Borderstep Institute for
Innovation and Sustainability

Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market

Recommendations for Future R&TD Policy

Simon Hinterholzer | Ralph Hintemann | Severin Beucker

Legal notice

Authors:

Ralph Hintemann (Borderstep Institute) | hintemann@borderstep.de

Severin Beucker (Borderstep Institute) | beucker@borderstep.de

Simon Hinterholzer (Borderstep Institute) | hinterholzer@borderstep.de

Contact person:

Simon Hinterholzer, hinterholzer@borderstep.de, +49 (0) 3030 6451 0032

Publishing information:

Part of the study "Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market" (SMART 2018/0028)

Berlin | September 2019

Partners:

Environmental Agency Austria (Umweltbundesamt Österreich)

Content

1 Introduction and background of the recommendations

The Borderstep Institute and the Environmental Agency Austria are preparing a study about "Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market" for the European Commission.

The partners already prepared calculations about the energy consumption of the cloud computing data centres (Task 1) and a description of all relevant technological elements (hardware and software) from the edge device to the data centre that are needed to provide fully fledged cloud services (Task 2).

Based on the research in Task 2 the following six areas of research and technical development have been identified and described as promising for fostering the energy efficiency of cloud computing:

- IT equipment: from edge devices to hyperscale data centres (server, storage, network)
- Infrastructure for IT environments (cooling, ventilation, power supply)
- Communication networks (wired, mobile, core)
- ICT energy metering, control and analytics for precise allocation of consumption
- Efficient cloud (scaling) management
- Efficient cloud application software

An online survey with experts who have worked on this topic confirmed the relevance of all six areas for energy-efficient cloud computing.

Even though the online consultation and the expert interviews for the development of recommendations on further R&TD policy options are still ongoing, preliminary results for the need for R&TD in each of the six identified key technological areas have been identified on the basis of the online consultation (Figure 1).

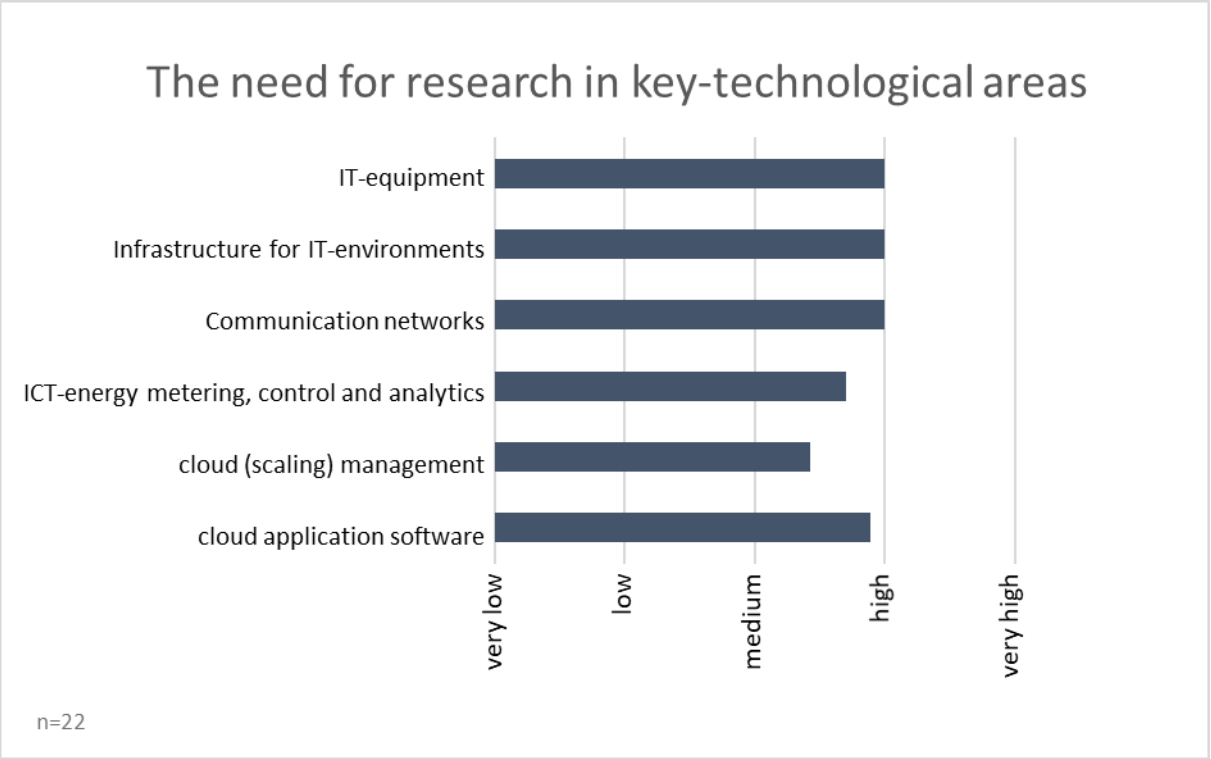


Figure 1: Need for R&TD in key technological areas - result of the online consultation

Additionally, policy recommendations for research and technological development (R&TD) are prepared and presented in this document, that are expected to contribute to energy efficiency of cloud computing in the EU-28. The main contributions of R&TD for energy efficiency in cloud computing can be grouped in four characteristic areas:

- Transparency, data availability, allocation of energy consumption and standards
- Improvement of management and operation optimization in cloud computing
- Improvement of energy efficiency in individual technological components
- Improvement of software efficiency

The ideas and suggestions presented in this paper are based on telephone interviews with various experts of various stakeholders like data centre operators, ICT manufacturers, software developers, cloud providers and scientific institutions. Also, in a two staged online survey, various stakeholders could suggest recommendations which were included as well. Similar recommendations were combined. The recommendations were discussed, adapted and prioritised with stakeholders in a validation workshop (see next chapter).

