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

FINAL STUDY REPORT

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Contact: CNECT-E2@ec.europa.eu

European Commission
B-1049 Brussels

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TABLE OF FIGURES

TABLE OF TABLES

LIST OF ABBREVIATIONS

ABBREVIATION	EXPLANATION
5G	FIFTH GENERATION TECHNOLOGY - STANDARD FOR CELLULAR NETWORKS
ACPI	ADVANCED CONFIGURATION AND POWER INTERFACE
AI	ARTIFICIAL INTELLIGENCE
API	APPLICATION PROGRAMMING INTERFACE
ARM	ADVANCED RISC MACHINE (ACORN RISC MACHINE)
ASIC	APPLICATION-SPECIFIC CHIPS
CAGR	COMPOUND ANNUAL GROWTH RATE
CDN	CONTENT DELIVERY NETWORK
CMOS	COMPLEMENTARY METAL-OXIDE-SEMICONDUCTOR
CSO	CIVIL SOCIETY ORGANISATION
CPU	CENTRAL PROCESSING UNIT
CRM	CUSTOMER RELATIONSHIP MANAGEMENT
DAS	DIRECT ATTACHED STORAGE
DER	DIGITAL ENVIRONMENTAL REPOSITORY
EED	ENERGY EFFICIENCY DIRECTIVE
EDGE DC	EDGE DATA CENTRE
DCIM	DATA CENTRE INFRASTRUCTURE MANAGEMENT
DFVS	DYNAMIC VOLTAGE AND FREQUENCY SCALING
DOCSIS	COAXIAL TV CABLE NETWORK
EB	EXABYTE
EC	EUROPEAN COMMISSION
EC2	ELASTIC COMPUTE CLOUD
EITO	EUROPEAN INFORMATION TECHNOLOGY OBSERVATORY
ERP	ENTERPRISE RESOURCE PLANNING
EU	EUROPEAN UNION
EU27	EUROPEAN UNION COUNTRIES AFTER THE UK EXIT
EUCO32325	THE EU REFERENCE SCENARIO TO ACHIEVE A SHARE OF 32% RENEWABLE ENERGY IN GROSS FINAL CONSUMPTION AND 32.5% EFFICIENCY

EUROSTAT	EUROPEAN STATISTICAL OFFICE
FPGA	FIELD-PROGRAMMABLE GATE ARRAY
FTTH/B	DIRECT FIBRE OPTIC CONNECTIONS
GB	GIGABYTE
GDP	GROSS DOMESTIC PRODUCT
GESI	GLOBAL ESUSTAINABILITY INITIATIVE
GHG	GREENHOUSE GAS
GPP	GREEN PUBLIC PROCUREMENT
GPU	GRAPHICS PROCESSING UNIT
HDD	HARD DISK DRIVE
I/O	INPUT/OUTPUT
IAAS	INFRASTRUCTURE AS A SERVICE
ICT	INFORMATION AND COMMUNICATION TECHNOLOGY
IDC	INTERNATIONAL DATA CORPORATION
IEA	INTERNATIONAL ENERGY AGENCY
IEXEC	FIRST BLOCKCHAIN-BASED DECENTRALIZED MARKETPLACE FOR CLOUD RESOURCES
ICT	INFORMATION AND COMMUNICATIONS TECHNOLOGY
IOPS	INPUT/OUTPUT PER SECOND
IOT	INTERNET OF THINGS
IP	INTERNET PROTOCOL
ISDN	INTEGRATED SERVICES DIGITAL NETWORK
ISO	INTERNATIONAL ORGANIZATION FOR STANDARDIZATION
IT	INFORMATION TECHNOLOGY
ITU	INTERNATIONAL TELECOMMUNICATION UNION
KPI	KEY PERFORMANCE INDICATOR
KW	KILOWATT
KWH	KILOWATT-HOUR
M.2	A SPECIFICATION FOR INTERNALLY MOUNTED COMPUTER EXPANSION CARDS SND ASSOCIATED CONNECTORS

