costs

Electricity costs, provided by the SVD CoolEmAll toolkit, are calculated according the following formula:

$$\text{Electricity costs} = E_{DC} * \text{Electricity price} = [\text{€}] \quad \text{Eq. 30}$$

In Annex 2 several references to select the appropriate electricity price are shown. In the framework of CoolEmAll, to assess the potential savings that can be reached using the CoolEmAll SVD toolkit [D6.4] it has been used 0.0942 €/kWh, based on [EUROSTAT, 2013].

According [RASMUSSEN-2, 2011] cost for electricity is around 2 000 €/year per kW of IT load installed for a traditional data centre.

3) ROI: Return of Investment

ROI is a metric that provides information about the time necessary to recover an investment considering the benefits provided by it. The metric is used to assess the efficiency of an investment or to compare different investment efficiency. A high ROI means the investment profit compare favourably to investment costs.

$$ROI = \frac{Net\ profit}{Investment} * 100 = \frac{OPEX_2 - OPEX_1}{CAPEX} = [\%] \quad \text{Eq. 31}$$

Net profit corresponds to savings in OPEX, particularly electricity costs, associated to energy efficiency measures implemented in a certain data centre.

Investment corresponds to CAPEX associated to the corresponding energy efficiency strategy to evaluate.

4 Classification of metrics in CoolEmAll SVD toolkit

This Chapter classifies the metrics presented above depending on the following factors:

- Level of granularity
- Continuous or aggregated metrics
- Provided in test-bed experiments or in simulation experiments

The level of granularity can be at node level, node-group level, rack level or data centre level. The data centre level is only available in the simulation framework.

The metrics are suitable of being calculated in continuous form or in aggregated form. Continuous metrics show the value each time-stamp and the maximum, average and minimum.

In following tables (Table 4-1 to Table 4-5 have been included the name of the metrics depicted in Chapter 3 as well as simple measurements (power, temperatures) that are also of interest on assessing the IT performance.

Table 4-1. Presentation of metrics in SVD CoolEmAll toolkit for test-bed experiments (I)

level	name	description
node	Continuous	
	<i>CPU Usage</i>	CPU usage (min, av, max)
	<i>Server Usage</i>	Server usage (min, av, max)
	<i>Network Usage</i>	Network usage (min, av, max)
	<i>Memory Usage</i>	Memory usage (min, av, max)
	<i>Node-Power-Usage</i>	Node power usage (min, av, max)
	NCl_{HI}	Node cooling index high(min, av, max)
	NCl_{LO}	Node cooling index low (min, av, max)
	P_{node}	Power used (min, av, max)
	T_{CPU}	Temperature of CPU (min, av, max)
	T_{in}	Air inlet temperature (min, av, max)
	T_{out}	Air outlet temperature (min, av, max)
	Aggregated	
	E_{node}	Total power used (energy)
	<i>Node Productivity</i>	Productivity of the node

Table 4-2. Presentation of metrics in SVD CoolEmAll toolkit for test-bed experiments (II)

level	name	description
node-group	Continuous	
	IoT_{NG}	Imbalance of CPU temperature (min, av, max)
	Aggregated	
	E_{NG}	Total power used (energy)
	$DH-UR$	Deployed hardware utilisation ratio
	$SWaP$	Space Watts and Performance
	$NG\ Productivity$	Node group Productivity
rack	Continuous	
	IoT_{rack}	Imbalance of CPU temperature (min, av, max)
	Aggregated	
	E_{rack}	Total power used (energy)
	$DH-UR$	Deployed hardware utilisation ratio
	$Rack\ Productivity$	Productivity of the rack

Table 4-3. Presentation of metrics in SVD CoolEmAll toolkit for simulation experiments (I)

level	name	description
node	Continuous	
	P_{node}	Power used (min, av, max)
	<i>Load</i>	Percentage of total load (min, av, max)
	Aggregated	
	E_{node}	Total power used (energy)
	<i>Node Productivity</i>	Productivity of the node
node-group	Continuous	
	P_{node_group}	Power used (min, av, max)
	<i>Load</i>	Percentage of total load (min, av, max)
	Aggregated	
	E_{NG}	Total power used (energy)
	<i>DH-UR</i>	Deployed hardware utilisation ratio
	<i>SWaP</i>	Space Watts and Performance
	<i>NG Productivity</i>	Productivity of the node-group

Table 4-4. Presentation of metrics in SVD CoolEmAll toolkit for simulation experiments (II)

level	name	description
rack	Continuous	
	P_{rack}	Power used (min, av, max)
	$Load$	Percentage of total load (min, av, max)
	Aggregated	
	E_{rack}	Total power used (energy)
	$DH-UR$	Deployed hardware utilisation ratio
	$Rack\ Productivity$	Productivity of the rack
data centre	Continuous	
	P_{DC}	Power used (min, av, max)
	$Load$	Percentage of total load (min, av, max)
	Aggregated	
	EER	Energy Efficiency ratio (chiller)
	E_{DC}	Total power used (energy)
	$DH-UR$	Deployed hardware utilisation ratio
	$DC\ Productivity$	Productivity of the data centre
	PUE_3	Power Usage Effectiveness. Level "3"
	PUE_4	Power Usage Effectiveness. Level "4"
	$DCiE$	Data Centre Infrastructure Efficiency
	EWR	Energy wasted ratio
	$CAPEX$	Capital expenditure
	$OPEX$	Electricity costs
	CO_2	Carbon emissions (related to power consumption)
$Embedded- CO_2$	Carbon emissions (related to Life Cycle Analysis of components used in data centres)	

Table 4-5. Presentation of metrics in SVD CoolEmAll toolkit for CFD (COVISE) simulation experiments

level	name	description
rack	Time-stamp visualization	
	$CI_{NG,HI}$	Node-group cooling index high (min, av, max)
	$CI_{NG,LO}$	Node-group cooling index low (min, av, max)
	T_{out}	Node-group's air outlet temperature (max)
data centre	Time-stamp visualization	
	$RCI_{,HI}$	Rack cooling Index high (min, av, max)
	$RCI_{,LO}$	Rack cooling Index low (min, av, max)
	T_{out}	Racks' air outlet temperature (max)

5 Final benchmarks selected for CoolEmAll

This benchmarks selection is composed of 15 HPC benchmarks and ___3 cloud benchmarks used for evaluation purposes for the CoolEmAll infrastructure, middleware and proposed metrics related to power, energy and heat.

As we are interested in the benchmarks impact on resource consumption, the rationale behind the choice of benchmarks were to test a variety of different behavior. From past experience we already knew that impact on resources were less depending on the field (being HPC or Cloud) than on the exact benchmark. The main difference is for low level of loads which can be attained by cloud benchmarks but rarely by HPC one as shown below.

The selected benchmarks below represents a large coverage of classical benchmark from micro-benchmark (MemLoop) to full-blown applications (ABINIT or test3d) passing by functional benchmarks (Fourrier Transform, LU transform).

5.1 HPC benchmarks

The HPC benchmarks selection includes the following benchmarks:

Benchmark name	License / Website	Description
Open-SSL	Apache-style licence - https://www.openssl.org	5.1.1
C-ray	http://openbenchmarking.org/test/pts/c-ray	5.1.2
Pybench	http://svn.python.org/projects/python/trunk/Tools/pybench	5.1.3
MPI ep.C.4	New BSD license - https://www.open-mpi.org	5.1.4
MemLoop	Internally developed	5.1.5
ABINIT	GPL - http://www.abinit.org	5.1.6
FFTE – test3d	http://www.ffte.jp	5.1.7
Intel Optimized LINPACK benchmark	http://software.intel.com/en-us/articles/intel-math-kernel-library-linpack-download	5.1.8

TAR (bzip2)	http://www.bzip.org	5.1.9
-------------	---	-------

5.1.1 OpenSSL

The OpenSSL Project [OSSL] is a collaborative effort to develop a robust, commercial-grade, full-featured, and Open Source toolkit implementing the Secure Sockets Layer (SSL v2/v3) and Transport Layer Security (TLS v1) protocols as well as a full-strength general purpose cryptography library. The openssl application that ships with the OpenSSL libraries can perform a wide range of crypto operations and can be used as a benchmark for processors and memory. As a benchmark, it tests the signing and decoding of messages using several cryptographic algorithms such as MD5, SHA1, RSA and others.

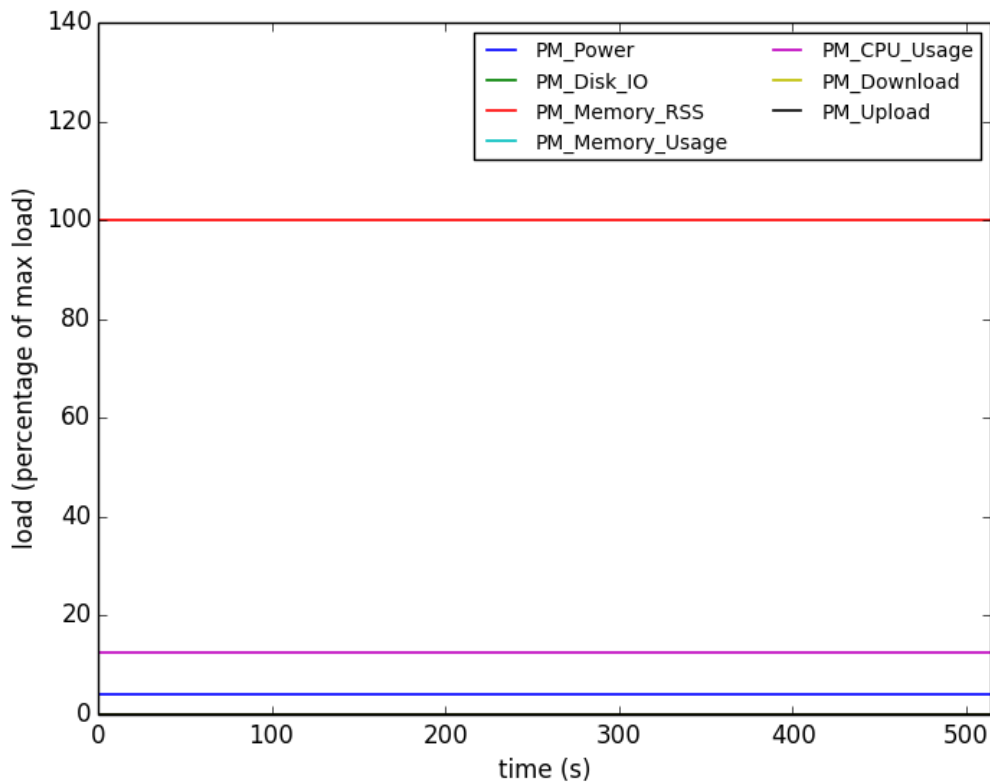


Figure 5-1 Profile of the OpenSSL speed benchmark

5.1.2 C-ray

This is a simple ray-tracing benchmark [CRAY], usually involving only a small amount of data. This software measures floating-point CPU performance. The test is configured with a significantly big scene, requiring about 60 seconds of computation but the resulting image is written to /dev/null to avoid the disk overhead.

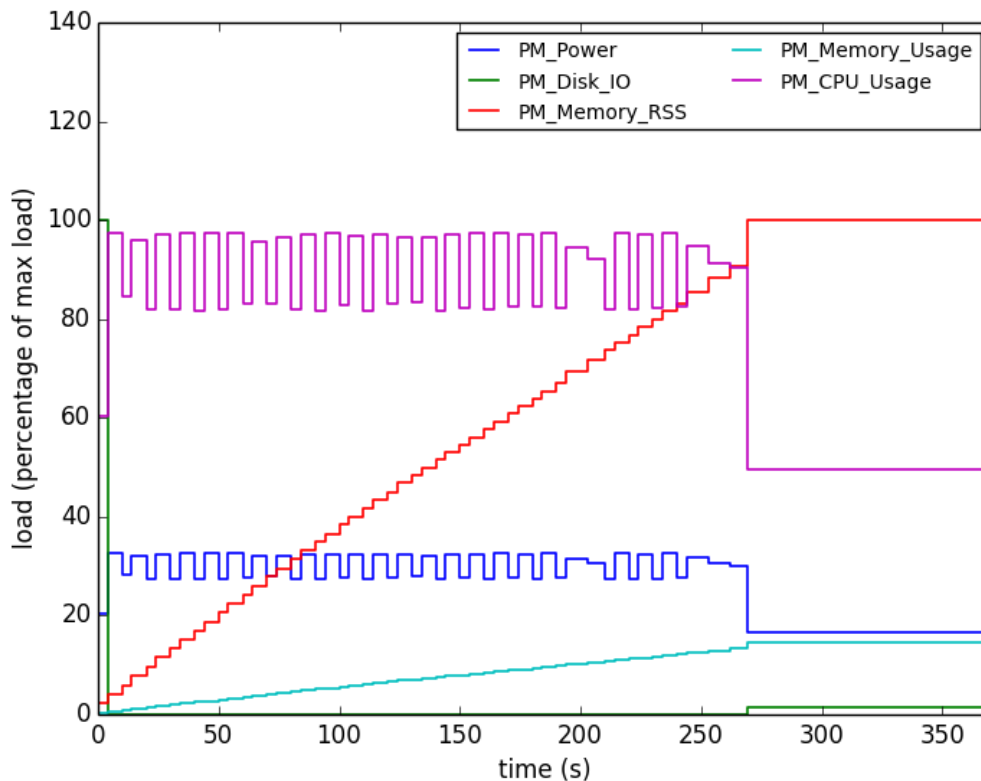


Figure 5-2 Profile of the C-ray benchmark (AMD Fusion CPU)

5.1.3 Pybench

It offers a standardized way to measure the performance of Python implementations. In the past it has been used to track down performance bottlenecks or to demonstrate the impact of optimization and new features in Python. In contrast to the other benchmarks, it was run on one core only to test the power profile of servers running single-threaded applications.

Pybench is a single-threaded application; it therefore places much smaller load on the processor.

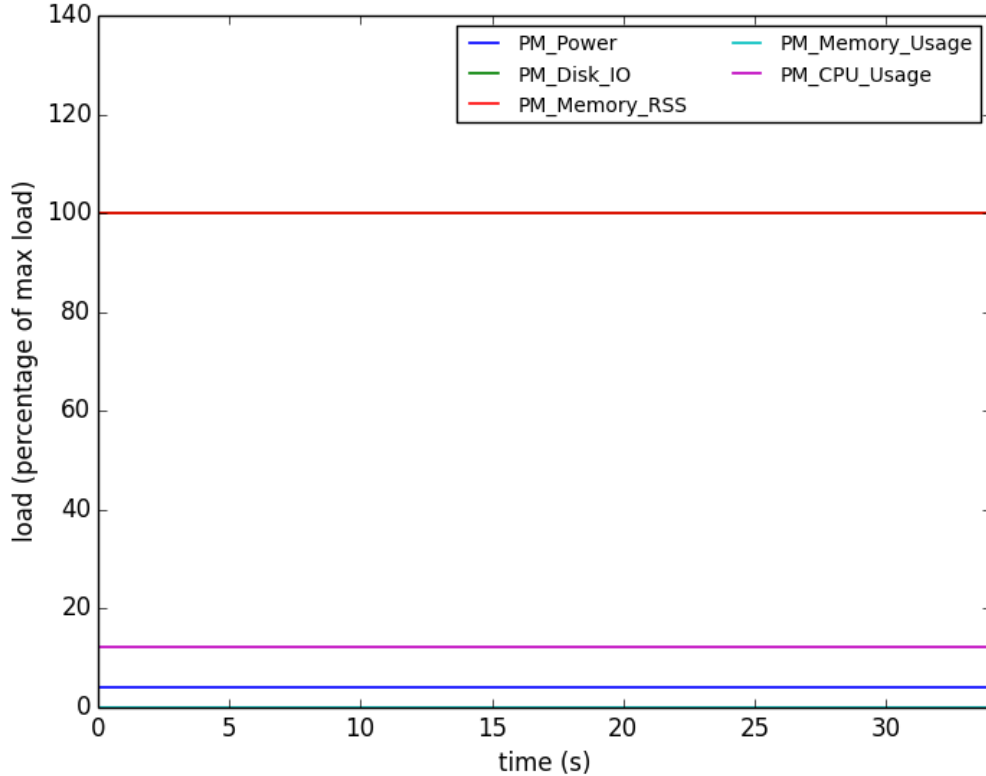


Figure 5-3 Profile of the Pybench benchmark

5.1.4 MPI ep.C.4

This application is included in the Nas Parallel Benchmark which is one of the most used HPC benchmark is the NAS Parallel Benchmark suite [NPB].

This benchmark provides 7 applications (IS, FT, EP, BT, LU, CG and SP) with workloads representatives of HPC applications. They exhibit a range of behaviors between an embarrassingly parallel code (EP) to LU decomposition of matrix (LU) encompassing both computations and communications phases. Each of those applications is well described in the literature and presents well known communication and computing patterns.

EP which stands for Embarrassingly Parallel is the one described in details here but all 7 benchmarks are used in this study.

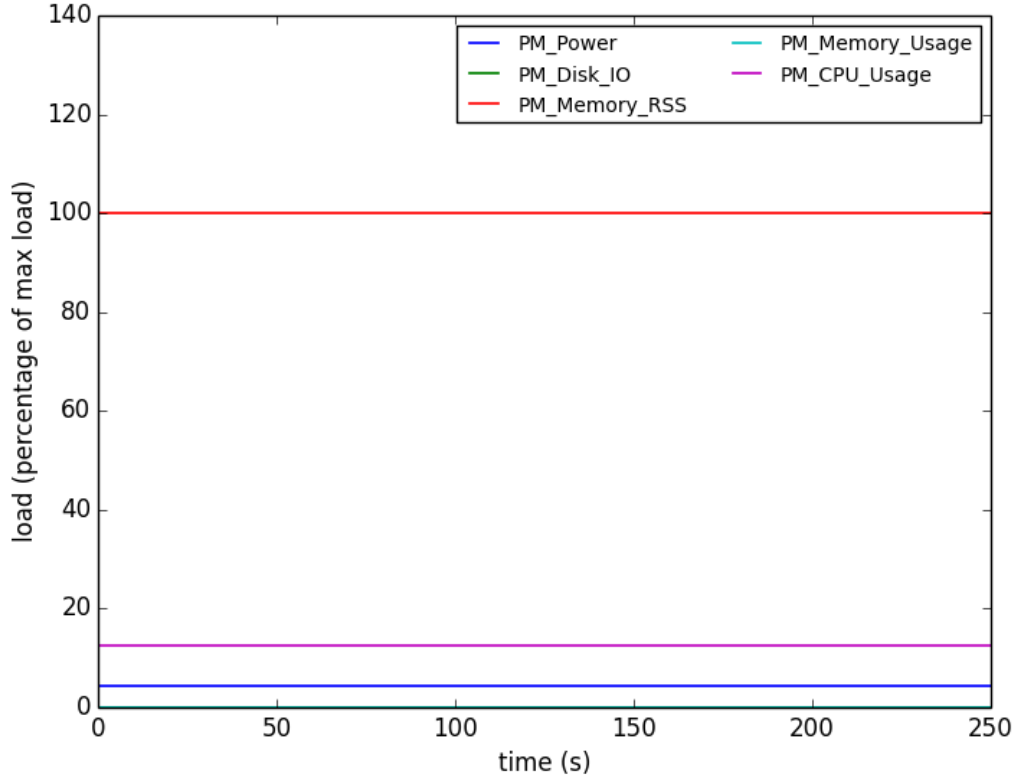


Figure 5-4 Profile of the MPI ep.C.4 benchmark

5.1.5 MemLoop

MemLoop [MEML] is a micro-benchmark used to load the memory subsystem. It can load at several levels the memory hierarchy and has been used in other projects in order to model the impact of memory accesses on node power consumption. In the current benchmark case, it is used to charge the memory at full capacity.