2 Workshop to validate the R&TD recommendations

A validation workshop with 33 stakeholders was conducted on September, 10th 2019 in Brussels with relevant stakeholders and various experts (see workshop report in appendix 1 for details). After the workshop, the recommendations were revised in line with the comments made at the workshop.

All suggested recommendations for future R&TD policy are listed in appendix 2 of this report.

The recommendations that were considered as priority by more than two tables are described in detail in the next chapter.

3 Priority recommendations

In the following section, the recommendations that were considered as priority recommendations by two or more groups on the R&TD validation workshop are described in the following sections detailed and possible instruments for implementation are suggested. All based on stakeholder and expert comments on the validation workshop on September 10th 2019.

3.1 REC 1. Development of KPI for the energy efficiency of cloud computing

There are already various key performance indicators (KPI) to describe the energy efficiency of ICT devices, data centres and networks, but KPI that embeds all efficiency related factors within the cloud computing continuum does not yet exist. Therefor it is recommended, that a specific KPI will be developed, that might build on some existing KPIs and combines them to describes the energy efficiency for producing a final cloud computing product. The KPI could be designed, to directly use digital available information about energy consumption of various components that are involved to provide a certain cloud service. From this basis, one day live information would be available to optimize the resource allocation within a huge cloud computing environment.

Further it could be discussed whether other (external) factors like CO2 emissions per electric unit or the reuse of waste-heat should also be considered to make it more meaningful in terms of climate protection. As a challenge it is seen that it should provide enough transparency but without disclosing infrastructure providers intellectual property.

Developing a new KPI for the energy efficiency of cloud computing and establishing it in the industry is a complex and lengthy task. A joint project of science, standardisation and pilot cloud providers could serve as a basis to clarify the scope and feasibility of such a KPI. In a further step, the KPI could be applied in pilot projects together with a standardization body and practical partners before a broad introduction can begin. Findings from the development of existing KPIs (best practice, gaps, etc.) should play a major role and be used for the development of the new KPIs.

3.2 REC 3 Research of the influence of 5G and edge computing on the energy demand of cloud computing

For 5G mobile radio it is already clear that the energy consumption per GB will be considerably lower than in previous generations, but the side effects of very small radio cells and edge services cannot yet be quantified.
Declining consumption per GB is offset by a sharp increase in data volumes, which could lead to an overall increase in energy consumption. Edge computing, which enables decentralized computing power in the network, has an impact on network topologies. Possible savings due to shorter data paths are offset by additional consumption due to the additional decentralized servers.

Basic research funding and case studies are proposed as instruments for this. The energetic effects of the component level are to be examined more closely in a holistic picture from the system level.

3.3 REC 9. Optimized load and resource management to increase relevant utilization of data servers and data centres and usage of AI

Server utilization has long been an important issue, as many servers are often idle and although they do not do any work, they still consume power. cloud providers are already incentivized to do this, as energy is one of their key costs. Also, artificial intelligence could help to optimize cloud computing resource utilization.
In any cases, a higher utilization should not result from dummy workload that has no use in the end.
Further research projects in this field are recommended. Knowledge that exists already should be better published; the code of conduct for energy efficiency in data centres could be a good example for this.

Financial support for innovative pilot projects could be an effective R&TD instrument. EU shall establish partnerships with companies already using AI for data centres and - more important - other topics.

Open source-based cloud administration tools like Kubernetes are exactly made for optimized resource usage in cloud environments. Further dissemination and use of these tools should be sought, funding of open source projects in this area could provide a better availability of these tools for smaller cloud providers.

(through overlapping, this also includes the REC 10, 20)

3.4 REC 13 Improve cloud performance analysis tools to evaluate cloud performance and energy consumption

In management of cloud resources, there is often a trade-off between performance and efficient operation. For some applications performance features like reaction delay is of higher importance, for some applications it is less important. Analysis tools can help to fit the parameters better to the requirements and thus to improve energy efficiency. There are already tools, that assess the performance of cloud computing, but not considering the energy consumption.

A model, that describes the real energy consumption per cloud resource (virtual machine / vCPU) as function of the already transparent usage of CPU, network RAM etc. would help to assess the energy consumption on cloud service level.

These fundamental analysis tools could help to asses the energy consumption for further cloud management tools.

To bring such tools into use, a first step requires basic research with field trials. If this results in suitable products in the form of independent programs or program libraries, further market-related measures in the area of GPP and regulation will probably be required for the dissemination of such tools.