MBI	MARKET BASED INDICATORS
MBPS	MEGABITS PER SECOND
MEC	MOBILE EDGE COMPUTING
MIMO	MULTIPLE INPUT-MULTIPLE OUTPUT
MW	MEGAWATT
NIST	NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
ODM	ORIGINAL DESIGN MANUFACTURER
OECD	ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
OS VIRTUALISATION	OPERATING SYSTEM VIRTUALISATION
OSI	OPEN SYSTEMS INTERCONNECTION
P-STATES	PERFORMANCE STATES
PAAS	PLATFORM AS A SERVICE
PPUE	PARTIAL POWER USAGE EFFECTIVENESS
PCLE	PCI EXPRESS
POS	PROOF-OF-STAKE
POW	PROOF-OF-WORK
PSTN	PUBLIC SWITCHED TELEPHONE NETWORK
PUE	POWER USAGE EFFICIENCY
R&T	RESEARCH AND TECHNOLOGY
RTD	RESEARCH AND TECHNOLOGICAL DEVELOPMENT
RAM	RANDOM-ACCESS MEMORY
SAAS	SOFTWARE AS A SERVICE
SDG	SUSTAINABLE DEVELOPMENT GOALS
SDN	SOFTWARE-DEFINED NETWORKING
SMD	FROM SMART MOBILE DEVICES
SME	SMALL AND MEDIUM-SIZED ENTERPRISES
SOC	ENERGY-EFFICIENT SYSTEM ON A CHIP
SSD	SOLID STATE DRIVE
TDP	THERMAL DESIGN POWER

TMR	TRANSPARENCY MARKET RESEARCH
TWH/A	TERAWATT-HOUR/YEAR
UNFCCC	UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE
UPS	UNINTERRUPTED POWER SUPPLY
VCORES	VIRTUAL (CPU) CORE
VCPUS	VIRTUAL CENTRAL PROCESSING
VM	VIRTUAL MACHINE
VPN	VIRTUAL PRIVATE NETWORK
VR	VIRTUAL REALITY

TABLE OF CONTENTS

1. Abstract

The study on “Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market” is a 16-month service contract funded by the European Commission, Directorate-General for Communication Networks, Content and Technology, which addresses the issue of exponentially growth in energy consumption due to the expansion of cloud services at a European level, covering all aspects related to the underlying technological and structural base. An overview over the relevant technological developments, as well as current voluntary and regulatory policy instruments are developed and provide insights into potentials for a reduction of energy consumption as well as suitable policy options (including Green Public Procurement) to foster eco-friendly efficient cloud services and an energy efficient data centre and network landscapes.

The final study report provides a compilation of all study activities and presents the final findings.

2. Executive Summary

The study on “Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market” which has been funded by the European Commission, Directorate-General for Communication Networks, Content and Technology, addresses the issue of the exponential growth in energy consumption due to the expansion of cloud services at a European level, as well the development of voluntary and regulatory policy instruments. In addition, suitable policy options are provided with a view to fostering ecofriendly efficient cloud services and an energy-efficient data centre and network landscape.

These topics are explored in the study, which consists of three main parts: an overview, a technological assessment and a policy analysis.

The technological part includes an analysis and modelling of the future energy demand of data centres across the EU Member States (Task 1), a technological analysis (Task 2) and an assessment of research and technological developments (RTD) (Task 4). The technology part was concluded at a stakeholder workshop with recommendations for RTD policy.

The policy analysis starts with an overview of policy instruments and the current framework for private and public procurement in the EU. The results of the analysis of existing approaches, available instruments, best practices and the results from the gap analysis (Task 3 and 5) served as a basis for the recommendations. The recommendations for policy instruments for energy-efficient cloud computing were discussed with stakeholders at a validation workshop (Task 6).

The analysis and modelling of the future energy demand of data centres across the EU Member States shows that the energy consumption of data centres in the EU28 increased from 53.9 TWh/a to 76.8 TWh/a between 2010 and 2018. This means that in 2018, data centres accounted for 2.7% of the electricity demand in the EU28. Ongoing digitisation and especially the increasing availability of cloud services are leading to a significant growth in data centre capacities. This growth is so strong that it has more than off-set the significant efficiency gains achieved at all levels (hardware, software, data centre infrastructure) and consequently, the total energy consumption of data centres in Europe has risen. Compared to 2018, the energy consumption of data centres is expected to increase by 21% to 92.6 TWh/a by 2025. While the share of cloud data centres accounted for 10% of data centre energy consumption in 2010, it increased to 35% in 2018 and is expected to rise to 60% in 2025. The share of edge data centres will also increase significantly in the future. By 2025, edge data centres are expected to account for 12% of the energy consumption of data centres in EU28.

Regionally, the biggest data centres are located in Northern and Western Europe. These regions were responsible for 82% of the energy consumption of data centres in 2018. By the year 2025, this proportion will rise to 87%. Especially for the energy consumption of data centres in Northern Europe a strong increase of 48% from 26.3 to 38.9 TWh/a is predicted for the period 2018 to 2025. The range of possible future developments in Europe is wide. If all potentials are exploited, however, it will be possible to reduce the energy consumption of data centres to the 2010 level.