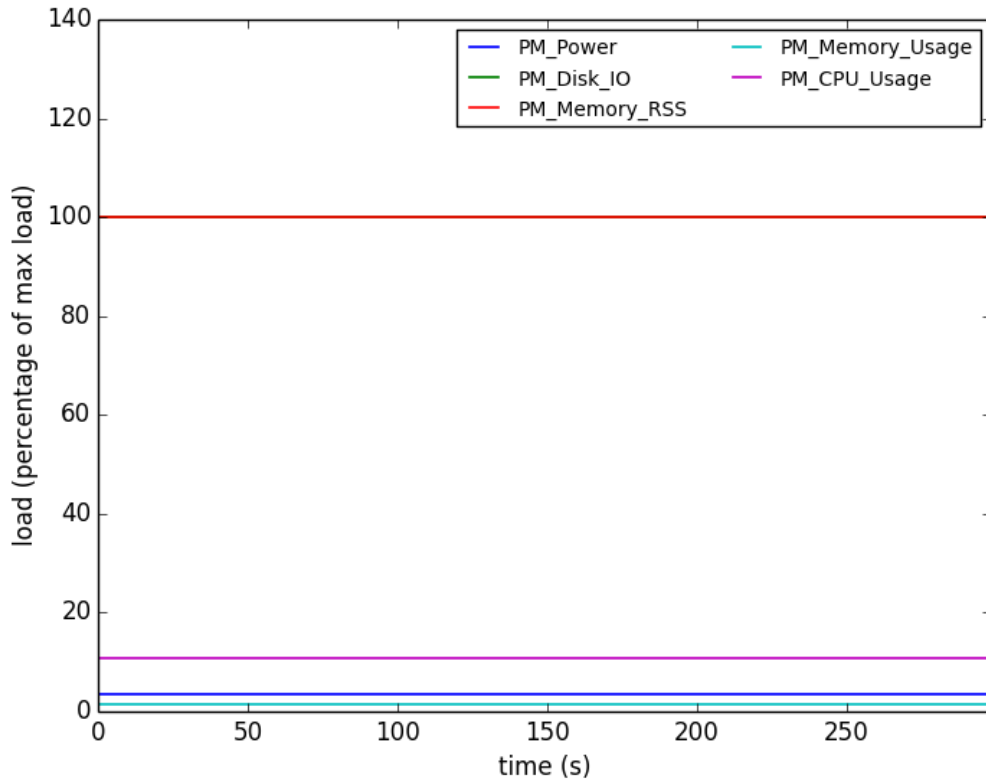


Figure 5-5 Profile of the MemLoop benchmark

5.1.6 ABINIT

ABINIT is a package whose main program allows to find the total energy, charge density and electronic structure of systems made of electrons and nuclei (molecules and periodic solids) within Density Functional Theory, using pseudopotentials and a planewave basis, or augmented plane waves, or even wavelets.

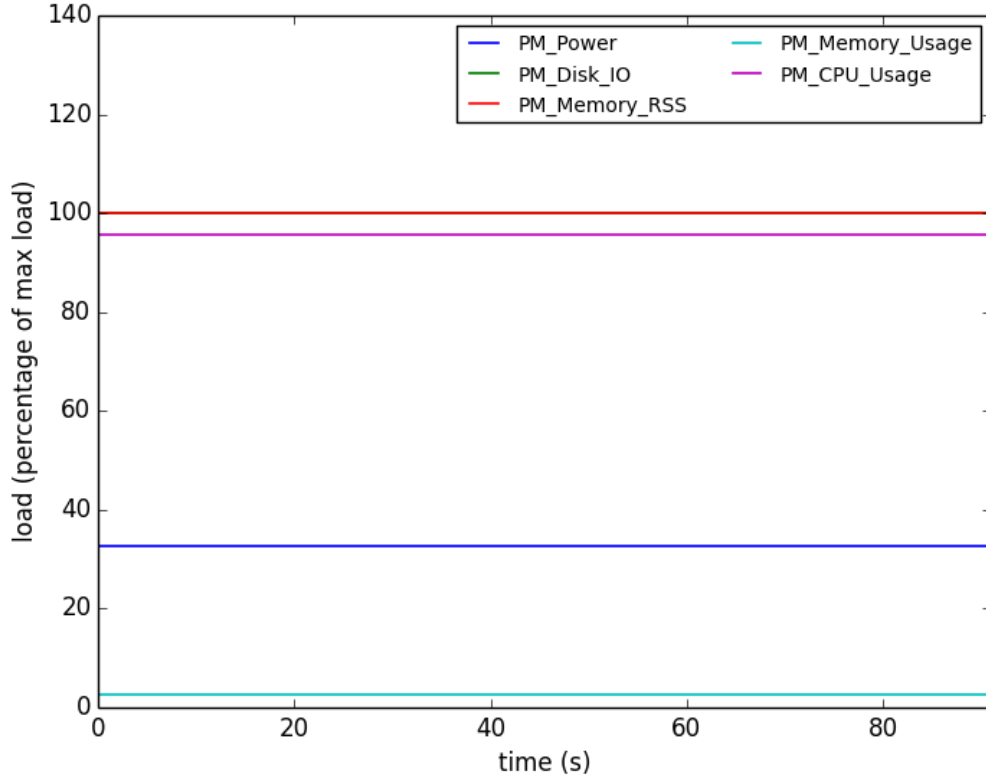


Figure 5-6 Profile of the ABINIT benchmark

5.1.7 FFTE – test3d

FFTE is a package to compute Discrete Fourier Transforms of 1-, 2- and 3-dimensional sequences.

In the scope of this project we profiled the test3d application which is a test for the 3-D real-to-complex FFT routine.

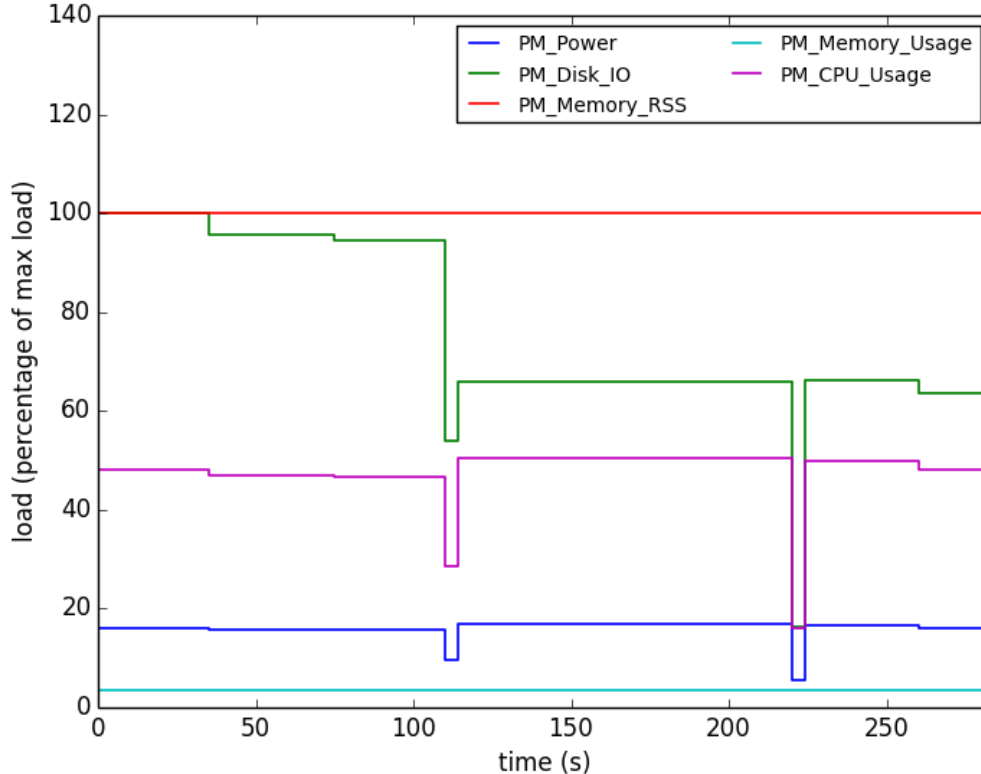


Figure 5-7 Profile of the FFT-test3d benchmark (AMD Fusion CPU)

5.1.8 Intel Optimized LINPACK Benchmark

Intel Optimized LINPACK Benchmark is a generalization of the LINPACK 1000 benchmark. It solves a dense system of linear equations ($Ax=b$), measures the amount of time it takes to factor and solve the system, converts that time into a performance rate and tests the results for accuracy. The generalization is in the number of equations (N) it can solve, which is not limited to 1000. It uses partial pivoting to assure the accuracy of the results.

Parameters of this benchmark are describe in the deliverable [D6.3].

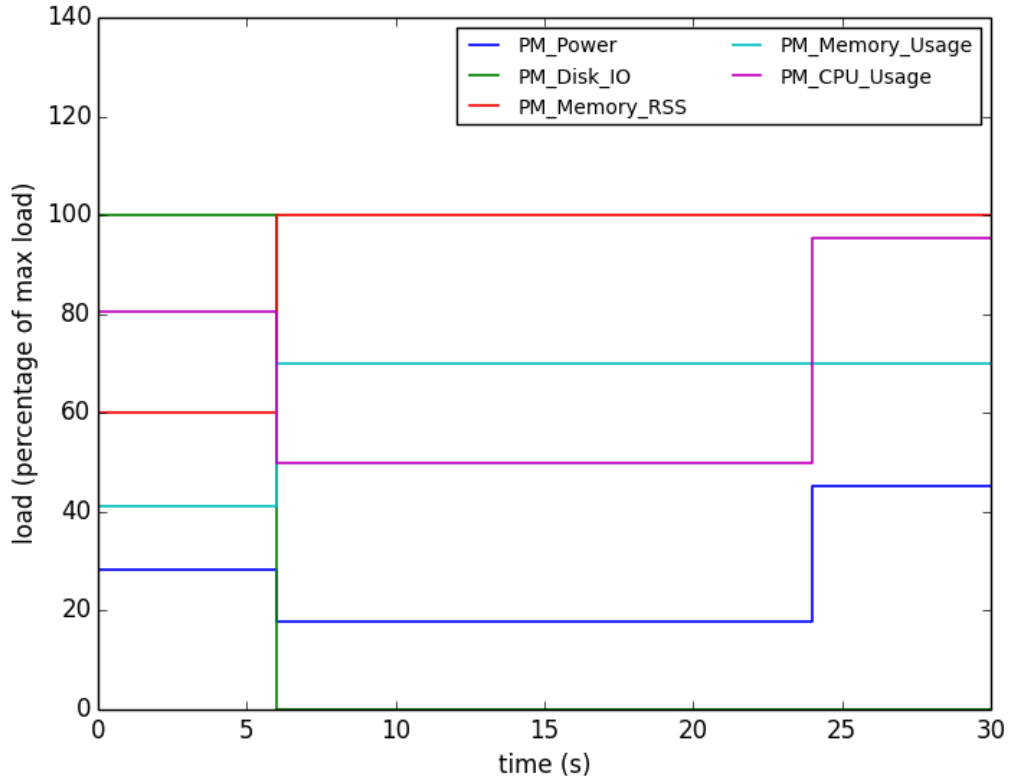


Figure 5-8 Profile of the Linpack 1GB benchmark (Intel i7 CPU)

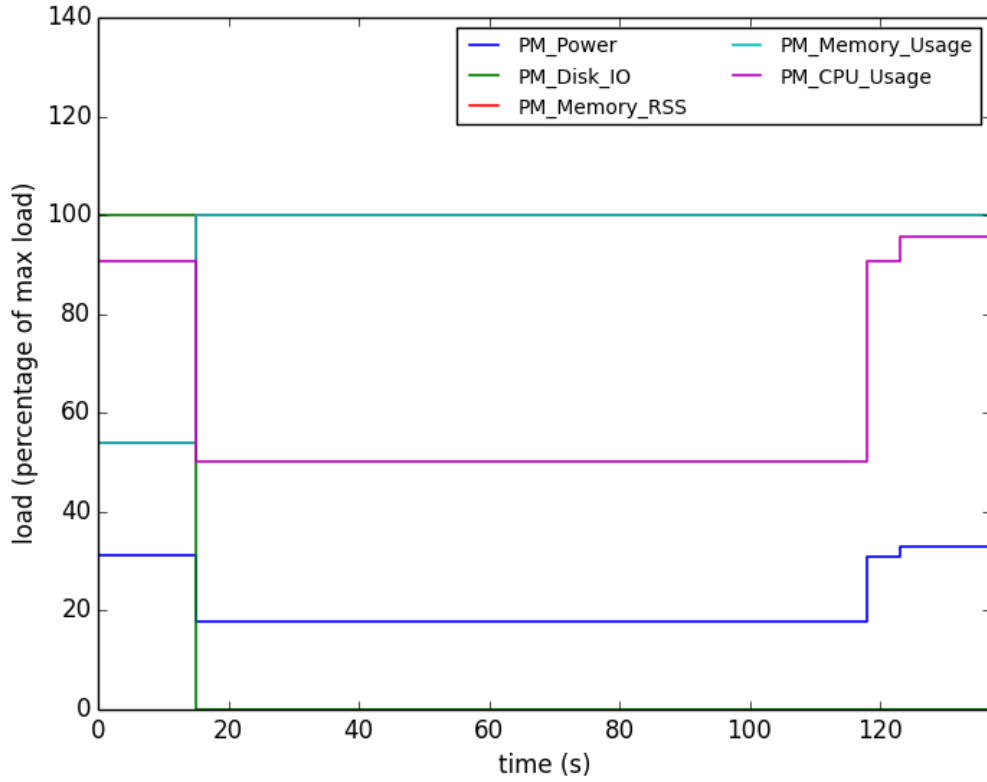


Figure 5-9 Profile of the Linpack 3GB benchmark (Intel i7 CPU)

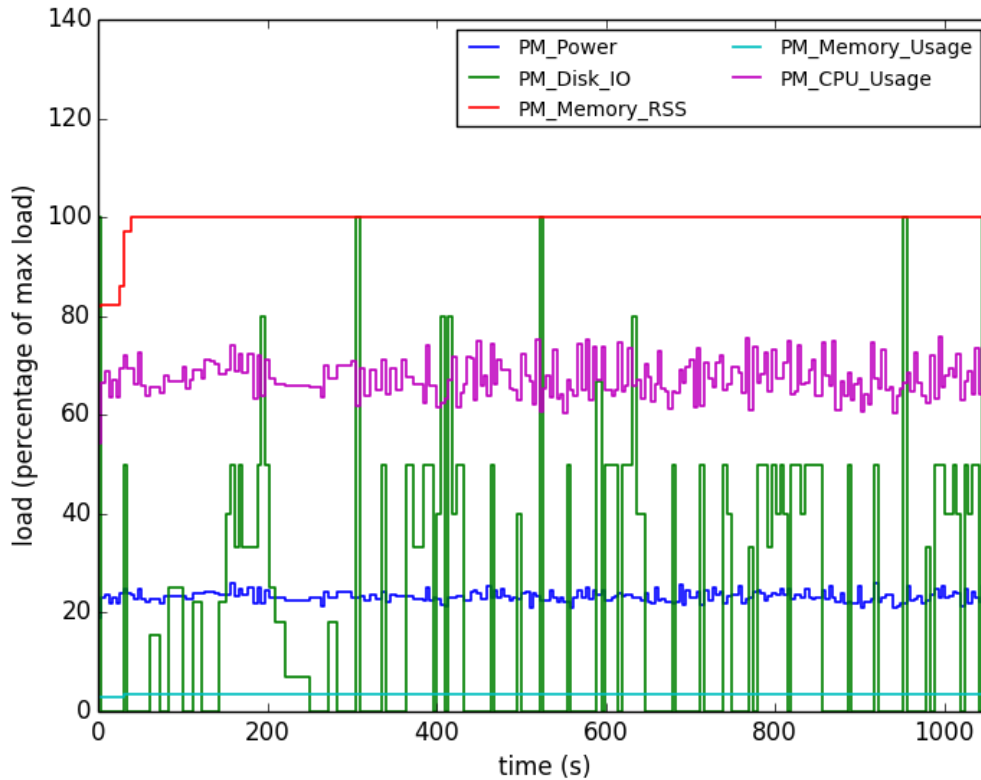


Figure 5-10 Profile of the Linpack tiny benchmark (Intel Atom CPU)

5.1.9 TAR (bzip2)

Bzip2 is a file compressor that uses the Burrows-Wheeler algorithm. It compresses data in blocks of size between 100 and 900 kB and uses the Burrows-Wheeler transform to convert frequently-recurring character sequences into strings of identical letters. It then applies move-to-front transform and Huffmand coding.

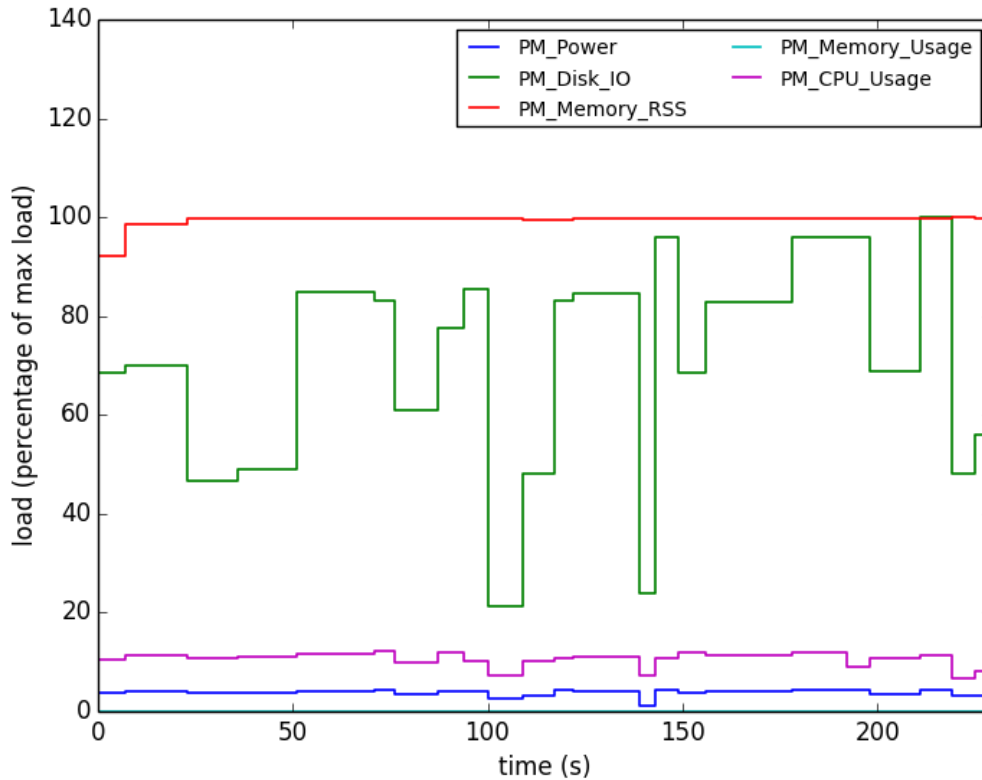


Figure 5-11 Profile of the TAR benchmark

5.2 Cloud benchmarks

The Cloud benchmarks selection includes the following benchmarks:

Benchmark name	License / Website	Description
Benchmark Test-suite 150 benchmarks (annex 4)	GPL v3 - www.phoronix-test-suite.com	5.2.1
PhotoAlbum 3Tier - JBOSS - MySQL - HAproxy	- LGPL - https://www.jboss.org/ - GPL - www.mysql.com - GPL - haproxy.1wt.eu	5.2.2
Hadoop Data Analytics - Hadoop	- Apache License v.2 - hadoop.apache.org - Apache License v.2 -	5.2.3

- Mahout	mahout.apache.org/	
----------	--------------------	--

5.2.1 Benchmark Test Suite

Batch processing benchmarks take advantage of the cloud capabilities of a pre-configured benchmark test suite VM which is ready to install, configure and run more than 150 benchmarks with different resource consumption. The benchmarks stressed different resources: disk, processor, graphics, system, memory, network.