3.5 REC 15 Communication aware application

In the optimization of cloud computing in terms of energy efficiency many factors are relevant. For the perspective of a cloud-based application it is for example highly relevant, to which point on the internet it exchanges data. In a cloud environment, there might be data pieces that are available in many places (like edge nodes or different data centre locations) and can be retrieved on many different physical routes a synchronized updated in different time interval. In order to optimise energy efficiency in coordination with other relevant parameters such as speed and latency and, awareness of the relevant network is required. If these findings are available, applications themselves can optimise their energy efficiency and QoS locally as required.
For contributions here, the existing research on future networks should be encouraged to focus more on efficiency enhancement as a cross-cutting issue. Technologies closely related to this are software-defined networks and network functions in 5 G mobile radio networks, among others.

3.6 REC 21 Reuse of heat generated by data centres

The use of waste heat from data centres can be implemented with existing technologies, which is already common in the Scandinavian countries. However, individual technologies can be further developed, such as liquid cooling of all elements of server systems.

However, the demand for heat depends on regional conditions. If necessary, processes such as adsorption and absorption cooling can be considered to use excess heat for cooling.

There is a risk that, with higher heat requirements and better IT-efficiency, data centres will deliberately be operated inefficiently in order to achieve the heat quantities. However, the study authors believe that monetary mechanisms can prevent this for example by guaranteeing that per kWh of heat a lower price is reimbursed than a data centre operator pays per kWh of electricity (additional heat generation in servers always creates additional costs).

Effective instruments are mostly demonstration projects for specific use cases for heat consumers and technology related pilots for hot fluid cooling.

3.7 REC 30 General research on central cloud computing vs. decentralised edge computing in terms of energy efficiency

Edge computing is growing very strongly and according to various market forecasts it will continue to grow strongly in the coming years. However, it is unclear how this will affect overall energy efficiency.

What is known, however, is that there are some trade-offs in energy efficiency if one takes a holistic view. While some components are relieved in the network, additional power consumption is generated by the decentralized computing units. However, these are subject to completely different framework conditions (if necessary direct cooling, longer maintenance cycles, other types of workload, etc.), which makes an assessment of the effects on energy efficiency very complex.

The integration of the topic of energy efficiency into general research projects on edge computing should be aimed at. In addition, own research projects with a specific focus on energy efficiency and climate protection could be financed.

3.8 Energy efficient programming (in general)

The program code design of an applications has a high impact on energy consumption. Studies have shown that sometimes very similar applications cause completely different consumption of IT capacity (CPU load/RAM/network) and thus different energy consumption. The so called law of Wirth (N. Wirth, 1995) blames software to getting slower as hardware becomes faster. Software can be seen as a big factor for energy efficiency when the final cloud computing product is compared with the energy consumed.

Software development therefore should focus more on efficient code to provide the same functions on less hardware and thus with less energy. Partly this could be delivered through better knowledge about energy efficient software development; especially in cloud computing. Partly this could be reached with a study that produces developer guidelines for energy efficient software development. To achieve a wider dissemination, this could be done in cooperation with a relevant cloud computing software association like the cloud native computing foundation. In a second step, it could be investigated, how these developer guidelines can be provided for training of software developers.

Appendix 1: Workshop report on "Validation workshop on research and technological development of energy efficiency in cloud computing"

September 10, 2019 | 'the office brussels' Rue d'Arlon 80, 1040 Bruxelles, Belgium

Agenda

09:00 Registration

Welcome, session aims, agenda and process

Bertil Heerink, Environmental Agency Austria

Peter Woodward, Facilitator

Why is this agenda an EC priority area?

Pierre Chastanet & Dirk Von Rooy, DG Connect

Energy demand of cloud computing, development and trends

Dr. Ralph Hintemann, Borderstep Institute

Keynotes from industry, standardisation and research

Alban Schmutz, OVH Group

Dr. Andreas Hantsch, Cloud&Heat Technologies GmbH

Thomas H. Wegmann, CEN/CENELEC/ETSI

Dr. Vlad Coroamă, ETH Zürich

11:00 *Refreshments*

Development of the recommendations,

Simon Hinterholzer, Borderstep Institute

Introduction to the workshop

Peter Woodward, Facilitator

Exploration Area 1: Transparency, data availability, allocation of energy consumption and standards

Introduction to recommendations

Table discussions for verification, additional ideas for policy options

Feedback to plenary with comments by 'popup' panel

12:40 *Lunch*

Exploration Area 2: Management and operation optimization in cloud computing

Introduction to recommendations

Table discussions for verification

Feedback to plenary with comments by 'popup' panel

Exploration Area 3: Technological innovation support for specific issues and software efficiency

Introduction to recommendations

Table discussions for verification

Feedback to plenary with comments by 'popup' panel

15:30 *Refreshments*

Conclusions in plenary

Final opportunity to suggest recommendations

Group/plenary/panel discussion

Closing remarks

16:30 Close

Minutes

Welcome, session aims, agenda and process (Bertil Heerink, Environmental Agency Austria)

Why is this agenda an EC priority area? (Pierre Chastanet & Dirk von Rooy, DG Connect)

Pierre Chastanet and Dirk von Rooy explain that the issues of digitisation and sustainability have a very high priority in European politics and in the EU Commission. Digitization has a disruptive character for all industries. The topic of energy efficiency in cloud computing represents a major challenge for the future. How will the digital infrastructure of the future be structured? Centralized or decentralized? The results of the project and the workshop will be of great importance for the future activities of the EU Commission in this field.