The main driver for improving the computing capacity to energy consumption ratio over the past decades has been the continuous improvement of computing performance, also called Moore's Law. As the demand for computing capacity has steadily increased, the total energy demand of ICT equipment has grown as well, but at a much slower rate in relative terms. Whether the fundamental physical conditions will allow Moore's Law to continue to provide further efficiency gains is a subject of controversy.

Infrastructure efficiency and the PUE of data centres have improved over the past few years. The remaining energy-efficiency potentials are becoming smaller as technology is moving closer towards the physical limits. At the same time, unlocking the remaining potentials is becoming more complicated. Energy aware software development plays a major role in the efficiency of cloud computing, especially when it comes to compute intensive applications like crypto mining and AI. Transmission in data networks is becoming more efficient in terms of energy consumption per GB, but total energy consumption is expected to further increase due to additional networks. The rollout of new access networks (e.g. 5G, FTTH) is very fast and the goals are ambitious. At the same time, old network technologies cannot be phased out because of existing equipment inventories. This can lead to further increases in energy consumption, especially in mobile networks.

The provision of ICT resources through public cloud and edge computing offers several opportunities to increase energy-efficiency, compared to traditional data centres. Higher utilisation of compute resources, continuous renewal of custom made hardware and advantages of professional operations through cloud computing providers can lead to improved energy-efficiency. At the same time, however, cloud computing has a high risk of rebound effects due to its fast scalability and low financial entry barrier. The low hanging fruit of technology in energy-efficiency is identified and described in Task 2.

The ever increasing demand for central computing capacity in the EU due to digitisation requires high efficiency gains in order to prevent a rapid growth of energy consumption. Additional technological potentials for efficiency improvements exist already. Whether and how quickly these potentials can be tapped depends on a suitable RTD policy. An extensive dialogue with providers of cloud computing services, data centre operators, consulting firms, IT and energy experts and academic institutions has shown that there is broad agreement on the key technological areas, energy-efficiency potentials for cloud computing, the starting points for further improvements and RTD policy options.

Seven summary recommendations for a suitable RTD policy were formulated on the basis of the technology analysis and an extensive stakeholder consulting process, including an online survey, telephone interviews, and a validation workshop. In short, they are:

- Stipulate transparency requirements and foster uniform indicators for energy-efficiency
- Promote the use of cloud native optimisation tools for cloud computing
- Support technological innovation for specific issues
- Improve software efficiency

- Exploit the potential of SMEs and make SMEs cloud-ready
- Focus on researching emerging trends
- Integrate the energy-efficiency of cloud services into other RTD programmes

A screening exercise was performed investigating policy instruments and best practice examples in private and public procurement, in order to identify current practices, but also to define to which extent GPP has the potential to play a role in delivering energy-efficient cloud computing in Europe. In total, 195 sources of information relevant to procurement, Green Public Procurement, and cloud computing were identified and screened at EU and Member States level.

As regards GPP, the investigation produced the following results:

Public procurement accounts for a large share of Europe's GDP. The EU has already undertaken several actions to ensure the uptake of GPP in procurement practices, including voluntary actions such as procurement platforms and networks (e.g. ICLEI, GPP2020, The Procura +, etc.), guidelines for GPP, criteria, tools, and standards, and research projects, etc. EU actions on public procurement have a consistent focus on energy-efficiency in building, infrastructure and IT products, the vast majority of cases being related to end-user appliances. To date, the EU does not have a cloud specific procurement framework, which means that cloud service procurement has to go through the same process as any other service. In general, the topic energy-efficient cloud computing is not a mainstream argument in GPP.

The European Commission has published the documents "EU green public procurement criteria for data centres[1], server rooms and cloud services and the EU Code of Conduct on Data Centre Energy efficiency".

As evidenced by the analysis, the uptake and implementation of these criteria at the Member State level, especially in National Action Plans or in GPP, are still lagging behind. There is little awareness of cloud computing services in the GPP groups and platforms. There seems to be a knowledge gap in GPP groups (GPP competence centres and GPP Advisory Groups) when it comes to energy-efficient cloud computing. In addition, the people in these groups are mostly not those who are in charge of procuring cloud based services. The topic of energy efficient cloud computing has become a priority topic on the EU political agenda and important documents like the European strategy for Data (European Commission, 2020a) and the European Green Deal (European Commission, 2019e) have been adopted. The screening exercise for the EU Member States National Action Plans and Green Public Procurement has highlighted that the topic "energy-efficiency of cloud services and data centres" has not been included in any of the screened National Action Plans or sets of criteria. Hence, there are clearly gaps in the Member States when it comes to the inclusion of GPP criteria for energy-efficient cloud computing, and especially for data centres and server rooms, in National Action Plans.