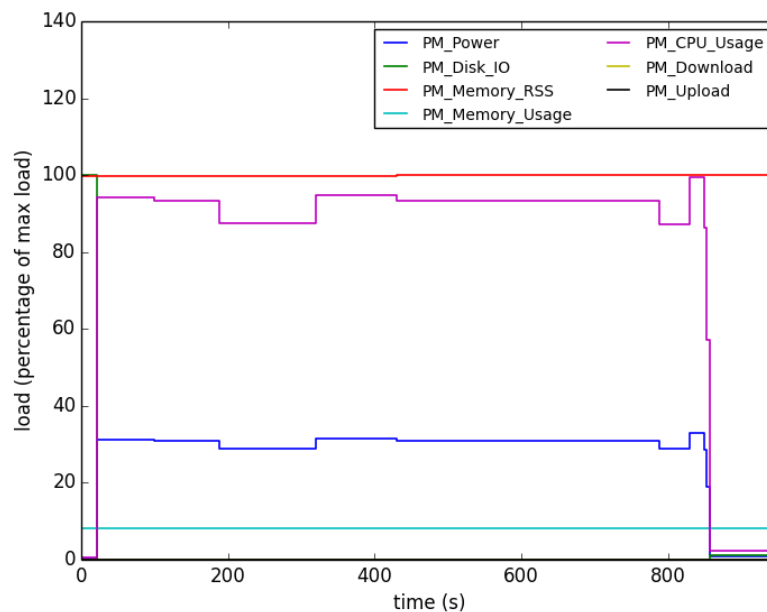


Figure 5-12: CRAY - profile when running on INTEL with 8 cores VM

5.2.2 PhotoAlbum 3Tier Application

A Scalable PhotoAlbum WebApp composed by a minimum of 3 virtual images, this benchmark is contextualized to balance the load between 1 to N worker nodes which is essential capability to react in front of unpredictable spikes in traffic where you are getting more traffic than you have ever had before. The 3Tier benchmark is composed by a load balancer, a MySQL database and as many JBoss servers as required.

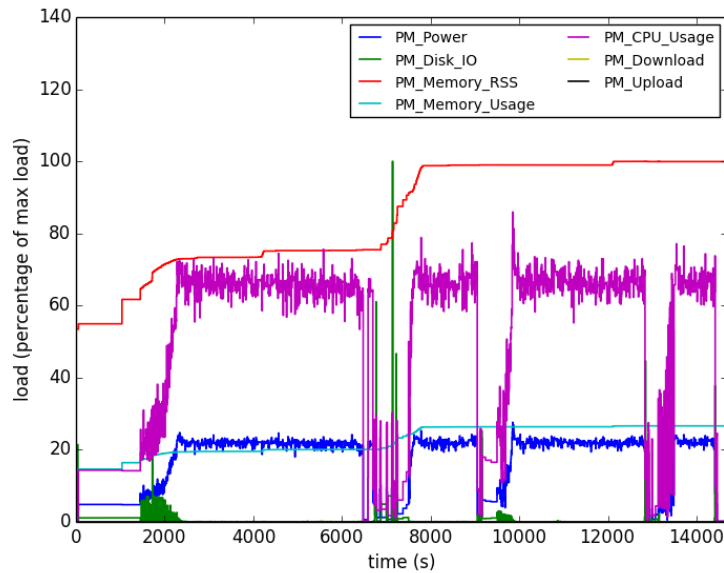


Figure 5-3: JBOSS profile in 3TierApp with stressed with random concurrent users

5.2.3 Hadoop Data Analytics

This benchmark uses the Hadoop MapReduce Framework to perform machine learning analysis on a large-scale datasets, taking advantage of Mahout machine learning library provided by Apache.

The benchmark runs a modified Bayes classification algorithm with a data set of around 30 GB, such benchmark can be executed in a single-node running in a single VM or each component can be installed in a separate VM working as a cluster.

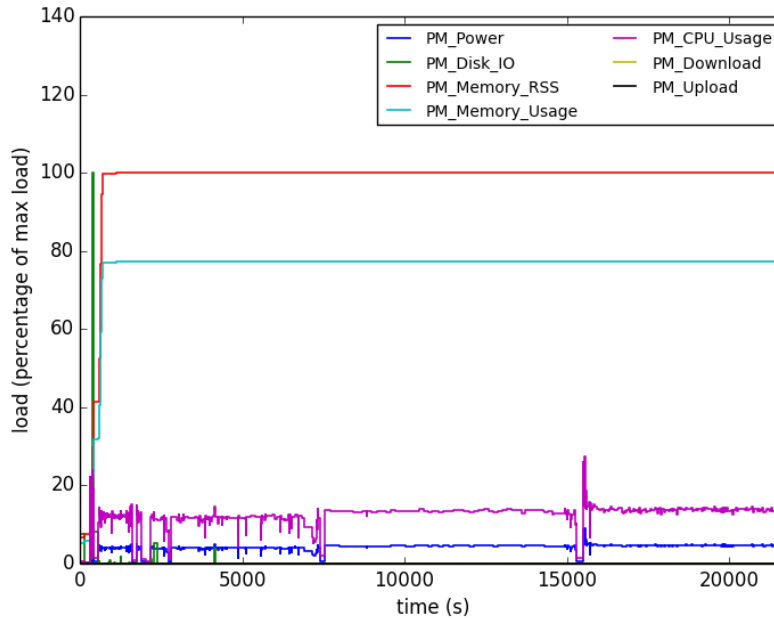


Figure 5-3: Hadoop DataAnalytics benchmark single-node profile

5.3 Selection of benchmarks

Using the monitored data a first clustering on resource consumption is shown on Table 5-1 below. In the context of CoolEmAll, the monitored resources are Network usage, Amount of Memory used, Cache access rate, Branch Instruction number, Disk load and Processor Load. The three categories are low, medium and high level of usage.

Table 5-1 Benchmark resources usage

Level	Network	Main memory	Cache	Branch Instruction	Disk	Load

Low	EP, CpuBurn, C-ray, MemLoop, OpenSSL, PyBench, ABINIT, test3d, tar, hadoop, JBOSS	EP, CpuBurn, OpenSSL, PyBench, ABINIT	MemLoop, JBOSS	C-ray, tar, hadoop, JBOSS	All others	tar
Medium	CG, SP, BT, LU	FT, SP, BT, LU, CG, C-ray, linpack	CG, SP, LU, IS, PyBench, test3d, linpack, tar	SP,BT, EP, LU, CpuBurn, OpenSSL, PyBench, test3d	JBOSS	test3d, hadoop
High	IS, FT, linpack	IS, MemLoop, test3d, tar, hadoop, JBOSS	FT, EP, BT, CpuBurn, OpenSSL, C-ray, ABINIT, hadoop	IS,FT, CG, MemLoop, ABINIT, linpack	test3D, tar	All others

Table 5-2 describes the power and heat impact of each of these benchmarks using the same three levels as described in D5.5 Energy- and Heat-Aware benchmark deliverable.

Table 5-2 Benchmark power-consumption

Level	Power Consumption	Length	Thermal Impact
-------	-------------------	--------	----------------

Low	IS, EP, Pybench, MemLoop, tar, hadoop, JBOSS	EP, IS, Pybench	EP, IS, Pybench, linpack, tar, hadoop, JBOSS
Medium	FT, C-ray, test3d, linpack	CG, FT, ABINIT, linpack, tar	FT, CG, MemLoop, test3d
High	SP,BT,LU,CG, OpenSSL, CpuBurn, ABINIT	SP, BT, LU, CpuBurn, OpenSSL, C-ray, MemLoop, test3d, hadoop, JBOSS	LU, SP, BT, CpuBurn, C-ray, OpenSSL, ABINIT

Using the same methodology that was described in D5.5, a relevant set of sensible benchmarks is EP, CpuBurn, IS, LoopMemory, tar, test3d and CG which is a minimum set of benchmark to asses a maximum number of behaviors.

6 Conclusion

This deliverable describes the knowledge attained during the lifetime of the CoolEmAll project. Several classical benchmarks and metrics were shown to be lacking precision in a realistic and complex environment. In some cases improving the quality of a data centre would result in decreasing the value of a metric used to assess it.

The proposed metrics and benchmark try to improve the coverage of the assessment quality by taking into account not only performance and instantaneous power, but also heat production and energy.

10 most important metrics are described in detail as they provide better insight on the quality of a data centre and seven benchmarks are selected to provide a good coverage of the impact of application on a whole data centre at a minimum cost.

7 Annex 1. Other metrics not included in D5.6

This Annex includes a description of those metrics that finally have not been included in CoolEmAll SVD Toolkit, but have been considered along the research activity of the project.

At the end, selection of metrics depended on the available measures and parameters obtained by simulation and in the abilities of CoolEmAll tool. However, other interesting metrics have been included in this chapter since they are considered relevant for future research steps.

1. Heat dissipation

Heat dissipation is not directly measurable but is directly linked with temperature, cooling system, air-flow volume, and inlet and outlet temperatures of node. Measure is in J/s or Watt and its expression depends on the exact physical architecture. The following schema is considered on CoolEmAll testbed.

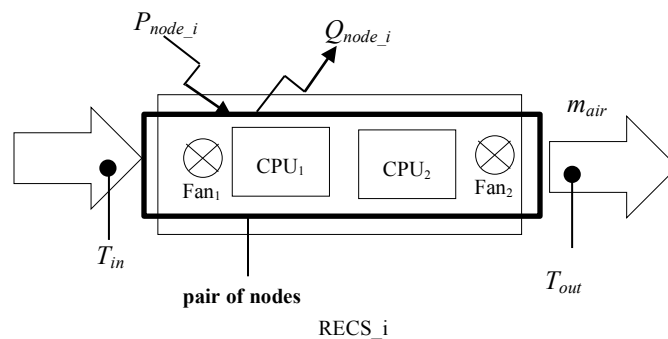


Figure 7-1. Node scheme. Frontal view

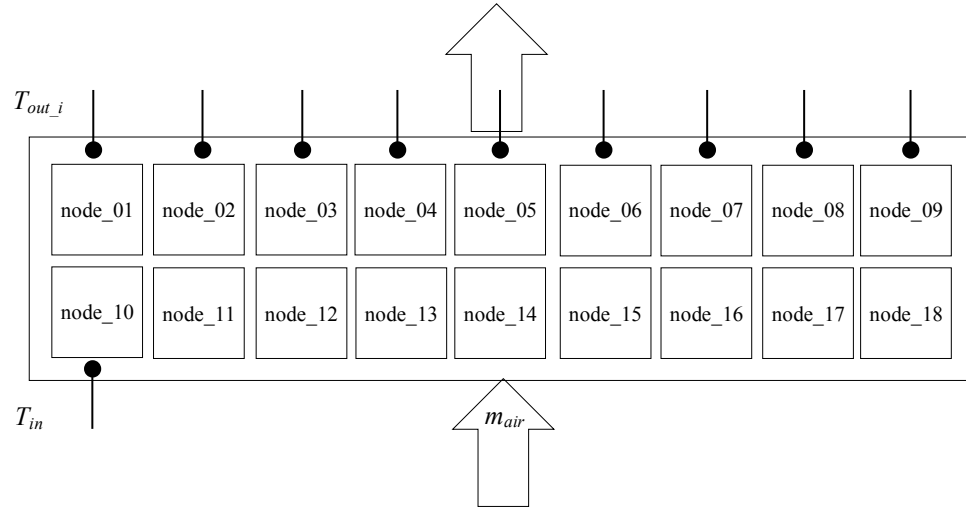


Figure 7-2. Node scheme. Top view. Black dots indicate physical sensors in testbed from which data is recorded in data-base.

Heat dissipation can be calculated using the expression in **Eq. 32**.

$$\dot{Q}_{node} = \dot{m}_{node} \cdot C_p \cdot \Delta T_{node} \quad \text{Eq. 32}$$

Where,

\dot{Q}_{node} is the heat dissipated by the node, [W].

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

Value of air mass flow will come from experiments or simulation. In [D2.3.1] in section 3.2 it is explained how the air mass flow is estimated according the different status of nodes in operation.

C_p is the specific heat of the air used to cool the node, [J/kg·K]. Constant value of 1004 J/kg/°C can be assumed for metric calculation or other one introduced by the end-user.

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

$$\Delta T_{node} = T_{out} - T_{in} \quad \text{Eq. 33}$$

Where,

T_{out} is the temperature at the outlet of the node, obtained from real experiments or from simulations (CFD).

T_{in} is the temperature at the inlet of the node.

There is only one sensor at the air inlet at this corresponds to node_10. The same value will be assumed for all nodes from node_10 to node_18.

It must be taken into account that the designing practices of infrastructures approximate the heat dissipated by the IT hardware with the power consumed (P_{node}) in a ratio of 1:1. The experiments on CoolEmAll test bed might help to define the appropriate relation between heat dissipated and power consumed in a certain node.

$$\dot{Q}_{node} \approx \dot{P}_{node} \quad \text{Eq. 34}$$

The analysis of heat dissipated at node level can be done each time-stamp to compare it with power consumption. However, also the aggregated value is relevant due to this shows the total amount of energy that it is necessary to be dissipated. With this meaning it is defined:

$$TotalQ_{node} = \sum_{t_i=1}^t \dot{Q}_{node} \quad \text{Eq. 35}$$

The assessment of this metric was originally foreseen at starting stage of CoolEmAll. This was included in [D5.1] however, finally has not been included in metric calculator due to the difficulties to properly assessment of air mass flow.

2. Imbalance of heat generation at node-group level

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. This metric aims to provide an overview of a performance of nodes inside a group, relating the heat dissipated in a certain time-stamp. $Im_{NG,Heat}$ values close to 0 indicate good heat generation balance.

$$Im_{NG,Heat} = \frac{Q_{node,max} - Q_{node,min}}{Q_{node,avg}} * 100 = [\%]; \quad Q_{node,avg} = \frac{1}{N} \sum_i^N Q_{node,i} \quad \text{Eq. 36}$$

Where,

$Q_{node,i}$ is the heat generated by each i node in the node-group, [W]. The heat dissipation of each node must be calculated according Eq. 32, in each time-stamp. The value of $Q_{node,i}$ represents the aggregated value of heat dissipated [W] along all the time period of the experiment or simulation, for a certain node i .

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, along all the period of the experiment or simulation [W].

The same metric can be extended at rack level.

The assessment of this metric was originally foreseen at starting stage of CoolEmAll. This was included in [D5.1] however, finally has not been included in metric calculator due to the difficulties to properly assessment of air mass flow.

3. Imbalance of heat generation at rack level

The imbalance of heat generation can be calculated according Eq. 37 and in the same way that it has been defined the Imbalance of heat generation at node-group level (Eq. 36)

$$Im_{rack,Heat} = \frac{Q_{NG,max} - Q_{NG,min}}{Q_{NG,avg}} * 100 = [\%]; \quad Q_{NG,avg} = \frac{1}{N} \sum_i^N Q_{NG,i} \quad \text{Eq. 37}$$

Where,

$Q_{NG,i}$ is the heat generated by each i node-group in the rack, [W]. The heat dissipation of each node-group must be calculated according Eq. 38, in each time-stamp, where, the inlet and outlet temperatures of each node-group used to calculate $\Delta T_{NG,i}$ are the average between the inlet/outlet temperatures of the nodes in the node-group, respectively, in that time-stamp.

$$\dot{Q}_{NG,i} = \dot{m}_{NG,i} \cdot C_p \cdot \Delta T_{NG,i} \quad \text{Eq. 38}$$

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].

$Q_{NG,avg}$ is the averaged thermal heat generated by the nodes-groups in the rack, along all the period of the experiment or simulation [W].

$Im_{rack,Heat}$ values close to 0 indicate good heat generation balance.

4. Return Temperature Index

This metric was also defined by Herrlin [Herrlin, 2007] as the Rack Cooling Index, but instead of focusing on inlet temperatures, it analyses the temperature gradient between inlet and outlet air in the racks.

$$RTI = \frac{T_{return} - T_{supply}}{\Delta T_{IT}} * 100 = [\%] \quad \text{Eq. 39}$$

Where,

T_{return} is the return air temperature (weighted average)

T_{supply} is the supply air temperature (weighted average)

ΔT_{IT} is the temperature rise across the nodes or racks

5. PoC-ODCA

This metric named PoC corresponds to the proof-of-concept metric about carbon footprint and energy efficiency in a data center. The relation to calculate this value is based on the following product [ODCA, 2013]:

[amount of IT equipment used, Standard Units] x

[kWh electricity used per Unit] x

[energy overhead of data center]

[carbon emission of electricity source (s)+transmissions losses]

6. PAR⁴

PAR⁴ is a comprehensive metric for IT energy efficiency measurement, tested by Underwriters Laboratories (UL) to comply with UL standard UL2640 with the aim of measuring IT equipment power usage. This metric has been developed by Power Assure Inc [PA, 2014].

The PAR⁴ rating measures servers under real-life load conditions to certify and rate IT equipment accurately, as well as provide normalized measurements to compare efficiency across multiple generations of IT equipment.

The PAR⁴ methodology takes four measurements to obtain real-world power consumption figures: when the equipment is off, idle, loaded and at peak. With these measurements, PAR⁴ calculates the transactions per second per watt (Tps/W) at 100% CPU load.

8 Annex 2. Carbon Emission Factor and Price of Electricity

Electricity price

As it is mentioned in [MEEUP, 2005], to fix the **Electricity Price** is a complex issue. On one side, Eurostat-15 has fixed an average price around 0.103 €/kWh. On the other side, the Middle European consumer's association has found out higher electricity prices: 0.16 – 0.18 €/kWh. This methodology recommends using the real tariffs including taxes in the Life Cycle Cost calculations. However, it is suggested **0.15 €/kWh** as a default value.

Other source of most updated prices is Eurostat. The value proposed for industrial consumption for 2013 as average of EU-28 countries is **0.0942 €/kWh**¹.

Carbon Emission Factor

The **Carbon Emission Factor (CEF)** is defined in reference to power plant operation as the amount of CO₂ emitted in kilograms per unit of kilowatt energy. This value is generally available as data from local governments in relation to individual power plants and other facilities [ODCA, 2013].

The **Total Utility CEF** corresponds to the value of CEF increased by the transmission losses of the grid to represent a carbon efficiency factor for the entire system (including generation and transmission) [ODCA, 2013].

As stated in [TGG, 2010] in case of co-producing on-site electricity together with grid electricity, the data of CO₂ must come from a combination of:

- The percentage of grid-sourced energy per above sources
- The actual CO₂ emission data from locally produced electricity or generating source

The value of CO₂ emission coming from the grid will be determined for the actual mix of energy delivered to the site (e.g. the electricity may have been generated from varying technologies with different CO₂ impact, for instance, coal or gas generate more CO₂ than hydro or wind). Different factors will be considered depending on the source as well as the weight of each source.

¹ "This indicator presents electricity prices charged to final consumers. Electricity prices for industrial consumers are defined as follows: Average national price in Euro per kWh without taxes applicable for the first semester of each year for medium size industrial consumers (Consumption Band 1c with annual consumption between 500 and 2000 MWh). Until 2007 the prices are referring to the status on 1st January of each year for medium size consumers (Standard Consumer 1e with annual consumption of 2 000 MWh)".

In case of including also the emission of methane (CH₄) and all the GHGs the value of the factor is named Carbon Dioxide Equivalent (CO₂e). In this case, the metric is named **Carbon Footprint**.

In case of CoolEmAll, it will be considered the Total Utility CEF, considering only the CO₂ emissions, and assuming that all the electricity comes from the grid. The conversion factor will be determined based on the Methodology Study Eco-design of Energy-using Products (MEEUP) established by the European Commission (DG ENTR in collaboration with DG TREN) [MEEUP, 2005].

According [MEEUP, 2005] the emissions are based on EPER 2001 [EPER, 2014] for large combustion plants in EU-15 corrected for coal based electricity emissions in new EU-10 electricity (See Table 8-1). For fossil fuel extraction and mining 10% was added (CO₂ correction factor from GEMIS) [GEMIS, 2014]. Electricity distribution losses add 5 % additional. Finally, notice that energy figures are rounded data from Eurelectric EU-15 plus corrections for new EU with 5%.

Table 8-1 Main Emissions Power Generation

Air emissions	EU-15	nw EU-10	EU-25
CO ₂ kg/kWh	0.40	0.58	0.43
Fuel mix			
Solids (coal)	25 %	65 %	31 %
Gas & Oil	25 %		22 %
Non-fossil	50 %	35 %	47 %
Electricity			
TWh	2400	550	2950
% EU-25 el	81 %	19 %	100 %
Electricity conversion factor			
MJ/kg CO ₂	9.7	10.5	10.5

Therefore, the value of 10.5 MJ/ kg CO₂ corresponds to a **Total Utility CEF of 0.34 kgCO₂/ kWh of electricity consumed**

Another reference in case of not knowing the CEF corresponding the country of data center placed is the Standard EN 15603:2008 [EN 15603] which provide a



value of **0.617 kgCO₂/ kWh of electricity consumed**, according Ökoinventare für Energiesysteme-ETH Zürich (1996).

9 Annex 3. Test of metrics performance based on Experiments results

This Annex collects analysis of the performance of some metrics obtained from the Validation Experiments [D6.2.1].