Energy demand of cloud computing, development and trends (Dr. Ralph Hintemann, Borderstep Institute)

Dr. Hintemann reports on the study results on the development of the energy demand of cloud data centres in Europe. The presentation is attached to the workshop report.

Keynotes from industry, standardisation and research (Alban Schmutz, OVH Group, Dr. Andreas Hantsch, Cloud&Heat Technologies GmbH, Thomas H. Wegmann, CEN/CENELEC/ETSI, Dr. Vlad Coroamă, ETH Zürich)

The presentations of Dr. Hantsch, Mr. Wegmann are available on https://www.cloudefficiency.eu/workshop1

Mr. Schmutz from the OVH Group make the following statement on the subject.:

- Public sector datacentres, often under efficient in terms of energy consumption, should be closed, and workloads migrated to the cloud. The example of a strong move of the public sector would also help private sector to follow the same path.
- Considering that power consumption of datacentres depends only of the Cloud infrastructure providers is wrong: only the developers of application may have an impact on the way their applications use computing resources.
- Any policy developed at EU level needs to take into account SMEs, and should not lead to push them out of the market. This warning concern both the SMEs providing Cloud infrastructure, and worse, all the SMEs that are software vendors. Creating burdens for EU SMEs in a worldwide market may lead to reinforce competitive advantage of non-EU companies against our ecosystems.

Development of the recommendations (Simon Hinterholzer, Borderstep Institute)

Simon Hinterholzer describes how the recommendations for future R&TD policy have been developed in the stakeholder process. The presentation is attached to workshop report.

Exploration Area 1: Transparency, data availability, allocation of energy consumption and standards

The first workshop session deals with the topics transparency, data availability, allocation of energy consumption and standards.

Dr. Severin Beucker briefly introduces the topics. Subsequently, the eight recommendations are discussed and prioritized in five groups. The following table shows which of the recommendations were prioritised in the groups. The groups summarize their discussions on fact sheets and present the essential points in the plenum.

	Recommendation	**Number of groups that have prioritised the recommendation**
1	Development of KPI for the energy efficiency of cloud computing	5
2	Detailed management system and sensing to gather data to use those for adjusting the runtime environments	1
3	Research of the influence of 5G and edge computing on the energy demand of cloud computing	2
4	Metering tool for software applications regarding their energy consumption / Development of dedicated library for accounting at the OS level.	1
5	New energy measurement/monitoring solutions for existing DCs with moderate installation cost/lead time.	1
6	Development of standards to describe the energy efficiency of individual components of the cloud computing ecosystem	1
7	Investigation of necessary transparency requirements of energy related data for cloud providers (information relevant for research) / Integration of cloud products in online benchmark platform	
8	Public information about life cycle of cloud products + Comparison of alternatives	1

Exploration Area 2: Management and operation optimization in cloud computing

The second workshop session deals with the topics Management and operation optimization in cloud computing.

Simon Hinterholzer briefly introduces the topics. The twelve recommendations are again discussed and prioritized in five groups. The following table shows which of the recommendations were prioritised in the groups. Fact sheets were again drawn up for the prioritised recommendations. The main points of discussion were presented to the plenum.

	Recommendation	Number of groups that have prioritised the recommendation
9	Optimized load and resource management to increase relevant utilization of data servers and data centres	4
10	Artificial intelligence to optimize cloud performance and reduce power consumption	2
11	Self-organising self-managing heterogenous cloud architectures and extending this paradigm to the edge./ Development of new architectures from Cloud to Thing with self-management and self-optimization	1
12	Development of new data centre concepts for the reduction of data traffic (e.g. fog computing)	0
13	Improve cloud performance analysis tools to evaluate cloud performance and energy consumption	3
14	Development of integrated power measurement and energy management systems for cloud architectures	1
15	Communication aware application to decrease data transfers.	2
16	Development of software that is able to control its service quality in comparison to energy consumption	1
17	Cloud native programming (provisioning, runtime, logging)	
18	Decentralized pre processing of data	
19	Further dissemination and wider use of orchestration/management tools like Kubernetes for efficient operation	
20	Further improve the publicly available orchestration tools (like Kubernetes).	2

Exploration Area 3: Technological innovation support for specific issues and software efficiency

In the third topic area “Technological innovation support for specific issues and software efficiency”, 17 recommendations were presented and discussed. Dr. Hintemann briefly introduces the topic. Before the discussion in working groups, the group composition was changed. During the discussion, the further recommendation "Research to increase the overall network energy efficiency" (recommendation 38) was developed. The working groups have again drawn up fact sheets on the individual recommendations discussed. The following table shows which of the recommendations were prioritised in the groups.