As also evidenced by the analysis, there is still a high untapped potential for GPP to deliver energy-efficient cloud services. Especially the growing demand for digital services in the public sector should be used as a momentum to promote the inclusion of GPP criteria at the national level and their implementation at the regional level. The first step should indeed be the implementation of the EC criteria at the national level.

[1] The document was published during the finalization of this report

In addition, the analysis also highlighted that several best practice examples in energy-efficient cloud computing, and especially data centres, can be identified throughout Europe. Best practice in energy-efficient data centres and server rooms includes a variety of approaches, in public as well as in private procurement. The most common approaches are:

- More efficient cooling systems
- Heat reuse, e.g. for district heating
- Virtualisation of software, optimal use of server capacity
- Energy efficient genomics
- Eco-design for infrastructure efficiency
- Use of renewable energy to supply data centres
- Construction of data centres in regions with a cold climate

Whereas many examples of implemented energy-efficient data centres can be found, little to no evidence is available for energy–efficient cloud services for networks, data transmission and coding. There are only examples in research, but they have never been commercialised.

As evidenced by the analysis, some EU Member States are developing their digital roadmaps (e.g. Austria, United Kingdom, Slovakia, Italy), but, environmental aspects are not taken into account. The roadmaps tend to focus on aspects like “paving the way towards a digital future” and on internet accessibility, covering data security, transmission, and the building of infrastructures, especially in the light of the digital transformation which is expected to happen in the next few years. National digital plans should therefore include energy-efficiency aspects for cloud services in the future, in order to put this important aspect on the political agenda.

For most of the analysed policy instruments of public and private procurement, no evaluations of their feasibility and effectiveness for energy-efficiency are available. But even if any effects on energy-efficiency could be shown in evaluations, it is possible that energy-efficiency improvements are at least partly due to other factors such as independent technological developments or economic trends, and are not only caused by a policy instrument.

The study reveals that due to the nature of cloud computing and the diversity of cloud service providers, no blueprint for a policy instrument or a policy instrument mix for energy-efficient cloud computing is available. The transferability of the results for policy instruments used in ICT or data centres to policy instruments suitable for cloud computing is restricted. Nevertheless, existing instruments can – to varying degrees – be used as a starting point or at least as an inspiration for further developments or new designs of such instruments. An example of such an instrument is the EU Code of Conduct on Data Centre Energy efficiency, which can be used as a solid basis for a step-by-step development of a Code of Conduct for cloud computing.

As with the recommendations for RTD (developed for the technology part of the study), the recommendations for policy instruments fostering energy-efficient cloud computing were presented at a stakeholder workshop. They include the following types of policy instruments:

- information and raising awareness measures
- transparency enhancing measures

- guidelines for energy-efficient cloud computing
- certification schemes
- labels
- incentives
- standards
- adaptations of the legislative framework
- options to stimulate energy efficient cloud computing in GPP
- policy awareness raising
- development & innovation fostering measures

During the workshop, recommendations were ranked by the participants, hence the outcome of the workshop is a series of validated and prioritised policy recommendations for energy-efficient cloud computing in the EU. One instrument alone will not be enough to sufficiently improve energy-efficiency in cloud computing. Additionally, some recommendations and policy instruments from the R&D work package (Task 4) will be needed either for complementary actions or as a basis for some of the recommendations listed under Task 6. E.g. better metrics might provide important information for the development of a cloud footprint or a virtual smart meter (see recommendation No 3).

While the study was being conducted, important policies and strategies were developed by the European Union that partly also refer to energy-efficient cloud computing, e.g. the European Green Deal (European Commission, 2019e) and the European strategy for data (European Commission, 2020a). The recommendations of the study need to be embedded in a framework for the digital sector such as the European Green Deal. Under the European Green Deal, the Commission will also consider measures to improve the energy-efficiency and circular economy performance of the digital sector itself, from broadband networks to data centres and ICT devices. The Commission will also assess the need for more transparency as regards the environmental impact of electronic communication services and more stringent measures when deploying new networks (European Commission, 2019e). Framework conditions for cloud computing are also a topic that is mentioned in the European strategy for data (European Commission, 2020a). As stated in the European strategy for data (European Commission, 2020a), the European Commission is planning that a coherent framework should be in place by 2020 for the different applicable rules (including self-regulation) for cloud services, in the form of a ‘cloud rulebook’. In the first instance, the ‘cloud rulebook’ will offer a compendium of existing cloud codes of conduct and certification on security, energy-efficiency, quality of service, data protection and data portability. In the area of energy-efficiency, earlier action will be considered. (European Commission, 2020a).