It must be taken into account that the analysis was done from experiments running on test-beds designed to validate the 1st Prototype of CoolEmAll SVD Toolkit.

In that sense, not all the metrics could be properly tested due to the following reasons:

- Analysis of results contributed to be aware about mistakes in data storage in data base or problems in some monitoring sensor. However, experiments were not repeated in order to complete the analysis of the performance of the metrics.
- Most of the experiments did not provide extreme situations that permit to contrast the value of metrics to identify maximum and minimum levels and to establish a benchmark of the metrics.
- The analysis was done only at maximum granularity level of node-group (3 RECS) due to the experiments are on the test-bed, not on simulation environment (rack level and data centre level are possible only with this framework).

The metrics that has been analyzed are the following:

- Power (P)
- CPU Temperature(T_CPU)
- Output Air Temperature (T_out)
- Difference of temperature between inlet air and outlet air ($\Delta T = T_{out} - T_{in}$)

9.1 Description of experiments

9.1.1 Capacity management. Testbed PSNC

Description of the experiment: Execution of applications/benchmarks and capacity management

Testbed: PSNC

Experiment: EX_HPC_2

Level: RECS

Description of trials:

The experiment uses three node-groups (RECS) composing a rack as modelled and evaluated resource architecture. The first one is composed by Intel i7, the second one by Intel Atom and the third one by AMD Fusion. Executed workload consists of OpenSSL application and results in around 50% of system load.

The workload and resource management policies applied are the following:

- a) Load balancing – 50 % load: Workload is distributed between all the nodes in the way that balance the load. Load is 50 %.
- b) Load balancing – 90 % load: Workload is distributed between all the nodes in the way that balance the load. Load is 90 %.
- c) Consolidation – 50 % load: Tasks are assigned to nodes, starting from high performance CPUs, in order to consolidate the load on the nodes. Load is 50 %.
- d) Consolidation – 90 % load: Tasks are assigned to nodes, starting from high performance CPUs, in order to consolidate the load on the nodes. Load is 90 %.

9.1.2 Execution of applications/benchmarks. Testbed IRIT

Description of the experiment: Execution of applications/benchmarks

Testbed: IRIT

Experiment: EX_HPC_2

Level: RECS

Description of trials:

The applications C-ray and OpenSSL are running on the different three RECS (RECS 1, RECS 2 and RECS 3).

9.1.3 Execution of applications/benchmarks in Cloud environment. Testbed PSNC

Description of the experiment: Execution of applications/benchmarks in cloud environment

Testbed: PSNC

Experiment: EX_CLOUD_2

Level: RECS

Description of trials:

The applications C-ray, OpenSSL, Netloopback and StressCPU are running on 6 nodes of RECS 1 (i7_0_01 to i7_0_06).

9.2 Analysis of metrics

9.2.1 Power vs temperature of CPU

In the following figures it has been represented the relation between the power consumed in the nodes and the temperature of CPU reached in each state.

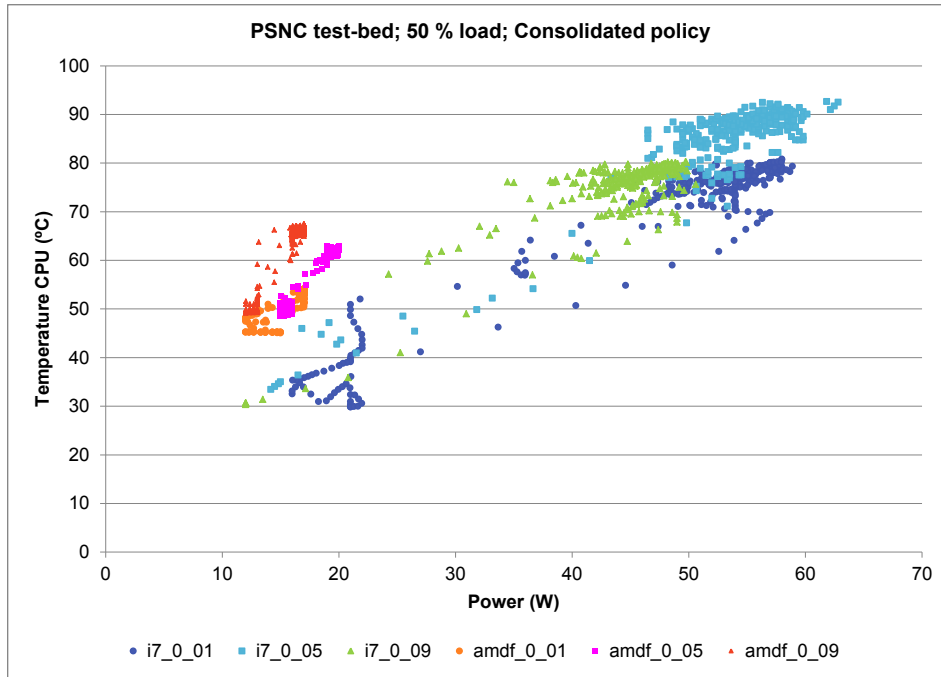


Figure 9-1. Relation Power vs Temperature of CPU. Consolidated 50 %

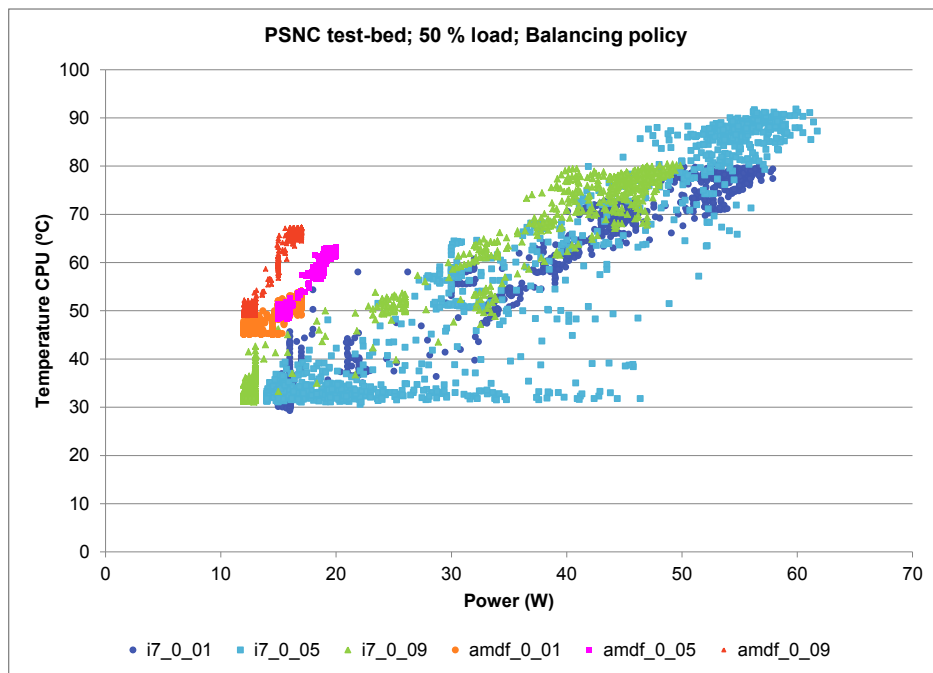


Figure 9-2. Relation Power vs Temperature of CPU. Balancing 50 %

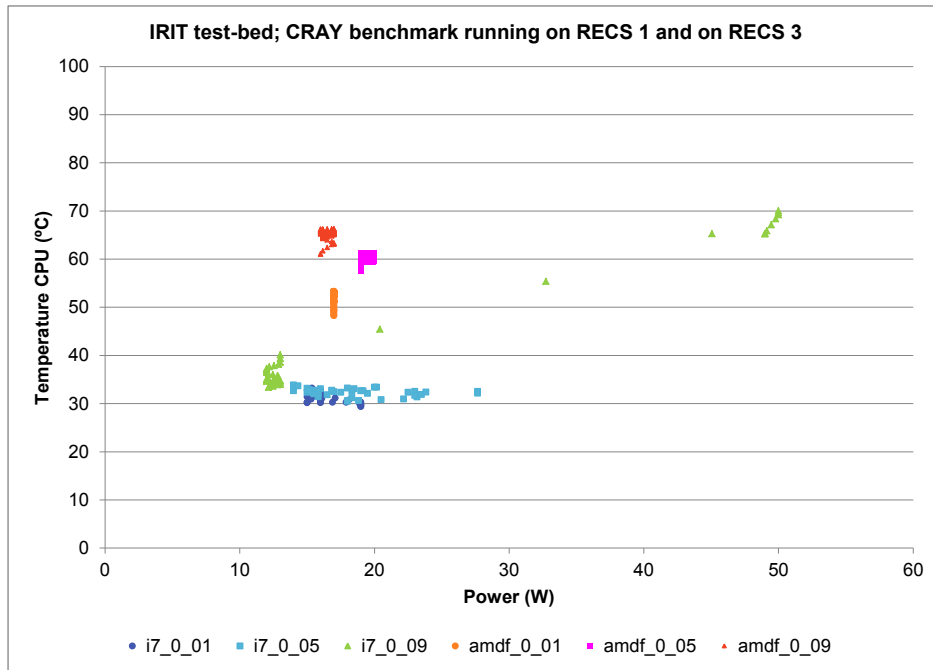


Figure 9-3. Relation Power vs Temperature of CPU. CRAY in RECS1 and in RECS 3

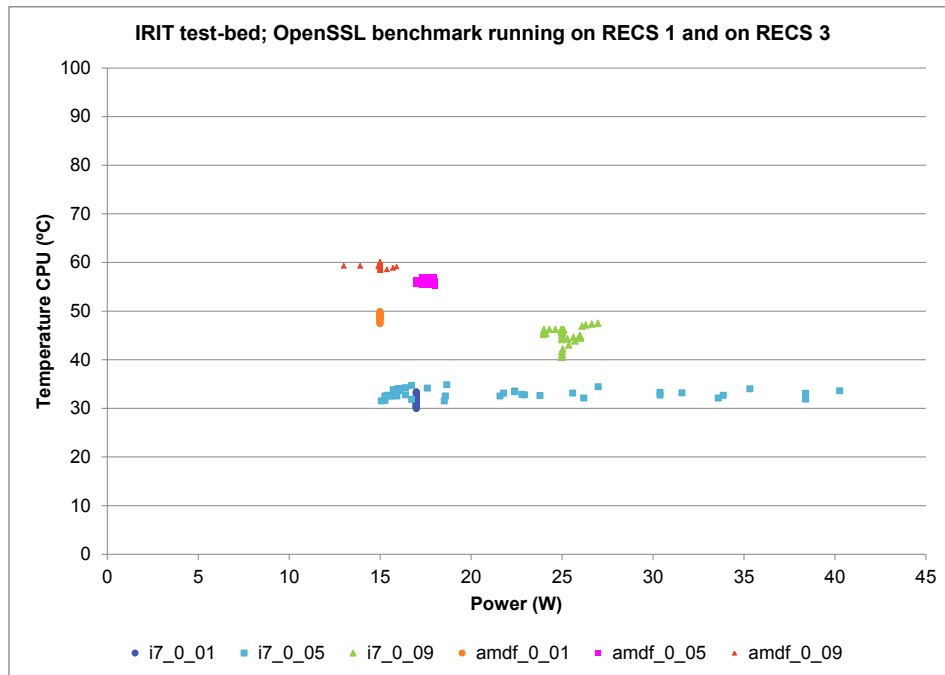


Figure 9-4. Relation Power vs Temperature of CPU. OpenSSL in RECS1 and in RECS 3

In all the 4 figures above it can be noticed that for the range of power between 10 W and 20 W the Intel i7 nodes reach lower temperature than the nodes AMD Fusion.

In Figure 9-1 and Figure 9-2 the amount of data is enough to see a linear correlation between power and temperature of CPU. However, in case of balancing operation, there are a relevant amount of points where although there is an increase in power, there is not an increase in temperature of CPU.

In case of Figure 9-3 and Figure 9-4 it seems that the model performs according a constant temperature for each node (except for i7_0_09 with Cray application), although the number or points assessed is not enough to confirm this statement.

9.2.2 Power vs difference between input air temperature and output air temperature (ΔT)

In these figures it has been represented the relation between the different power operation states and the influence in the cooling needs. The cooling needs have a direct relation with the difference between input air temperature (T_{in}) and output air temperature (T_{out}) assuming a constant air flow. In the figures it is named Delta T = $\Delta T = T_{out} - T_{in}$ ($^{\circ}C$).

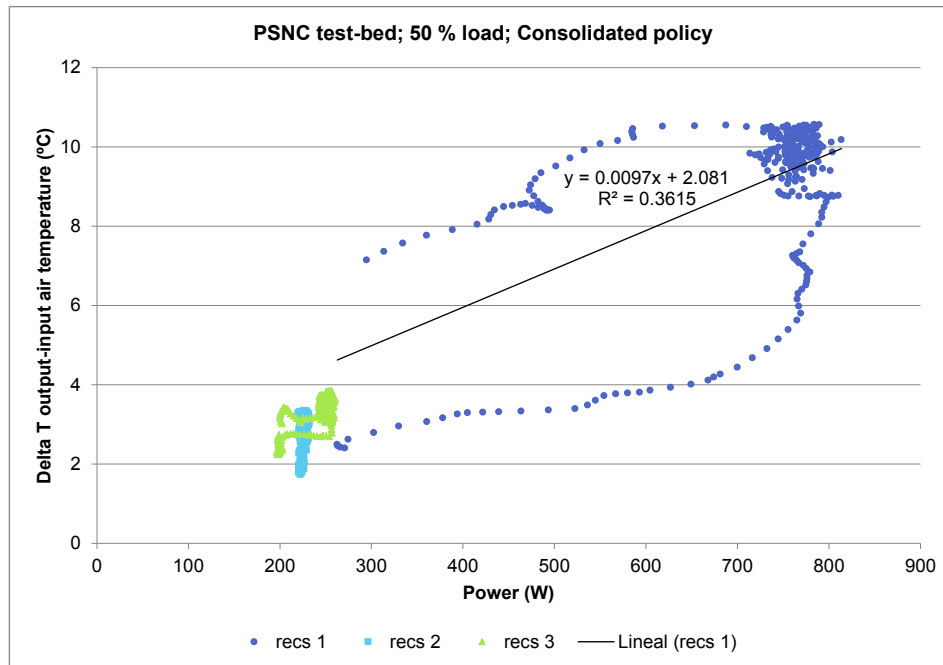


Figure 9-5. Relation Power vs ΔT . Consolidated 50 %

In Figure 9-5 there is a clear difference of performance between recs 1 and recs 2 or recs 3. In recs 1 the maximum ΔT reached are around $10.5^{\circ}C$ meanwhile in case of recs 2 or recs 3 the values are between $2^{\circ}C$ and $4^{\circ}C$.

Other fact that can be observed in case of recs 1 is that there are several points where for the same power consumed the cooling needs, related with ΔT , can be more than the double. For instance, fixing the attention in 600 W, we have one point at $\Delta T=4^{\circ}C$ and other at $\Delta T=10.5^{\circ}C$. It means that not always it is true that power consumed in the nodes is equal to the heat dissipated.

$$\dot{P}(t) \approx \dot{Q}(t)$$

$$\dot{Q}(t) = \dot{V} \cdot \rho \cdot C_p \cdot \Delta T(t)$$

$$\Delta T(t) = T_{out}(t) - T_{in}(t) \approx \frac{\dot{P}(t)}{\dot{V} \cdot \rho \cdot C_p}$$

As a consequence of that remark it can be identified the relevance of having separated metrics for assessing:

- Power consumption
- Cooling needs

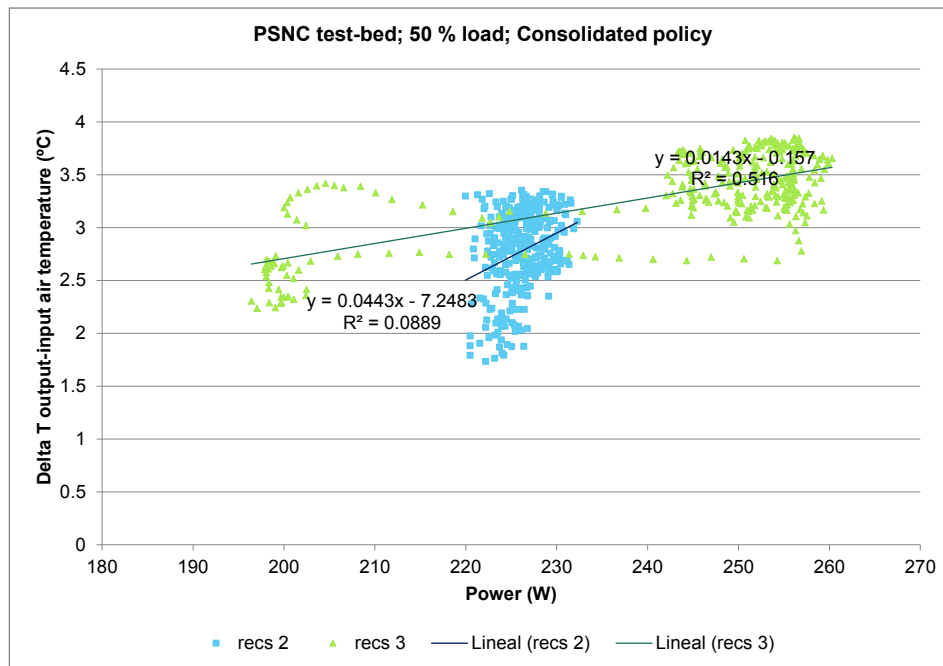


Figure 9-6. Relation Relation Power vs ΔT . Consolidated 50 % (detail of recs 2 and recs 3)

In Figure 9-6 (detail of recs 2 and recs 3 of Figure 9-5) it has been represented the equation of a linear correlation. In case of recs 2 (blue) it can be noticed that there are a lot of points out of the straight line. The ΔT can vary between 1.8 °C to 3.4 °C, it means 1.6 °C of difference, for a range of power between 220 W and 230 W. In case of recs 3 (green) the maximum variation of ΔT is around 1.6 °C for a range of power between 195 W and 260 W.