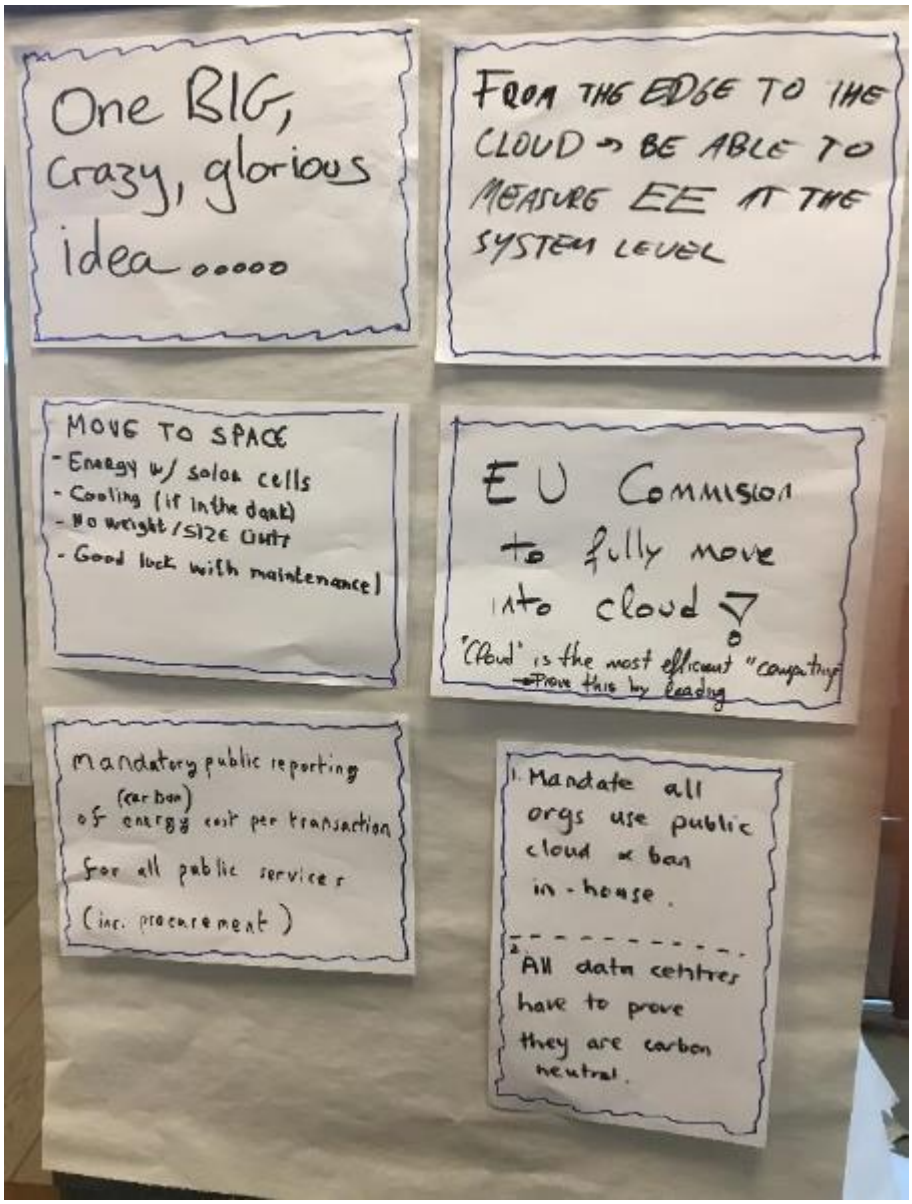
	Recommendation	Number of groups that have prioritised the recommendation
21	Reuse of heat generated by data centres	4
22	Use of artificial intelligence to optimise data centres, in particular to reduce the energy consumption of cooling systems	

23	Hardware acceleration and new SoC design	1
24	New communication strategies such as on-device machine learning and analog transmission	
25	"Standby ready" equipment and architectures	1
26	Modular computing (multiprocessing computer system where processing, memory, and peripheral units can be added or removed without disrupting its operation)	
27	Efficient chip cooling	
28	Water cooling of servers, storage systems and network components	
29	Use of quantum computers for dedicated applications	
30	General research on central cloud computing vs. decentralised edge computing in terms of energy efficiency	3
31	Energy efficient programming (in general)	2
32	Developer guidelines for energy efficient programming	1
33	Training of software developers, Increase awareness of energy-efficient programming	1
34	Slim/efficient design of hypervisor	
35	New programming languages for coding energy efficient cloud application	
36	Development of dedicated library for accounting at the OS level	
37	Develop tools that can easily assess the energy consequences of variations of programming (use of accelerators, data locality, data movements, ...).	
38	Research to increase the overall network energy efficiency	1

Conclusions in plenary

In the concluding discussion, the results of the validation workshop were briefly summarized. It is decided that the recommendations will be revised and adapted on the basis of the results recorded in the fact sheets of the discussion groups. The updated recommendations and the minutes of the workshop will be sent to all participants.

In a discussion round in five working groups, ideas were discussed on how cloud computing could use significantly less energy in the future. The ideas were briefly presented by the groups. The following figure shows the - not coordinated - ideas of the individual groups.