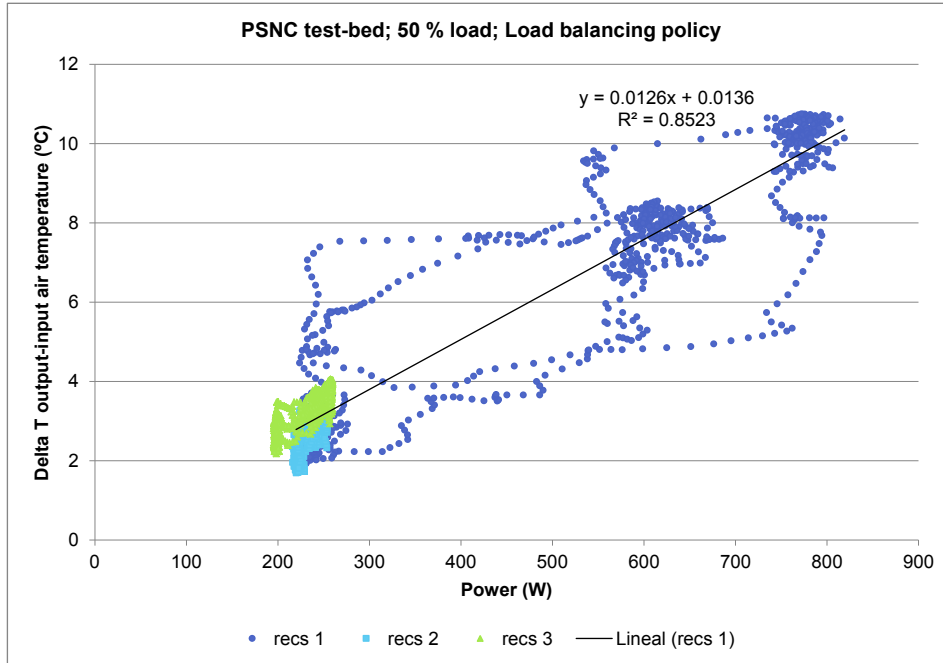


Figure 9-7. Relation Power vs ΔT. Balancing 50 %

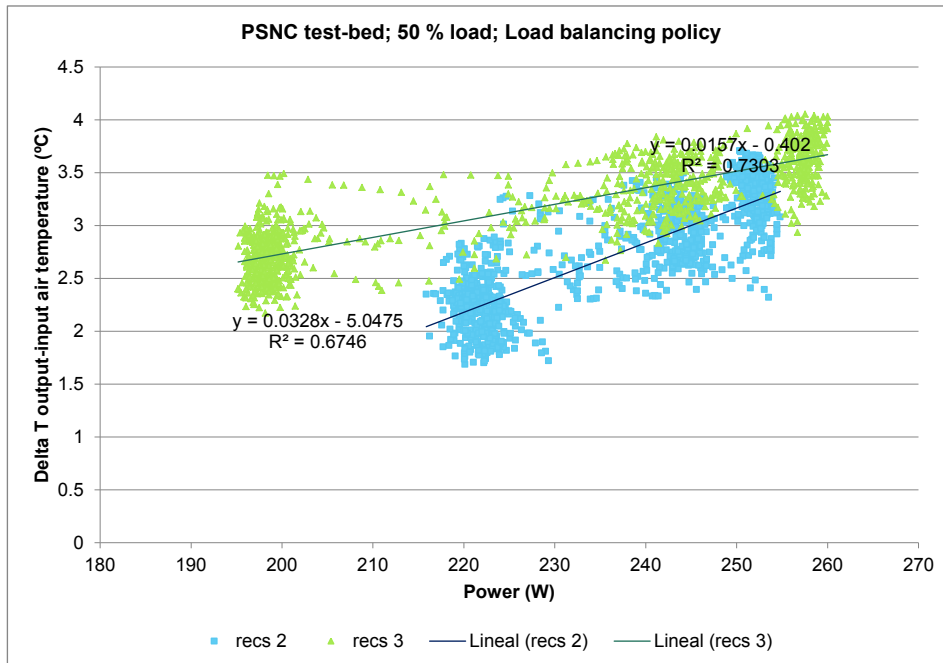


Figure 9-8. Relation Power vs ΔT. Balancing 50 % (detail of RECS 2 and RECS 3)

Figure 9-7 and Figure 9-8 correspond to the previous ones but in this case, a balancing policy has been applied instead of consolidated policy. The difference on the strategy corresponds to the fact that load balancing distributes the workload between all the nodes in the way that load is balanced, while in consolidation, tasks are assigned to nodes, starting from high performance CPUs, in order to consolidate the load on the nodes. The effect of this policy

affects the cooling needs; in sense that more dispersion of temperatures are obtained in balancing policy in comparison to consolidated policy (comparison between Figure 9-5 and Figure 9-7 and also between Figure 9-6 and Figure 9-8).

In the following figures, the results for recs 1 in case of consolidated policy and balancing policy are shown separating with different colours three different status of operation:

- Initial period
- Medium period
- Final period

Both policies, consolidation and load balancing, are shown. The analysis permits to identify the effect of the inertia, and also the deviation between the power consumed and the cooling needs, usually identified as the same value.

Looking at Figure 9-9, it can be noticed that the difference on temperatures are mainly associated to the inertia of the system. The hottest points correspond to the end of time of operation, when the system reaches higher temperatures due to the inertia of heat not completely dissipated in the previous time steps.

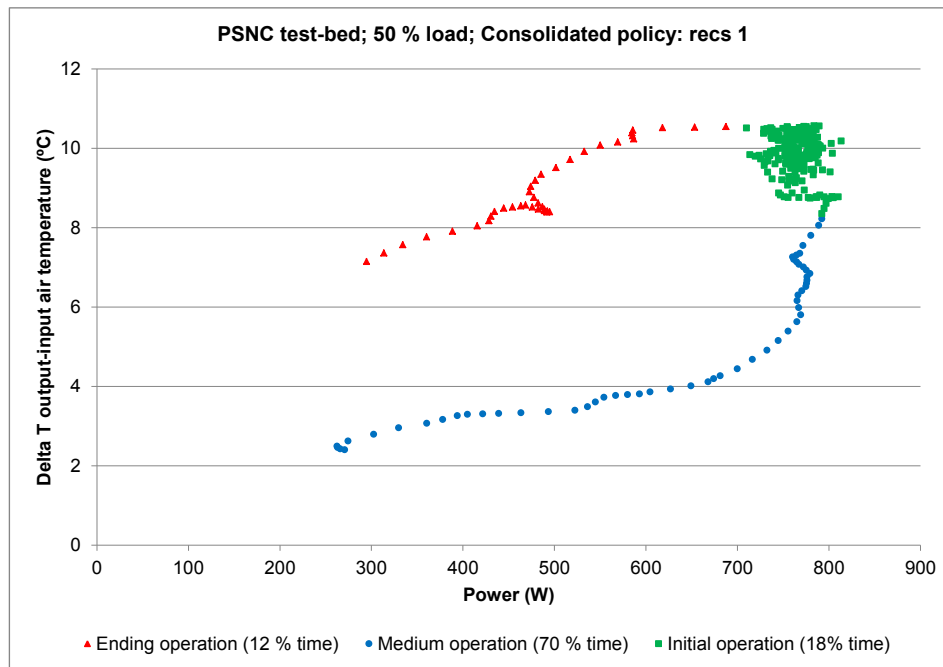


Figure 9-9. Relation Power vs ΔT depending on time of operation. Consolidated 50 % in recs 1

However, this performance is not so clear in case of Figure 9-10 corresponding to balancing policy. In this case, there are several transient states represented by the lines between the groups of points. As well, the ending period do not present the hottest points if not the coldest. It can be explained to the fact that the balanced distribution of load helps to the nodes to have better cooling

performance, due to they have more time without load when heat can be dissipated.

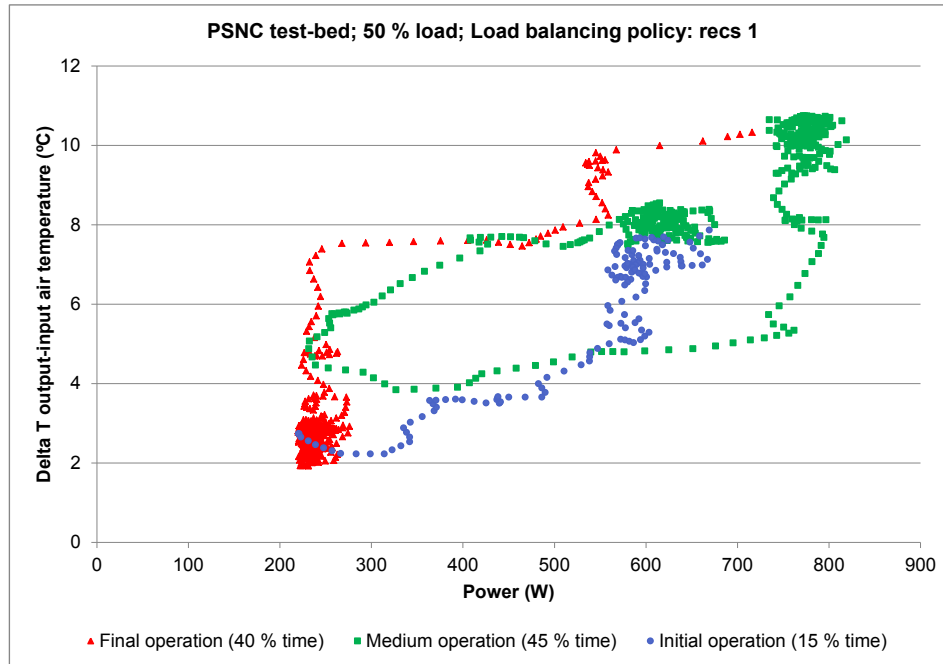


Figure 9-10. Relation Power vs ΔT depending on time of operation. Balancing 50 % in recs 1.

9.2.3 Imbalance of Temperature of CPU (IoT) vs difference between output air temperature and input air temperature (ΔT)

The aim of the analysis presented in this chapter is to find out the usefulness of the metric **Imbalance of CPU Temperature (IoT)** as an indicator of the cooling needs.

This metric is calculated as follows:

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

Where,

$T_{CPU,i}$ is the temperature of each i CPU in the node-group in a certain time-stamp.

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 in a certain time-stamp.

$T_{CPU,min}$ is the minimum temperature of the CPUs in the node-group in a certain time-stamp.

$T_{CPU,avg}$ is the average temperature of the CPUs in the node-group in a certain time-stamp.

This metric can offer an overview inside a group of nodes of unbalanced performance regarding the temperature of the CPU, and as a consequence, the possible presence of hot spots. However IoT metric has the problem to not allocate the level of need of cooling since the metric is divided by an average value. In that sense, if the metric addressed the cooling needs properly, increasing of average value of ΔT ($T_{out} - T_{in}$) would perform increasing the value of IoT. This performance is not obvious when looking at Figure 9-11, for instance, with the case recs 1 (higher IoT has lower ΔT).

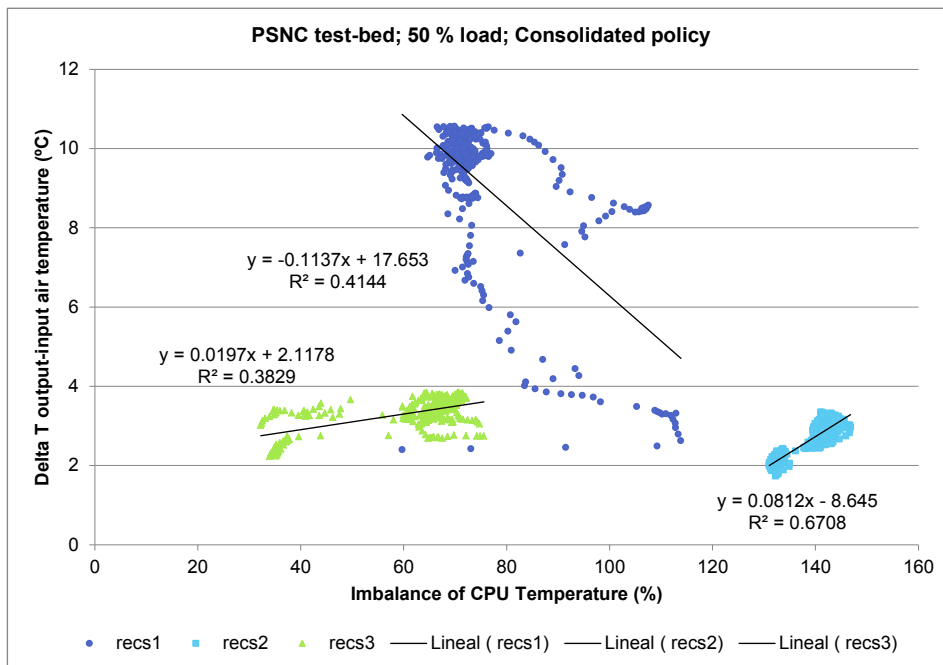


Figure 9-11. IoT vs ΔT . Consolidated 50 %

As well, if cooling need is identified by ΔT , in the Figure 9-12 can be noticed that the maximum cooling needs are present in recs 1 with an average value of ΔT around 10 °C and in case of recs 2 and recs 3 this value is around 3 °C. However, the maximum IoT is shown for recs 2, and the value of IoT for recs 1 and recs 3 is very similar.

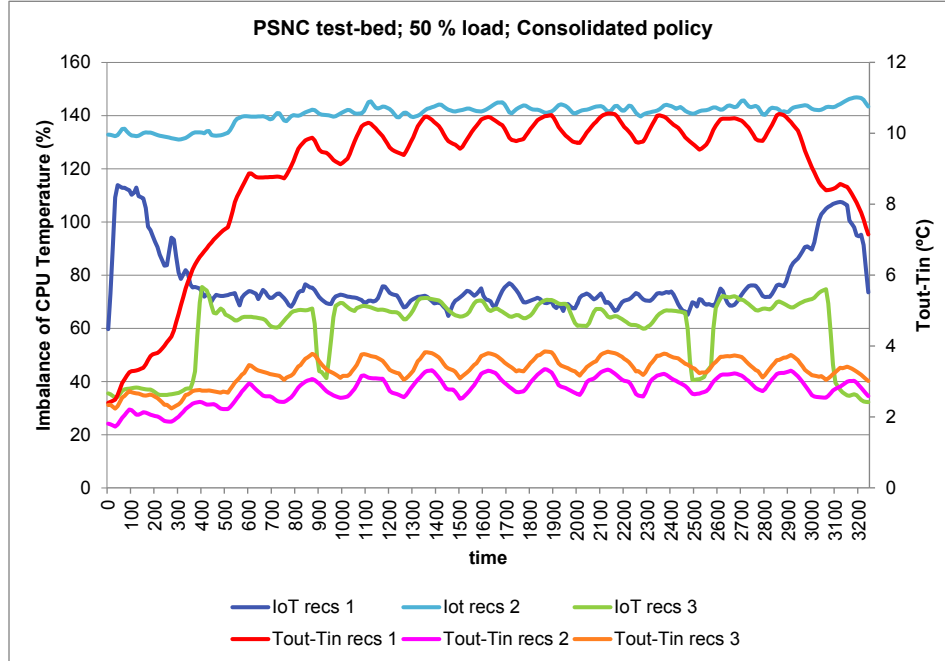


Figure 9-12. IoT and ΔT on time. Consolidated 50 %

To solve this problem it is proposed a new definition of IoT metric. The main idea is to refer this to a fixed temperature valued instead of average temperature value. The selected value is 100 °C, as an extreme value of CPU temperature.

$$Im_{NG,temp} = \frac{T_{CPU,max} - T_{CPU,min}}{T_{CPU,maxref}} * 100 = [\%]; T_{CPU,maxref} = 100^{\circ}C$$

The results obtained after this change are shown in the next pictures.

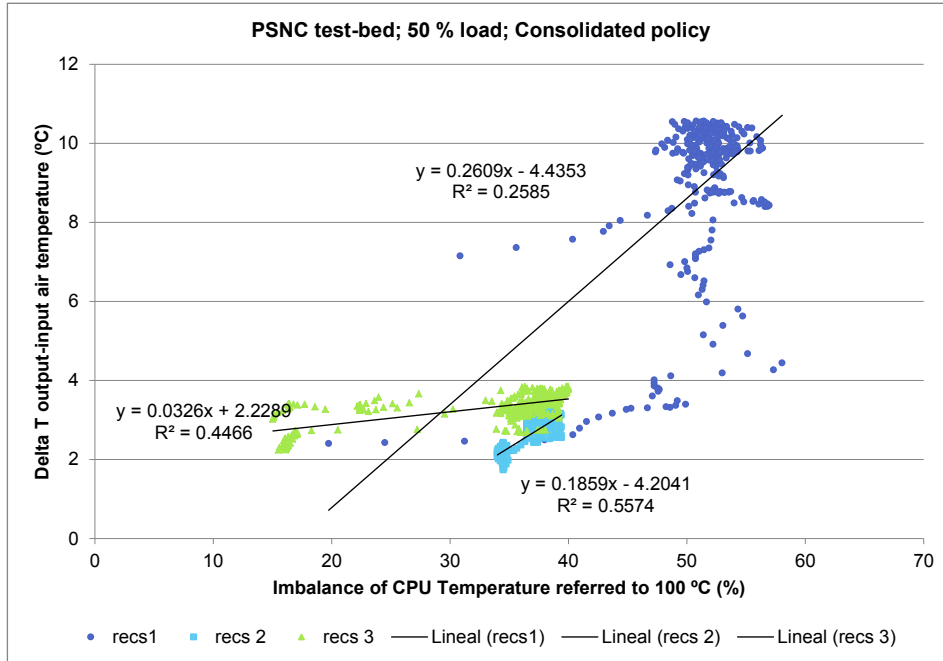


Figure 9-13. IoT referred to 100°C vs ΔT. Consolidated 50 %

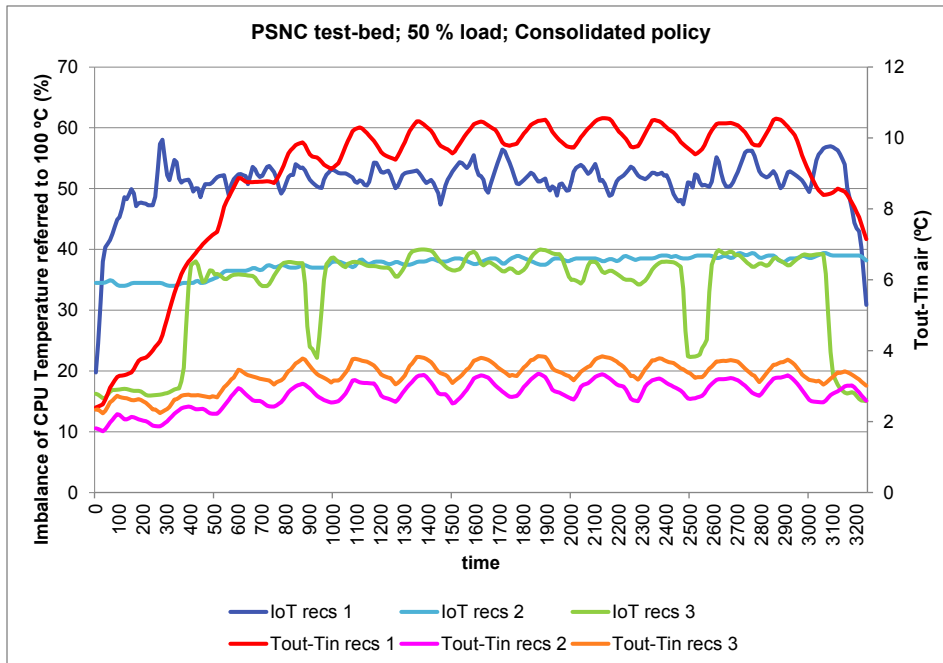


Figure 9-14. IoT referred to 100°C and ΔT on time. Consolidated 50 %

In Figure 9-14 It can be noticed that IoT for recs 1 is higher than IoT for recs 2 and recs 3. Also the value of the metric is similar for recs 2 and recs 3 as well as the value of ΔT.

And the figures are also extended to load balancing policy with 50 % load, as can be seen in Figure 9-15 and Figure 9-16.

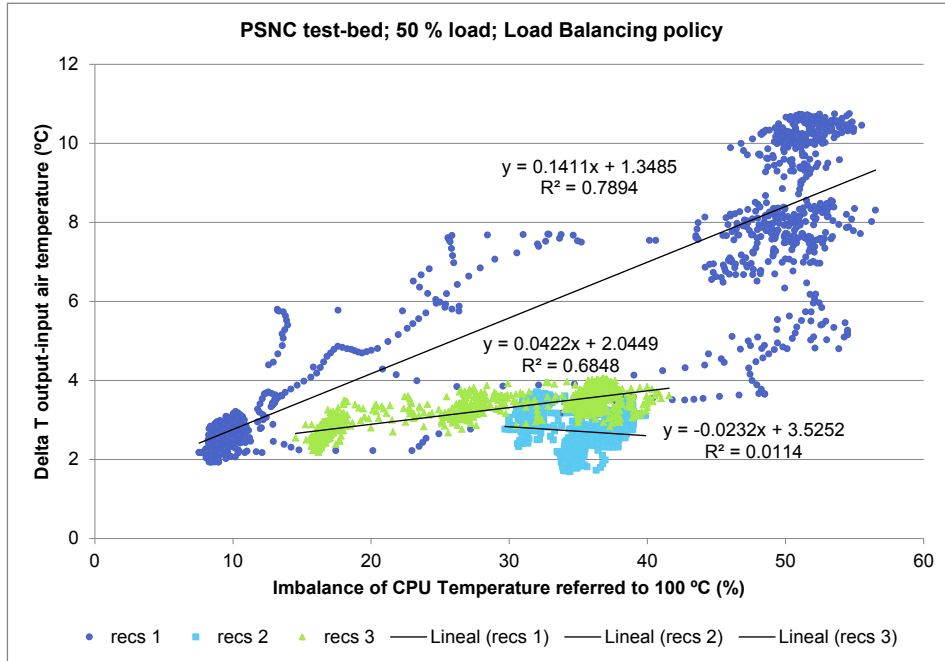


Figure 9-15. IoT referred to 100°C vs ΔT. Balancing 50 %

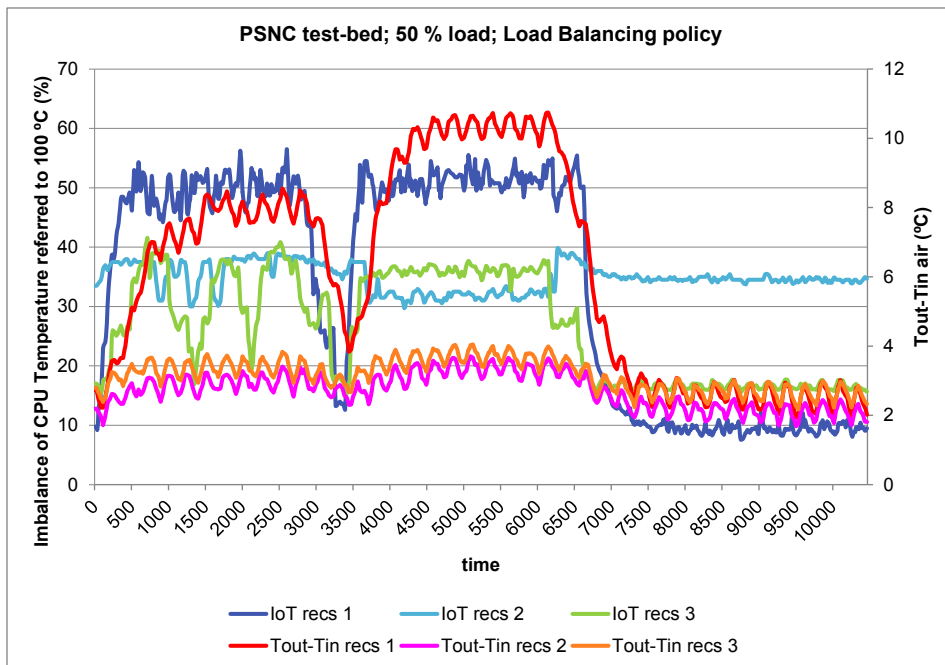


Figure 9-16. IoT referred to 100°C and ΔT on time. Balancing 50 %

With the new definition of the IoT metric it is obtained a linear increasing relation between IoT and ΔT as expected.