One BIG, crazy, glorious idea .....
FROM THE EDGE TO THE CLOUD → BE ABLE TO MEASURE EE AT THE SYSTEM LEVEL
MOVE TO SPACE
- Energy w/ solar cells
- Cooling (if in the dark)
- No weight / size limit
- Good luck with maintenance!
EU Commision to fully move into cloud
"Cloud" is the most efficient "computing"
→Prove this by leading
Mandatory public reporting of (carbon) energy cost per transaction for all public services (inc. procurement)
1. Mandate all orgs use public cloud ∝ ban in-house.
2. All data centres have to prove they are carbon neutral.

Appendix 2: All Recommendations

Here are all recommendations listed. The field workshop priority represents the figure how many stakeholder groups (tables) at the workshop on R&TD policy options on September 9th 2019 considered this recommendation as important.

Main focus on "Transparency, data availability, allocation of energy consumption and standards"

Recommendation	workshop priority[1]
REC 1: Development of KPI for the energy efficiency of cloud computing	5

Type of contribution
Improvement of transparency, data availability, allocation of energy consumption and standards

Short description (interpretation of the study authors)
A simple comparison of energy efficiency of cloud computing products is not possible today, a suitable KPI has yet to be developed.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
indirect impact	indirect impact	indirect impact	indirect impact	indirect impact	indirect impact

[1] The workshop priority indicates how many of the working groups have prioritised the recommendations.

Recommendation	workshop priority
REC 2: Detailed management system and sensing to gather data to use those for adjusting the runtime environments	1

Type of contribution
Improvement of transparency, data availability, allocation of energy consumption and standards

Short description (interpretation of the study authors)
The configuration of the runtime environment has a high impact on how efficiently software can be operated in it. Dynamic adaptation based on monitoring data enables the runtime environment to be better adapted to the requirements of the application, thereby increasing energy efficiency.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	indirect impact	indirect impact	medium impact

Recommendation	workshop priority
REC 3: Research of the influence of 5G and edge computing on the energy demand of cloud computing	2

Type of contribution
Improvement of transparency, data availability, allocation of energy consumption and standards

Short description (interpretation of the study authors)
For 5G mobile radio it is already clear that the energy consumption per GB will be considerably lower than in previous generations, but the side effects of very small radio cells and edge services cannot yet be quantified.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
medium impact	no impact	big impact	indirect impact	no impact	no impact

Recommendation	workshop priority
REC 4: Metering tool for software applications regarding their energy consumption / Development of dedicated library for accounting at the OS level.	1

Type of contribution
Improvement of transparency, data availability, allocation of energy consumption and standards

Short description (interpretation of the study authors)
Which application / which process consumes which amount of energy? A metering tool for the energy consumption of applications, potentially integrated into operating systems.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	medium impact	indirect impact	impact

Recommendation	workshop priority
REC 5: New energy measurement/monitoring solutions for existing DCs with moderate installation cost/lead time.	1

Type of contribution
Improvement of transparency, data availability, allocation of energy consumption and standards

Short description (interpretation of the study authors)
It is much more effort to integrate monitoring technologies into existing data centres than in new buildings. To this end, further technological approaches are to be researched.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
indirect impact	indirect impact	indirect impact	medium impact	no impact	indirect impact

Recommendation	workshop priority
REC 6: Development of standards to describe the energy efficiency of individual components of the cloud computing ecosystem	1

Type of contribution
Improvement of transparency, data availability, allocation of energy consumption and standards

Short description (interpretation of the study authors)
Through standardization, the complex components of cloud ecosystems can be evaluated in a uniform scheme in terms of energy efficiency.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
indirect impact	indirect impact	indirect impact	medium impact	indirect impact	indirect impact

Recommendation	workshop priority
REC 7: Investigation of necessary transparency requirements of energy related data for cloud providers (information relevant for research) / Integration of cloud products in online benchmark platform	

Type of contribution
Improvement of transparency, data availability, allocation of energy consumption and standards

Short description (interpretation of the study authors)
In order for independent science to be better able to research cloud related energy issues, it would be important for cloud providers to publish certain minimum information.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
indirect impact	indirect impact	indirect impact	indirect impact	indirect impact	indirect impact

Recommendation	workshop priority
REC 8: Public information about life cycle of cloud products + Comparison of alternatives	1

Type of contribution
Improvement of transparency, data availability, allocation of energy consumption and standards

Short description (interpretation of the study authors)
The energy consumption of operating physical hardware represents only part of the footprint of using cloud services. More knowledge must be available about the entire life cycle of manufacturing, transport, disposal, water consumption, etc.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
medium impact	medium impact	medium impact	indirect impact	no impact	indirect impact

Main focus on “Management and operation optimization”

Recommendation	workshop priority
REC 9: Optimized load and resource management to increase relevant utilization of data servers and data centres	4

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
Server utilization has long been an important issue, as many servers are often idle and although they do not do any work, they still consume power.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
indirect impact	indirect impact	indirect impact	medium impact	big impact	indirect impact

Recommendation	workshop priority
REC 10: Artificial intelligence to optimize cloud performance and reduce power consumption	2