9.2.4 Relation between power and difference between output air temperature and input air temperature (ΔT)

Accordinging the equations of heat balance:

$$\begin{aligned}\dot{P}(t) &\approx \dot{Q}(t) \\ \dot{Q}(t) &= \dot{V} \cdot \rho \cdot C_p \cdot \Delta T(t) \\ \dot{V} \cdot \rho \cdot C_p &\approx \frac{\dot{P}(t)}{\Delta T(t)}\end{aligned}$$

In the conditions of constant air volume flow, the relation of power divided by ΔT should be constant. In the Figure 9-17 and Figure 9-18 this fact can be stated with approximately constant values (with some fluctuations around the average). In case of consolidated policy (Figure 9-17) the air mass flow equals 80 g/s, that corresponds a volume flow of 4.110 m³/min (air density equal to 1.168 g/m³). If this value is divided by 9 groups of 2 nodes, the value that flows across two nodes is 0.457 m³/min. This value can be compared with the experimental results obtained of 0.280 m³/min [D2.3.1] stating that is nearly the double than the value previously estimated. As a result it is confirmed that detailed air flow measurements should be done to extend the present validation of cooling models defined in [D2.3.1].

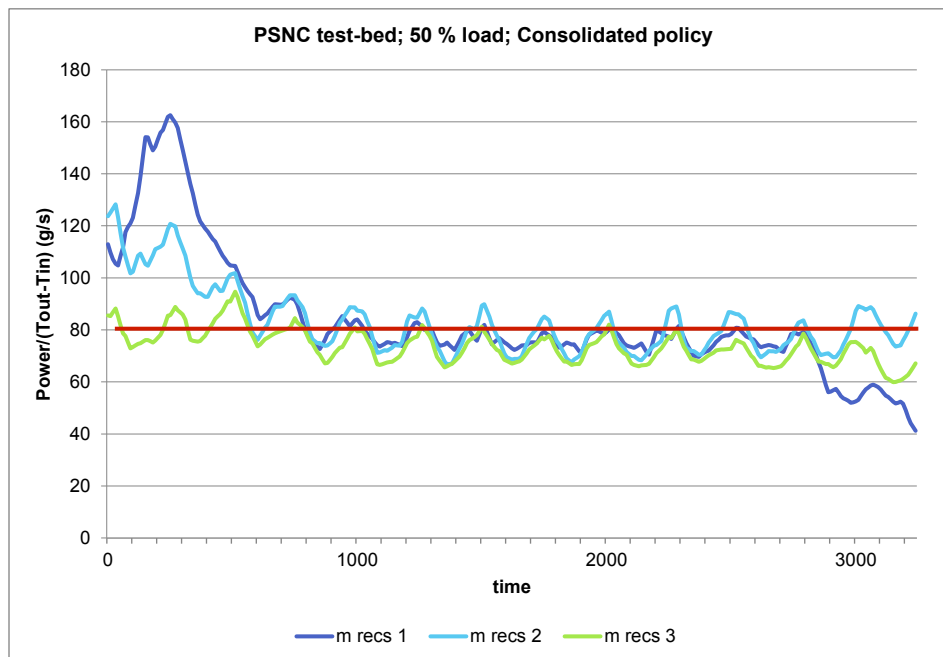


Figure 9-17. Power divided by output-input air temperatures difference. Consolidated 50 %

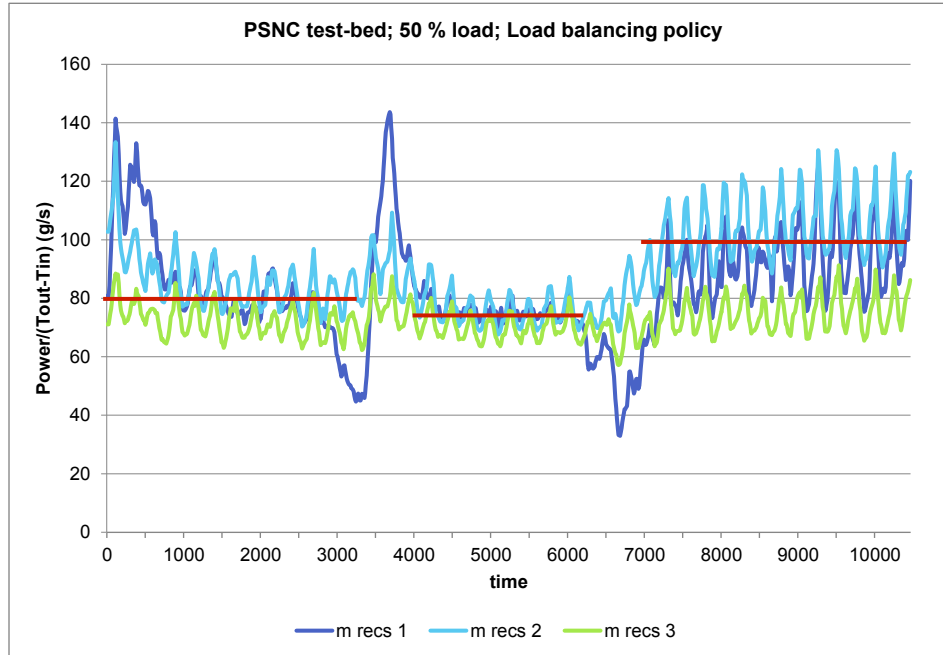


Figure 9-18. Power divided by output-input air temperatures difference. Balancing 50%

In case of Load Balancing policies it can be observed that at the end of the experiment the mass air fluctuations are higher than the previous time-stamps.

9.2.5 Power, CPU temperature and Imbalance of Temperature of CPU based on Cray and OpenSSL applications running in recs1, recs2 and recs3

This section is based on the experiments executed at IRIT test-bed. Those consist of two different applications, C-ray and OpenSSL running on recs1, recs2 and recs3 respectively.

The figures presented below show power, temperature of CPU (Figure 9-19, Figure 9-20, Figure 9-21 for C-ray and Figure 9-23, Figure 9-24 and Figure 9-25 for OpenSSL). It is also included Imbalance of CPU Temperature, calculated as proposed in D5.1 and with the reference to 100 °C (see section 9.2.3) (Figure 9-22 and Figure 9-26). The value of power and temperature are presented for 4 nodes per each recs, where a total of 18 are there.

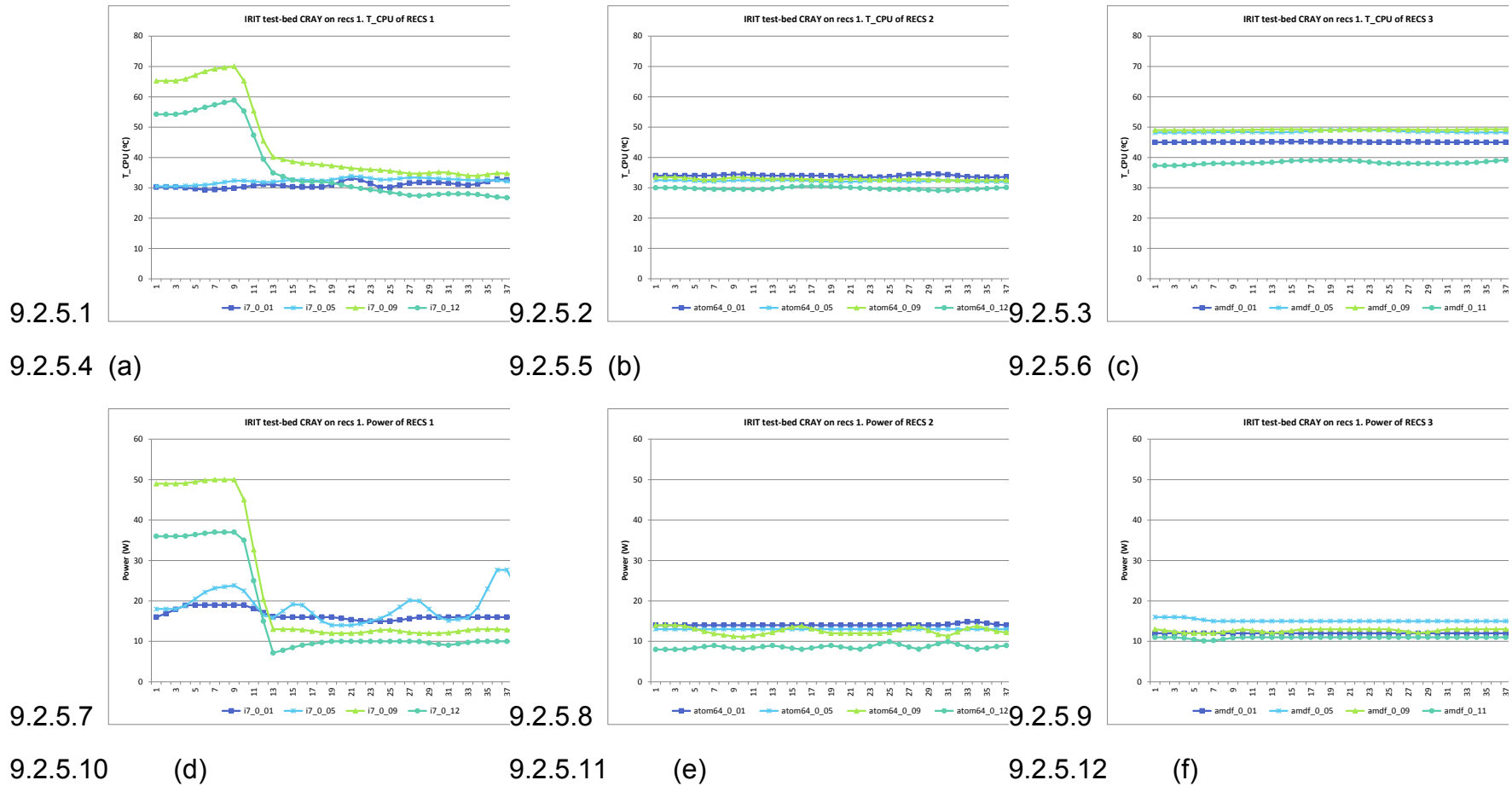


Figure 9-19. CPU Temperature and power executing C-ray on recs 1. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3

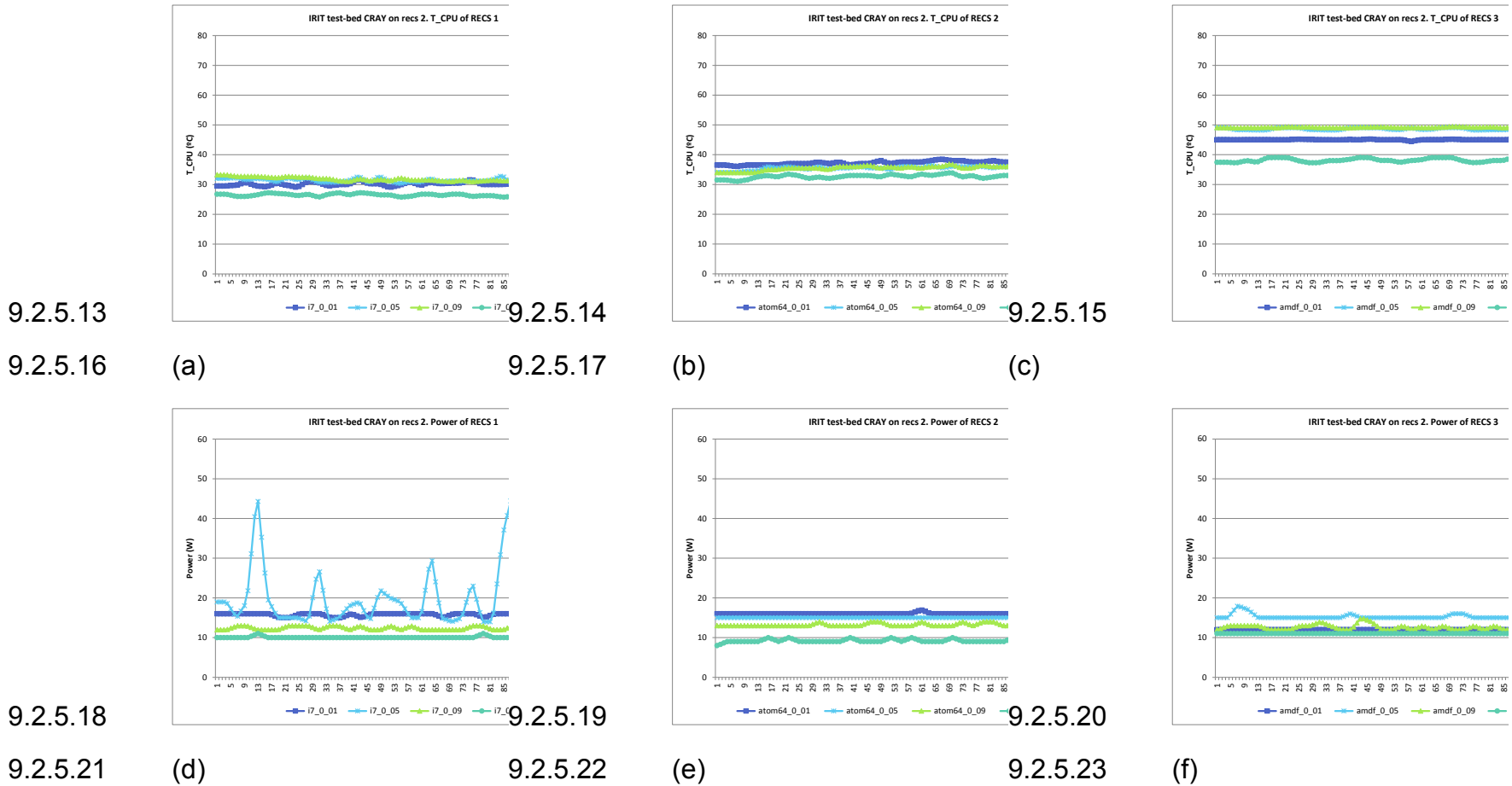


Figure 9-20. CPU Temperature and power executing C-ray on recs 2. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3

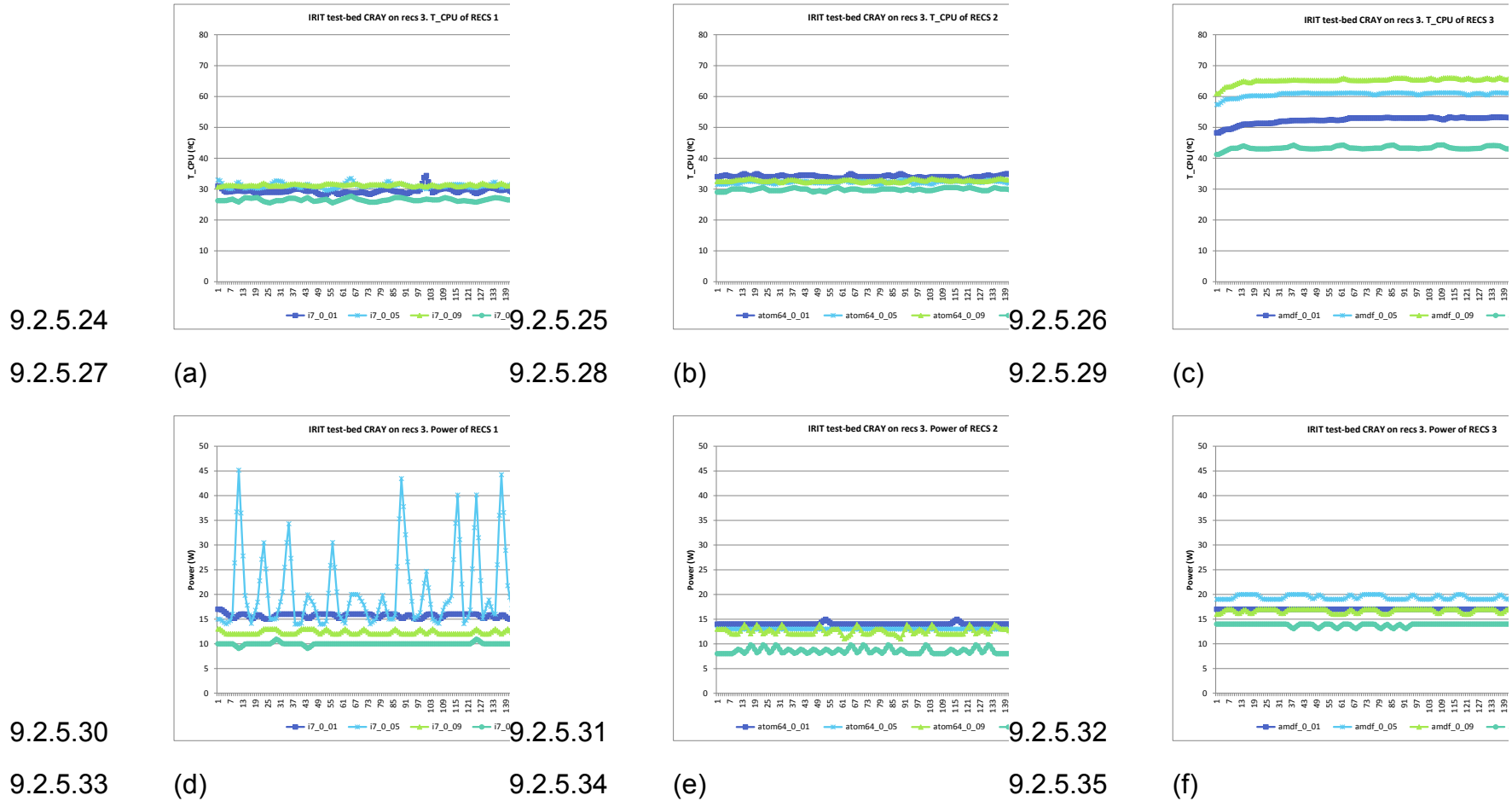
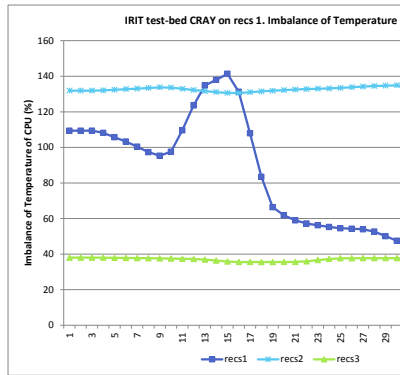
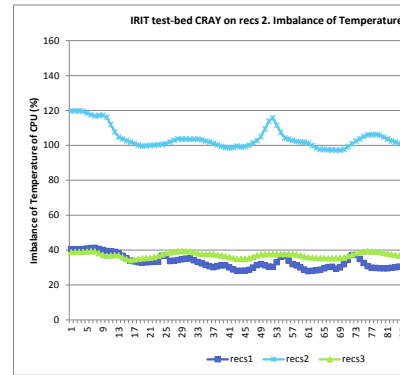


Figure 9-21. CPU Temperature and power executing C-ray on recs 3. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3

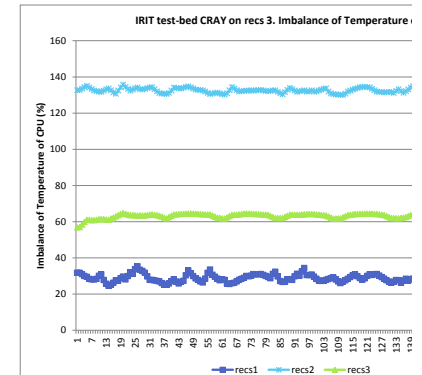
9.2.5.36



9.2.5.37



9.2.5.38



9.2.5.39

(a) recs 1

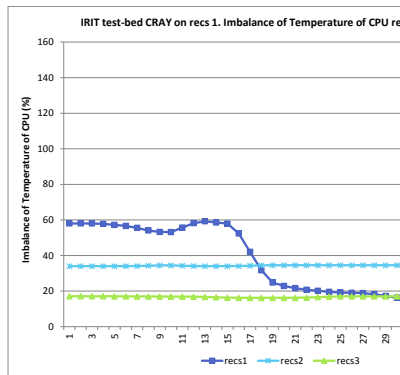
9.2.5.40

(b) recs 2

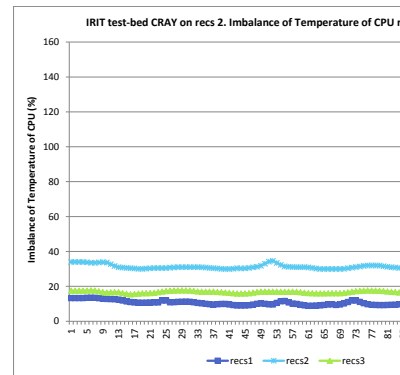
9.2.5.41

(c) recs 3

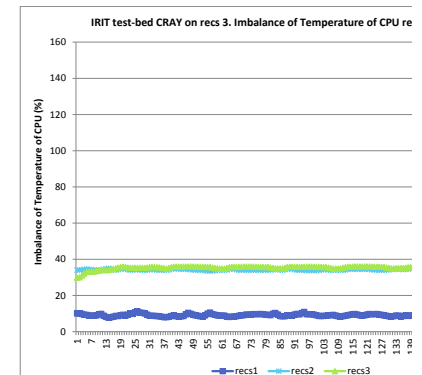
9.2.5.42



9.2.5.43



9.2.5.44



9.2.5.45

(d) recs 1

9.2.5.46

(e) recs 2

9.2.5.47

(f) recs 3

Figure 9-22. Imbalance of Temperature or CPU C-ray on recs 1 (a) recs 2 (b) recs 3 (c) and Imbalance of Temperature of CPU referred to 100 °C (d) recs 1 (e) recs 2 (f) recs 3

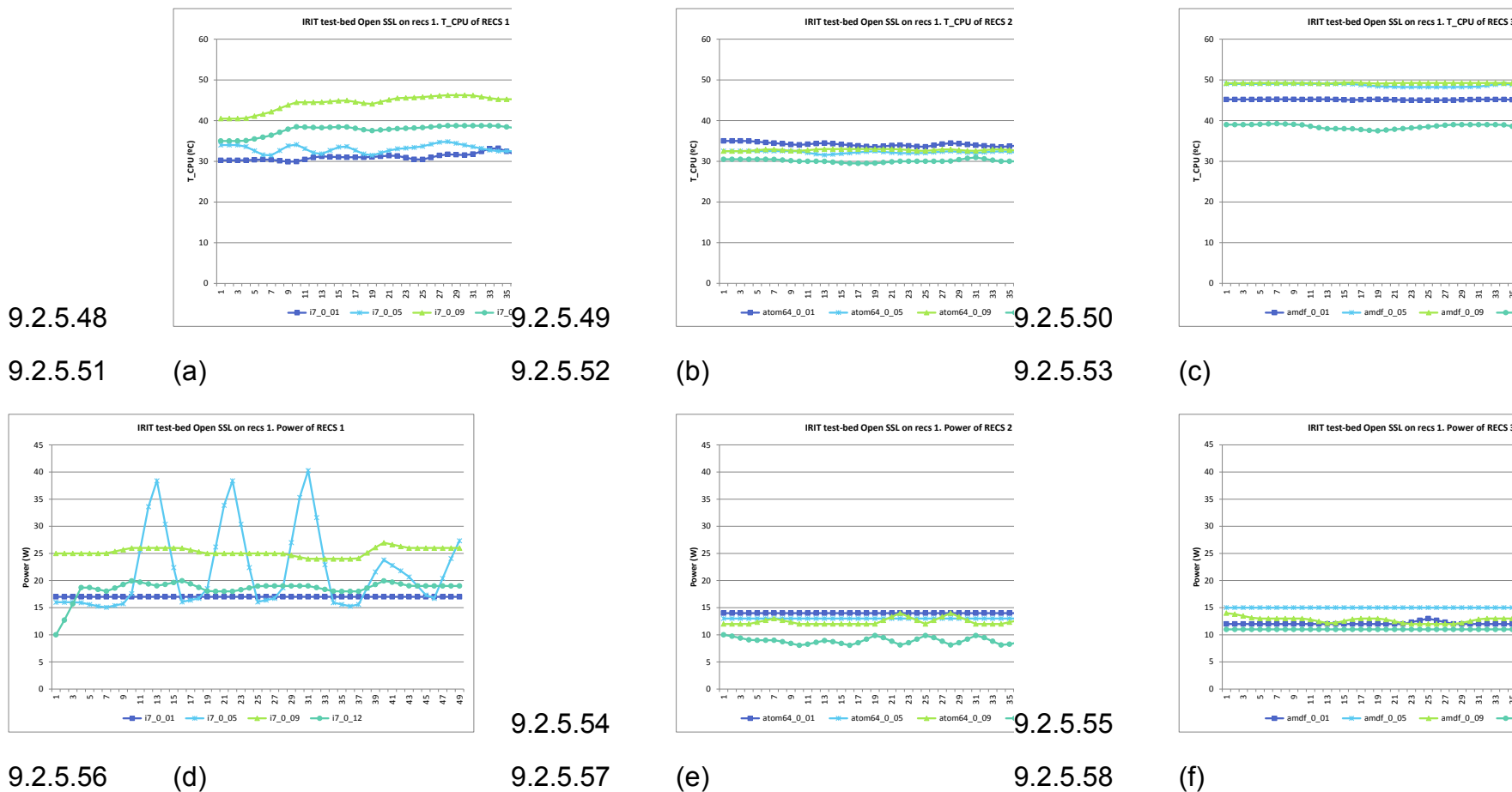


Figure 9-23. CPU Temperature and power executing Open SSL on recs 1. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3

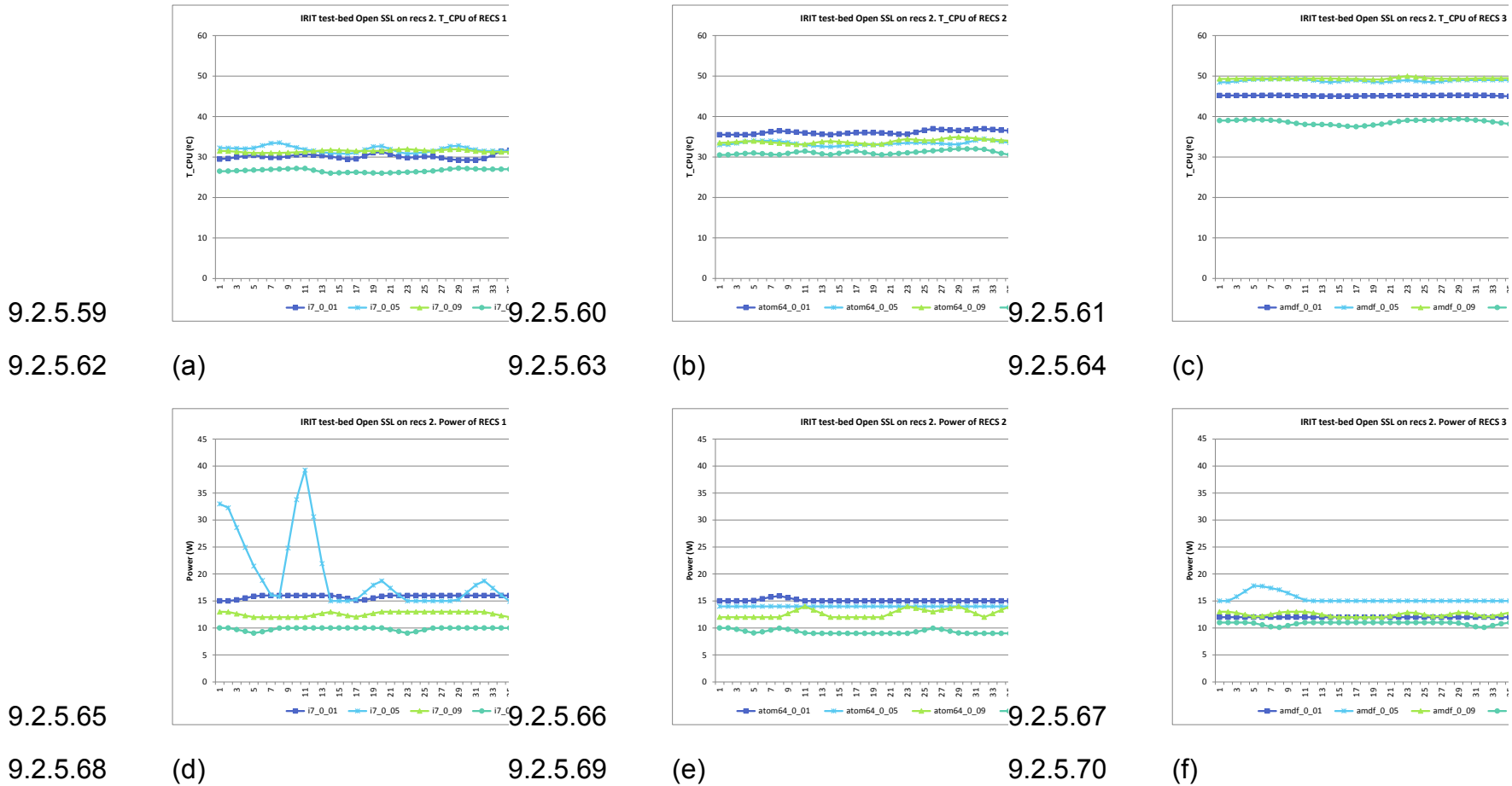


Figure 9-24. CPU Temperature and power executing Open SSL on recs 2. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3

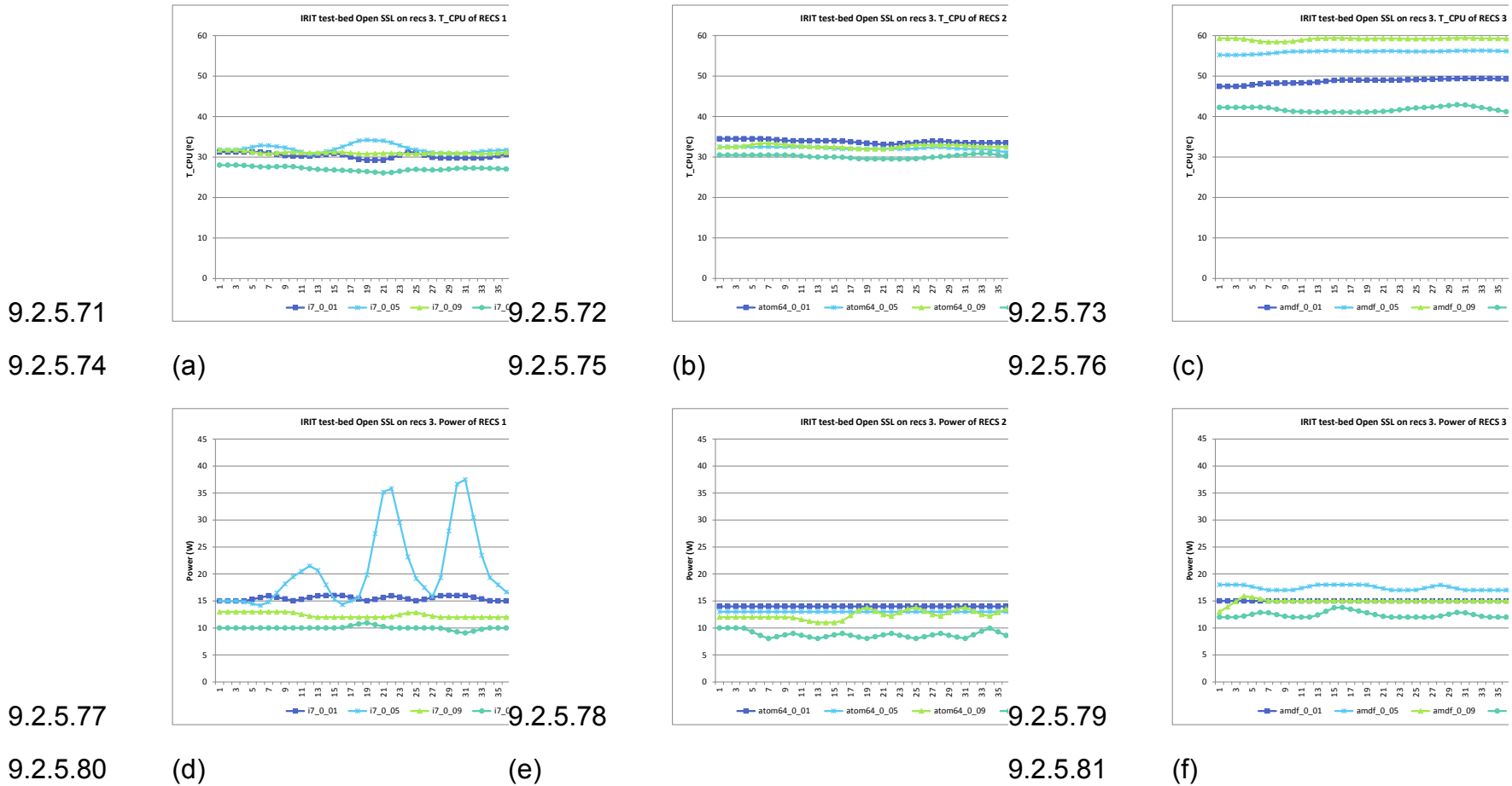
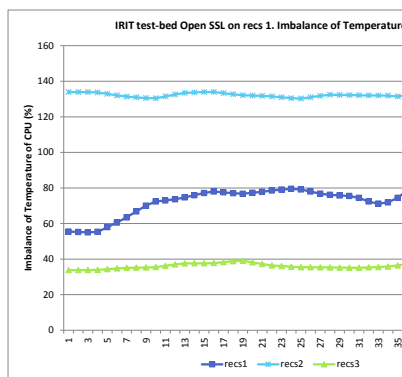
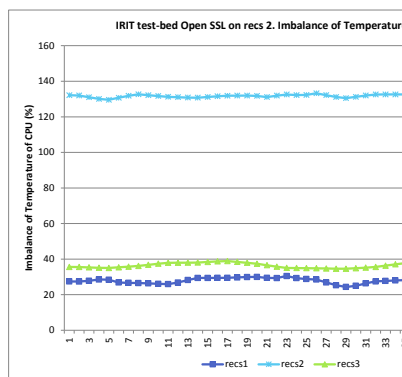


Figure 9-25. CPU Temperature and power executing Open SSL on recs 3. (a) CPU temperature recs 1 (b) CPU temperature recs 2 (c) CPU temperature recs 3 (d) power recs 1 (e) power recs 2 (f) power recs 3

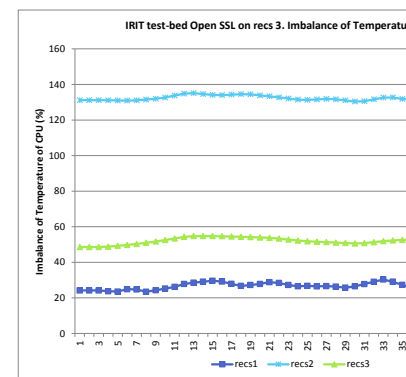
9.2.5.82



9.2.5.83



9.2.5.84



9.2.5.85

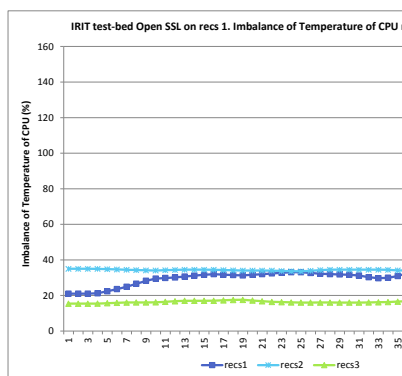
(a) recs 1

(b) recs 2

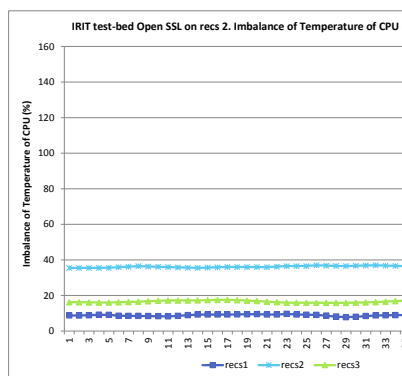
9.2.5.86

(c) recs 3

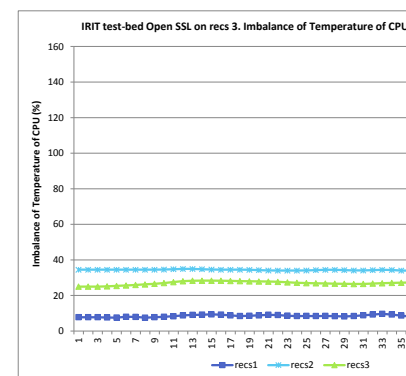
9.2.5.87



9.2.5.88



9.2.5.89



9.2.5.90

(d) recs 1

9.2.5.91

(e) recs 2

9.2.5.92

(f) recs 3

Figure 9-26. Imbalance of Temperature or CPU Open SSL on recs 1 (a) recs 2 (b) recs 3 (c) and Imbalance of Temperature of CPU referred to 100 °C (d) recs 1 (e) recs 2 (f) recs 3

The comparison between C-ray and Open SSL executed in recs 1, recs 2 and recs 3 do not show relevant differences. Only C-ray executed in recs 1 show an increase in temperature and power at the starting time-step of the application.

Recs 1 and recs 3 seem to react with changes in power and CPU temperature when application is executed but not recs 2.

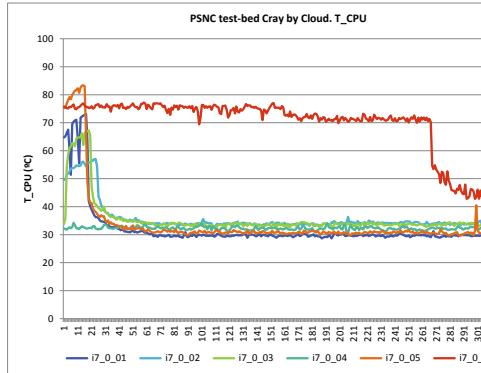
The metrics of Imbalance of Temperature performs in a more stable way to make comparison between recs when is referred to 100 °C instead of the average temperatures.

9.2.6 CPU temperature and Imbalance of Temperature of CPU based on C-ray, OpenSSL, Netloopback and StressCPU application executed in Cloud

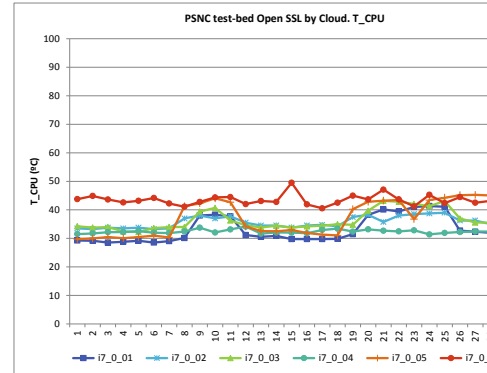
In this case, the applications C-ray, OpenSSL, Netloopback and StressCPU are executed by Cloud in the PSNC test-bed. Applications runned in six nodes recs 1 (i7_0_01 to i7_0_06).