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
Artificial intelligence offers great potential for the automatic optimization of cloud services in terms of performance and (energy) efficient operation.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
medium impact	medium impact	medium impact	big impact	big impact	medium impact

Recommendation	workshop priority
REC 11: Self-organising self-managing heterogenous cloud architectures and extending this paradigm to the edge./ Development of new architectures from Cloud to Thing with self-management and self-optimization	1

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
Cloud environments are usually operated self-organised. An efficient operation and selection of the optimum resource usage and the selection of best fitting equipment in heterogenous environments can massively improve energy efficiency of some applications.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	medium impact	big impact	medium impact

Recommendation	workshop priority
REC 12: Development of new data centre concepts for the reduction of data traffic (e.g. fog computing)	0

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
For many end-user applications, the proximity of the cloud service can help relieve traffic and thus power consumption in core and backbone networks. In certain cases, concepts of fog computing can be a favoured alternative to a central cloud.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy me-tering, control and analytics	cloud (scaling) management	cloud application software
medium impact	medium impact	medium impact	no impact	indirect impact	no impact

Recommendation	workshop priority
REC 13: Improve cloud performance analysis tools to evaluate cloud performance and energy consumption	3

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
In management of cloud resources, there is often a trade off between performance and efficient operation. For some applications performance features like reaction delay is of higher importance, for some applications it is less important. Analysis tools can help to fit the parameters better to the requirements and thus to improve energy efficiency.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy me-tering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	big impact	big impact	medium impact

Recommendation	workshop priority
REC 14: Development of integrated power measurement and energy management systems for cloud architectures	1

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
A permanently installed energy measurement and management system in cloud architectures can be used to support live optimization with regard to energy efficiency.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
indirect impact	indirect impact	indirect impact	medium impact	medium impact	medium impact

Recommendation	workshop priority
REC 15: Communication aware application to decrease data transfers.	2

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
Communication-aware software development can make a contribution to reducing data traffic on the Internet.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	big impact	medium impact	indirect impact	big impact

Recommendation	workshop priority
REC 16: Development of software that is able to control its service quality in comparison to energy consumption	1

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
Application-specific management for a comparison of the QoS with the energy consumption.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	medium impact	big impact

Recommendation	workshop priority
REC 17: Cloud native programming (provisioning, runtime, logging)	

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
Cloud environments offer very powerful tools for scaling individual application components, which enable, for example, different application parts to be scaled differently according to requirements. However, this requires cloud native programming, which is often not compatible with old application concepts (e.g. monolithic).

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	big impact	big impact

Recommendation	workshop priority
REC 18: Decentralized pre processing of data	

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
The IoT in particular will result in more and more data being generated decentral; complete processing in a central cloud would mean massive data traffic and thus increasing energy consumption in the communication networks. Decentralized pre-processing can massively reduce data traffic.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy me-tering, control and analytics	cloud (scaling) management	cloud application software
medium impact	medium impact	big impact	no impact	no impact	medium impact

Recommendation	workshop priority
REC 19: Further dissemination and wider use of orchestration/management tools like Kubernetes for efficient operation	

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
optimized resource management in cloud environment can provide services more efficient; popular examples have shown improvements of a factor 2 to 3.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy me-tering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	big impact	big impact

Recommendation	workshop priority
REC 20: Further improve the publicly available orchestration tools (like Kubernetes).	2

Type of contribution
Improvement of cloud management and operation optimization

Short description (interpretation of the study authors)
Kubernetes has still the potential to improve its functions in hindsight of efficient resource allocation.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy me-tering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	big impact	big impact

Main focus on “Improvement of energy efficiency in individual technological components”

Recommendation	workshop priority
REC 21: Reuse of heat generated by data centres	4

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
Although waste heat recovery does not reduce electricity consumption in the cloud itself, it can make a major contribution to saving energy and CO2 in nearby heat consumers.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	no impact	no impact

Recommendation	workshop priority
REC 22: Use of artificial intelligence to optimise data centres, in particular to reduce the energy consumption of cooling systems	

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
The control algorithms of cooling infrastructure in data centres still have a potential to be further optimized with artificial intelligence, especially machine learning, and for example to predict thermal situations in data centres. This will lower the PUE and save further energy in the infrastructure.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
medium impact	big impact	indirect impact	big impact	no impact	no impact

Recommendation	workshop priority
REC 23: Hardware acceleration and new SoC design	1

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
Hardware acceleration is a noble path that often increases not only performance gains but also the energy efficiency of applications. Very versatile chips (ARM, x86, GPU, ASICS...) in cloud environments can be used under certain circumstances to use the perfect hardware for each application (component).

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
big impact	no impact	big impact	no impact	no impact	no impact

Recommendation	workshop priority
REC 24: New communication strategies such as on-device machine learning and analog transmission	

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
The energy consumption of communication technologies depends strongly on the technology used and its configuration. AI-based control and alternative transmission methods have the potential to significantly reduce energy consumption.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
medium impact	indirect impact	big impact	medium impact	no impact	no impact

Recommendation	workshop priority
REC 25: "Standby ready" equipment and architectures	1

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
The energy consumption of ICT equipment in times of low utilization is still a big issue, even if the 2019 ecodesign regulation on servers and storage products will lower the idle consumption. Sending devices to complete standby and reactivating them on the basis of workload predictions has a huge potential for energy efficiency. A "standby-ready" standard or label could help to achieve this with defined wake-up times etc.