The following figures show the performance of temperature of CPU and also the Imbalance of Temperature. In this case, power was not been properly recorded so that this is not shown in Figures.

Analysis also confirms a more stable performance of the metric Imbalance of Temperature of CPU when it is referred to 100 °C.



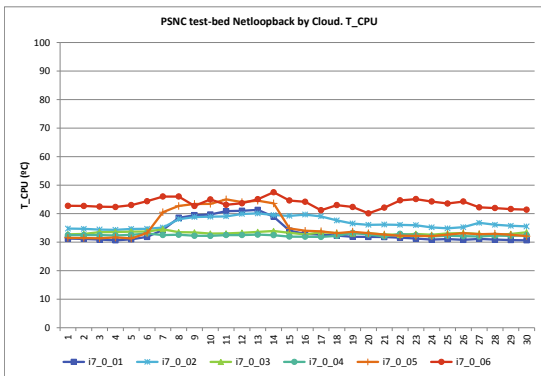
9.2.6.1



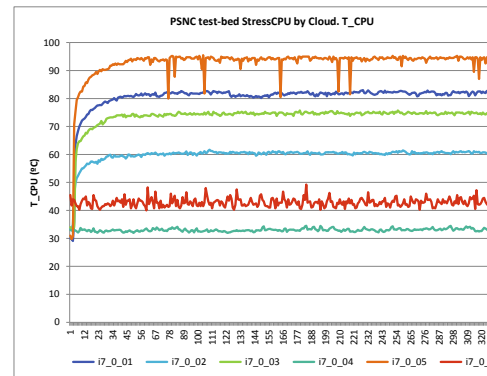
9.2.6.2

9.2.6.3 (a)

9.2.6.4 (b)



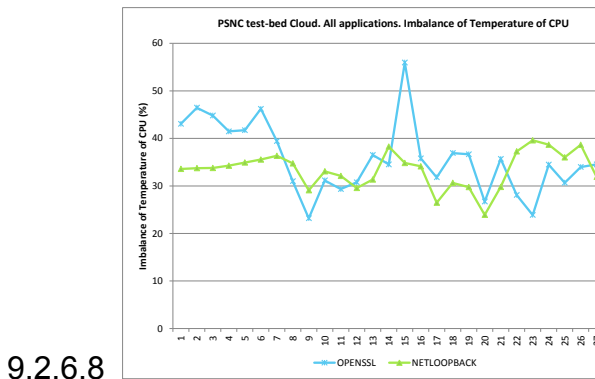
9.2.6.6 (c)



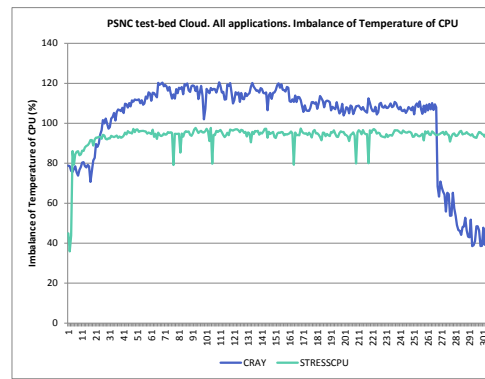
9.2.6.5

9.2.6.7 (d)

Figure 9-27. Temperature of CPU of (a) C-ray, (b) OpenSSL, (c) Netloopback and (d) StressCPU on Cloud



9.2.6.8



9.2.6.9

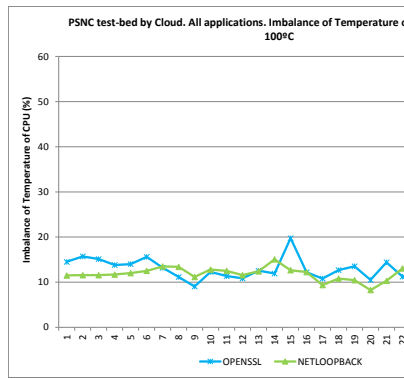
9.2.6.10

(a)

9.2.6.11

(b)

9.2.6.12



9.2.6.13

9.2.6.14

(c)

9.2.6.15

(d)

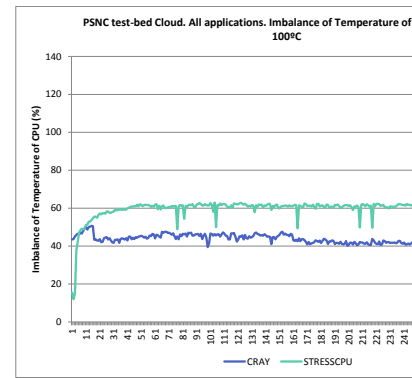


Figure 9-28. Imbalance of Temperature of CPU (a) OpenSSL and Netloopback, (b) C-ray and StressCPU on Cloud. Imbalance of Temperature of CPU referred to 100°C (c) OpenSSL and Netloopback, (d) C-ray and StressCPU on Cloud

10 Annex 4. List of available tests in Cloud Benchmark test-sui

pts/aio-stress	- AIO-Stress	Disk
pts/apache	- Apache Benchmark	System
pts/apitrace	- APITrace	Graphics
pts/battery-power-usage	- Battery Power Usage	System
pts/blake2	- BLAKE2	Processor
pts/blogbench	- BlogBench	Disk
pts/bork	- Bork File Encrypter	Processor
pts/botan	- Botan	Processor
pts/build-apache	- Timed Apache Compilation	Processor
pts/build-imagemagick	- Timed ImageMagick Compilation	Processor
pts/build-linux-kernel	- Timed Linux Kernel Compilation	Processor
pts/build-mplayer	- Timed MPlayer Compilation	Processor
pts/build-php	- Timed PHP Compilation	Processor
pts/bullet	- Bullet Physics Engine	Processor
pts/byte	- BYTE Unix Benchmark	Processor
pts/c-ray	- C-Ray	Processor
pts/cachebench	- CacheBench	Processor
pts/cairo-demos	- Cairo Performance Demos	Graphics
pts/cairo-perf-trace	- cairo-perf-trace	Graphics
pts/clomp	- CLOMP	Processor
pts/compilebench	- Compile Bench	Disk
pts/compress-7zip	- 7-Zip Compression	Processor
pts/compress-gzip	- Gzip Compression	Processor
pts/compress-lzma	- LZMA Compression	Processor
pts/compress-pbzip2	- Parallel BZIP2 Compression	Processor
pts/corebreach	- CoreBreach	Graphics
pts/crafty	- Crafty	Processor
pts/cstrike	- Counter-Strike Source	Graphics
pts/cyclictest	- Cyclictest	System
pts/dbench	- Dbench	Disk
pts/dcraw	- dcraw	Processor
pts/dolfyn	- Dolfyn	Processor
pts/doom3	- Doom 3	Graphics
pts/encode-ape	- Monkey Audio Encoding	

D5.6 Final metrics and benchmarks

pts/encode-flac	- FLAC Audio Encoding	
pts/encode-mp3	- LAME MP3 Encoding	
pts/encode-ogg	- Ogg Encoding	
pts/encode-opus	- Opus Codec Encoding	
pts/encode-wavpack	- WavPack Audio Encoding	
pts/espeak	- eSpeak Speech Engine	Processor
pts/et	- Enemy Territory	Graphics
pts/etqw	- ET: Quake Wars	Graphics
pts/etqw-demo	- ET: Quake Wars Demo	Graphics
pts/etqw-demo-iqc	- ET: Quake Wars Image Quality	System
pts/etxreal	- ETXreal	Graphics
pts/ffmpeg	- FFmpeg	Processor
pts/ffte	- FFTE	Processor
pts/fhourstones	- Fhourstones	Processor
pts/fio	- Flexible IO Tester	Disk
pts/fs-mark	- FS-Mark	Disk
pts/gcrypt	- Gcrypt Library	Processor
pts/glmark2	- GLmark2	Graphics
pts/gluxmark	- gluxMark	Graphics
pts/gmpbench	- GMPbench	Processor
pts/gnupg	- GnuPG	Processor
pts/gpu-residency	- GPU Residency	Processor
pts/gputest	- GpuTest	Graphics
pts/graphics-magick	- GraphicsMagick	Processor
pts/gtkperf	- GtkPerf	Graphics
pts/hdparm-read	- hdparm Timed Disk Reads	Disk
pts/himeno	- Himeno Benchmark	Processor
pts/hint	- Hierarchical INTegration	System
pts/hmmer	- Timed HMMer Search	Processor
pts/hpcc	- HPC Challenge	Processor
pts/hpcg	- High Performance Conjugate Gradient	Processor
pts/idle	- Timed Idle	System
pts/idle-power-usage	- Idle Power Usage	System
pts/interbench	- Interbench	System
pts/iozone	- IOzone	Disk
pts/j2dbench	- Java 2D Microbenchmark	Graphics
pts/java-scimark2	- Java SciMark	Processor
pts/jgfxbat	- Java Graphics Basic Acceptance Test	Processor
pts/john-the-ripper	- John The Ripper	Processor

D5.6 Final metrics and benchmarks

pts/juliagpu	- JuliaGPU	System
pts/jxrendermark	- JXRenderMark	Graphics
pts/lammps	- LAMMPS Molecular Dynamics Simulator	Processor
pts/lightsmark	- Lightsmark	Graphics
pts/luxmark	- LuxMark	System
pts/mafft	- Timed MAFFT Alignment	Processor
pts/mandelbulbgpu	- MandelbulbGPU	System
pts/mandelgpu	- MandelGPU	System
pts/mencoder	- Mencoder	Processor
pts/minion	- Minion	Processor
pts/mrbayes	- Timed MrBayes Analysis	Processor
pts/n-queens	- N-Queens	Processor
pts/nero2d	- Open FMM Nero2D	Processor
pts/network-loopback	- Loopback TCP Network Performance	Network
pts/nexuiz	- Nexuiz	Graphics
pts/nexuiz-iqc	- Nexuiz Image Quality	System
pts/nginx	- NGINX Benchmark	System
pts/noise-level	- NoiseLevel	Processor
pts/npb	- NAS Parallel Benchmarks	Processor
pts/open-porous-media	- Open Porous Media	Processor
pts/openarena	- OpenArena	Graphics
pts/opendwarfs	- OpenDwarfs	System
pts/openssl	- OpenSSL	Processor
pts/padman	- World of Padman	Graphics
pts/parboil	- Parboil	Processor
pts/pgbench	- PostgreSQL pgbench	System
pts/phpbench	- PHPBench	System
pts/polybench-c	- PolyBench-C	Processor
pts/postmark	- PostMark	Disk
pts/povray	- POV-Ray	Processor
pts/powertop-wakeups	- Powertop Wakeups	Processor
pts/ppracer	- Planet Penguin Racer	Graphics
pts/prey	- Prey	Graphics
pts/primesieve	- Primesieve	Processor
pts/pybench	- PyBench	System
pts/pyopencl	- PyOpenCL	System
pts/qgears2	- QGears2	Graphics
pts/quake4	- Quake 4	Graphics
pts/qvdpautest	- qVDPAutest	Graphics

D5.6 Final metrics and benchmarks

pts/ramspeed	- RAMspeed SMP	Memory
pts/reaction	- Reaction Quake 3	Graphics
pts/render-bench	- Render Bench	Graphics
pts/rodinia	- Rodinia	Processor
pts/sample-program	- Sample Pi Program	Processor
pts/scimark2	- SciMark	Processor
pts/smallpt	- Smallpt	Processor
pts/smallpt-gpu	- SmallPT GPU	System
pts/smokin-guns	- Smokin Guns	Graphics
pts/specviewperf10	- SPECViewPerf 10	Graphics
pts/specviewperf9	- SPECViewPerf 9	Graphics
pts/sqlite	- SQLite	Disk
pts/stream	- Stream	Memory
pts/stresscpu2	- StressCPU2 Stress-Test	Processor
pts/sudoku	- Sudoku	Processor
pts/sunflow	- Sunflow Rendering System	System
pts/supertuxkart	- SuperTuxKart	Graphics
pts/system-decompress-bzip2	- System BZIP2 Decompression	Processor
pts/system-decompress-gzip	- System GZIP Decompression	Processor
pts/system-decompress-tiff	- System Libtiff Decompression	Processor
pts/system-decompress-xz	- System XZ Decompression	Processor
pts/system-decompress-zlib	- System ZLIB Decompression	Processor
pts/system-libjpeg	- System JPEG Library Decode	Processor
pts/system-libxml2	- System Libxml2 Parsing	Processor
pts/systemd-boot-kernel	- Systemd Kernel Boot Time	Processor
pts/systemd-boot-total	- Systemd Total Boot Time	Processor
pts/systemd-boot-userspace	- Systemd Userspace Boot Time	Processor
pts/systester	- SysTester	Processor
pts/tachyon	- Tachyon	Processor
pts/tf2	- Team Fortress 2	Graphics
pts/tiobench	- Threaded I/O Tester	Disk
pts/tremulous	- Tremulous	Graphics
pts/trislam	- Triangle Slammer	Graphics
pts/tscp	- TSCP	Processor
pts/ttsiod-renderer	- TTSIOD 3D Renderer	Processor
pts/unigine-heaven	- Unigine Heaven	Graphics
pts/unigine-sanctuary	- Unigine Sanctuary	Graphics
pts/unigine-tropics	- Unigine Tropics	Graphics
pts/unigine-valley	- Unigine Valley	Graphics

D5.6 Final metrics and benchmarks		
pts/unpack-linux	- Unpacking The Linux Kernel	Disk
pts/unvanquished	- Unvanquished	Graphics
pts/urbanterror	- Urban Terror	Graphics
pts/ut2004-demo	- Unreal Tournament 2004 Demo	Graphics
pts/vdrift	- VDrift	Graphics
pts/video-cpu-usage	- 1080p H.264 Video Playback	Graphics
pts/viennacl	- ViennaCL	Graphics
pts/vpxenc	- VP8 libvpx Encoding	Processor
pts/warsow	- Warsow	Graphics
pts/x11perf	- x11perf	Graphics
pts/x264	- x264	Processor
pts/xonotic	- Xonotic	Graphics
pts/xplane9	- X-Plane	Graphics
pts/xplane9-iqc	- X-Plane Image Quality	System

References

[ASHRAE, 2012] ASHRAE Handbook 2012. Heating, ventilation and air conditioning systems and equipment.

[AT, 2010] Allied Telesis: Fundamental ways to reduce data center OPEX costs, 2010. [Online]. Available: <http://www.slideshare.net/IPEXpo/dco-day-1-0950allied-telelismelvyn-wray>.

[D2.3.1] Volk, E., Piątek, W., Jarus, M., Da Costa, G., Sisó, L., vor dem Berge, M. D2.3.1: Update on hardware and software models, CoolEmAll deliverable, 2013 (not published), <http://coolemall.eu>.

[D5.1] Sisó, L., Fornós, R., Napolitano, A., Salom, J., Da Costa, G., Volk, E., Donoghue, A. D5.1 White paper on Energy- and Heat-aware metrics for computing modules, CoolEmAll deliverable, 2012, <http://coolemall.eu>.

[D5.4] Juan Luis Prieto (Atos), Georges Da Costa (IRIT), Ariel Oleksiak (PSNC), Mateusz Jarus (PSNC). D5.4: Energy and Heat-aware classification of application, CoolEmAll deliverable, 2013, <http://coolemall.eu>.

[D5.5] Georges Da Costa (IRIT), Mateusz Jarus (PSNC), Thomas Zilio (IRIT). D5.5: Energy- and Heat-aware benchmarks, CoolEmAll deliverable, 2013, <http://coolemall.eu>.

[D6.2.1] Eugen Volk (HLRS), Daniel Rathgeb (HLRS), Laura Sisó (IREC), Tomasz Piontek (PSNC), Wojciech Piatek(PSNC), Mateusz Jarus (PSNC), Thomas Zilio (IRIT), Enric Pages (ATOS). D6.2.1: Updated first CoolEmAll model trial results, CoolEmAll deliverable 2013 (not published) <http://coolemall.eu>.

[D6.4] Laura Sisó (IREC), Jaume Salom (IREC), Eduard Oró (IREC), Enric Pages (ATOS), Eugen Volk (HLRS), Hongyang Sun (IRIT), Georges Da Costa (IRIT), Micha vor dem Berge (Christmann), Wojtek Piątek (PSNC), Ariel Oleksiak (PSNC). D6.4: Impact assessment of CoolEmAll, CoolEmAll deliverable 2014 <http://coolemall.eu>

[ECB, 2011] European Central Bank

<http://www.ecb.europa.eu/home/html/index.en.html>

[EN 15603] EN 15603:2008. Energy performance of buildings. Overall energy use and definition of energy ratings.

[EPER, 2008] The European pollutant emission register

<http://www.eea.europa.eu/data-and-maps/data/eper-the-european-pollutant-emission-register-4>. Last visit: 10-01-2014.

[EUROSTAT, 2013] Eurostat. European Commission.

<http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=ten00114> [Last access 06/03/2014]

[FORREST, 2008] W. Forrest et al.: Data Centres: how to cut carbon emissions and costs, McKinsey & Company, winter 2008

[GEMIS, 2014] Global Emissions Model for Integrated Systems.

<http://www.iinas.org/gemis.html>. Last visit: 10.01.2014.

[Herrlin, 2005] Herrlin, M.K. Rack Cooling Effectiveness in Data Centers and Telecom Central Offices: The Rack Cooling Index (RCI). ASHRAE Transactions, Vol. 111, Part 2, 2005.

[Herrlin, 2007] Herrlin, M. K. Improved Data Center Energy Efficiency and Thermal Performance by Advanced Airflow Analysis. Digital Power Forum 2007. San Francisco CA September, 10-12, 2007.

[Herrlin, 2008] Herrlin, M. K. Airflow and cooling performance of data centers: two performance metrics. ASHRAE Transaction, Vol. 114, Part 2. 2008

[JIANG, 2010] Jiang, T.; Kipp, A. et al. D2.1: Layered Green Performance Indicators. Deliverable GAMES Project, 2010.

[KIPP, 2011] Kipp, A.; Jiang, T.; Fugini, M.; Salomie, I.: Layered Green Performance Indicators, Future Generation Computer Systems, 2011.

[McMILLAN, 2014] . McMillan, R.: Data Center Servers Suck — But Nobody Knows How Much. Available:

<http://www.wired.com/wiredenterprise/2012/10/data-center-servers/>. [Accessed March 2014]

[MEEUP, 2005] Kemma, R.; Park, D.: Methodology Study Eco-design of Energy-using Products MEEUP. Final report. VHK. Delft, The Netherlands. 2005. http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/methodology/index_en.htm. Last visit: 10.01.2014.

[ODCA, 2013] Open Data Centre Alliance Proof of Concept: Carbon Footprint and Energy Efficiency Rev v1.0. 2013.

[PA, 2014] <http://www.powerassure.com/>

[RASMUSSEN, 2011] Rasmussen, N.: Implementing Energy Efficient Data Centres, White Paper 114, Revision 1, Schneider Electric, 2011

[RASMUSSEN-2, 2011] Rasmussen, N.: Determining Total Cost of ownership for data center and network room infrastructure. WP 6 APC. Schneider Electric's Data Center Science Center. 2011

[SHEAD, 2014] S. Shead: Energy costs mean tough decisions for datacenter owners. Available: <http://www.zdnet.com/energy-costs-mean-tough-decisions-for-datacentre-owners-7000013799/>. [Accessed March 2014]

[TGG, 2008] Beladai, C.; Patterson, M.: The Green Grid Productivity Indicator. The Green Grid, 2008.

[TGG, 2010] Belady, C. et al.: Carbon Usage Effectiveness (CUE): A Green Grid Data Center Sustainability Metric. The Green Grid. 2010.

[TGG, 2012] Avelar, V.; Azevedo, D.; French, A. PUETM: A comprehensive examination of the metric. The Green Grid. White paper #49. 2012.

[VanGEET, 2011] Van Geet, O. Best Practices guide for energy-efficient data center design. Federal Energy Management Program. US Department of Energy. 2011

[VASAN, 2009] A. Vasan et al., Worth their Watts? - An Empirical Study of Datacenter Servers, Innovation Lab Chennai, Tata Consultancy Services Limited, India, IEEE, 2009

[451, 2012] 451 Research: The economics of prefabricated modular datacenters. 2012