Impact on specific technological areas

IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
big impact	medium impact	big impact	no impact	no impact	no impact

Recommendation	workshop priority
REC 26: Modular computing (multiprocessing computer system where processing, memory, and peripheral units can be added or removed without disrupting its operation)	

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
Modular hot-pluggable systems facilitate the replacement of obsolete or error-prone components, especially in data centres. This can contribute to a faster renewal of hardware, which usually also has a positive effect on the CO2 footprint including production and disposal.

Impact on specific technological areas

IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
big impact	medium impact	no impact	no impact	no impact	no impact

Recommendation	workshop priority
REC 27: Efficient chip cooling	

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
Chip cooling is a critical application in ICT environments such as cloud computing. The transport of the refrigerant together with the generation of cold alone consumes the same amount of electricity as the chip itself. The limits of miniaturization in CMOS technology and thus a potential end to the Moore law make cooling all the more important.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
big impact	indirect impact	indirect impact	no impact	no impact	no impact

Recommendation	workshop priority
REC 28: Water cooling of servers, storage systems and network components	

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
Many examples have already shown that water is an excellent way to dissipate heat from ICT equipment. Current design of water cooling guarantees 100% tightness and can be operated in many regions without active chillers.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
big impact	big impact	big impact	no impact	no impact	no impact

Recommendation	workshop priority
REC 29: Use of quantum computers for dedicated applications	

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
First quantum computers are commercially available. This offers new possibilities in ICT and many applications will profit from it in performance but also in terms of energy efficiency.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	indirect impact	no impact	no impact	no impact	no impact

Recommendation	workshop priority
REC 30: General research on central cloud computing vs. decentralised edge computing in terms of energy efficiency	3

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
Supporting the research about the future impact on energy consumption of edge computing; and potential efficiency gains.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
indirect impact	indirect impact	indirect impact	indirect impact	indirect impact	indirect impact

Main focus on “Software efficiency”

Recommendation	workshop priority
REC 31: Energy efficient programming (in general)	2

Type of contribution
Improvement of software efficiency

Short description (interpretation of the study authors)
The general programming of applications has a high impact on energy consumption. Studies have shown that sometimes very similar applications cause completely different consumption of IT capacity (CPU load/RAM/network) and thus different energy consumption.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	medium impact	big impact

Recommendation	workshop priority
REC 32: Developer guidelines for energy efficient programming	1

Type of contribution
Improvement of software efficiency

Short description (interpretation of the study authors)
A guideline for developers could be created to support the development of efficient applications.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	big impact	big impact

Recommendation	workshop priority
REC 33: Training of software developers, Increase awareness of energy-efficient programming	1

Type of contribution
Improvement of software efficiency

Short description (interpretation of the study authors)
More efficient programming requires specific skills that are often not part of the training of software developers. Targeted training and sensitization to energy efficiency can make a contribution here.

Impact on specific technological areas

IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	big impact	big impact

Recommendation	workshop priority
REC 34: Slim/efficient design of hypervisor	

Type of contribution
Improvement of software efficiency

Short description (interpretation of the study authors)
The hypervisor is a central element in virtualized cloud environments. The larger and fuller the hypervisor is with pre-installed elements, the higher the specific power consumption is just to provide the virtual resources.

Impact on specific technological areas

IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	medium impact	no impact

Recommendation	workshop priority
REC 35: New programming languages for coding energy efficient cloud application	

Type of contribution
Improvement of software efficiency

Short description (interpretation of the study authors)
Completely new programming languages could be more oriented towards implementing applications more efficiently than is possible with previous programming languages and their methods.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	no impact	big impact

Recommendation	workshop priority
REC 36: Development of dedicated library for accounting at the OS level	

Type of contribution
Improvement of software efficiency

Short description (interpretation of the study authors)
A standard library in the operating system that enables monitoring and calculation of the resource consumption of applications.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	no impact	medium impact	big impact

Recommendation	workshop priority
REC 37: Develop tools that can easily assess the energy consequences of variations of programming (use of accelerators, data locality, data movements, ...).	

Type of contribution
Improvement of software efficiency

Short description (interpretation of the study authors)
Simple tools can help to estimate the effects of variations in programming. However, these still need to be developed, especially to be available to cloud application developers.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
no impact	no impact	no impact	big impact	medium impact	indirect impact

Recommendation	workshop priority
REC 38: Research to increase the overall network energy efficiency	1

Type of contribution
Improvement of energy efficiency in individual technological components

Short description (interpretation of the study authors)
The energy efficiency of network components can be further increased. So far, little attention has been paid to this topic in the use of cloud computing.

Impact on specific technological areas					
IT-equipment	Infrastructure for IT-environments	Communication networks	ICT-energy metering, control and analytics	cloud (scaling) management	cloud application software
medium impact	big impact	big impact	indirect impact	indirect impact	Indirect impact