3. Résumé

L'étude sur les «Technologies et politiques efficaces sur le plan énergétique d'informatique en nuage pour un marché de l'informatique en nuage respectueux de», réalisée dans le cadre d'un marché de services d'une durée de 16 mois, est une étude financée par la direction générale des réseaux de communication, du contenu et des technologies de la Commission européenne. Elle traite de la problématique de la croissance exponentielle de la consommation énergétique engendrée par l'expansion des services d'informatique en nuage à l'échelle européenne, en abordant tous les aspects technologiques et structurels qui entrent en jeu. Elle dresse un état des lieux des évolutions technologiques en lien avec la problématique posée ainsi que des moyens d'action volontaires ou réglementaires actuellement mis en œuvre, avant d'explorer les potentiels de réduction de la consommation énergétique ainsi que les leviers d'action envisageables (notamment les Marchés publics écologiques) propres à promouvoir des services d'informatique en nuage efficaces et respectueux de l'environnement ainsi qu'un environnement de réseaux et de centres de données efficaces sur le plan énergétique.

Le rapport d'étude final compile l'ensemble des travaux menés dans le cadre de l'étude et en présente les conclusions.

4. Résumé Exécutif

L'étude sur les «Technologies et politiques efficaces sur le plan énergétique d'informatique en nuage pour un marché de l'informatique en nuage respectueux de l'environnement», financée par la direction générale des réseaux de communication, du contenu et des technologies de la Commission européenne, traite de la problématique de la croissance exponentielle de la consommation énergétique engendrée par l'expansion des services d'informatique en nuage (cloud) à l'échelle européenne, et de l'élaboration de moyens d'action volontaires et réglementaires. Elle présente, en outre, les leviers d'action envisageables visant à promouvoir des services d'informatique en nuage efficaces et respectueux de l'environnement ainsi qu'un environnement de réseaux et de centres de données efficaces sur le plan énergétique.

Ces thématiques sont explorées dans l'étude, qui se compose de trois volets principaux : un état des lieux, une évaluation technologique et une analyse des mesures envisageables.

Le volet technologique comprend une analyse et une modélisation de la demande future en énergie liée aux centres de données dans les États membres de l'UE (tâche 1), une analyse technologique (tâche 2) et une évaluation des travaux de recherche et de développement technologiques (tâche 4). Le volet technologique s'est achevé par la formulation de recommandations pour la politique de RDT (recherche et développement technologiques) lors d'un atelier réunissant les parties intéressées.

L'analyse des leviers d'action débute par une vue d'ensemble des moyens d'action et par une présentation du cadre actuel d'approvisionnement dans l'UE, dans le secteur privé comme dans le secteur public. Les résultats de l'analyse des approches existantes, des moyens d'action disponibles et des bonnes pratiques ainsi que les résultats de l'analyse des écarts (tâches 3 et 5) ont permis de formuler des recommandations. Les moyens d'action recommandés en faveur d'une informatique en nuage efficace sur le plan énergétique ont été discutés avec les parties intéressées lors d'un atelier de validation (tâche 6).

L'analyse et la modélisation de la demande future en énergie liée aux centres de données dans les États membres de l'UE révèle que la consommation énergétique des centres de données (data centres) dans l'UE-28 est passée de 53,9 TWh/an à 76,8 TWh/an entre 2010 et 2018. Cela signifie qu'en 2018, les centres de données représentaient 2,7% de la demande en électricité de l'UE-28. La transformation numérique qui est en cours et, en particulier, le nombre croissant de services d'informatique en nuage disponibles entraînent une augmentation significative de la capacité des centres de données. Cette augmentation est si forte qu'elle a plus que neutralisé les gains d'efficacité notables réalisés à tous les niveaux (matériel, logiciels, infrastructure des centres de données) et qu'au total, on observe une hausse de la consommation énergétique des centres de données au niveau européen. Par rapport à 2018, la consommation énergétique des centres de données devrait augmenter de 21% pour atteindre 92,6 TWh/an en 2025. En 2010, les centres de données d'informatique en nuage (cloud data centres) représentaient 10% de la consommation des centres de données. Ce pourcentage est passé à 35% en 2018 et devrait atteindre 60% en 2025. La part des centres de données en périphérie de réseau (edge data centres) va également augmenter de manière significative. D'ici 2025, leur consommation énergétique devrait représenter 12% de la consommation énergétique de l'ensemble des centres de données de l'UE-28.

Sur le plan géographique, les plus gros centres de données sont situés dans les pays du nord et de l'ouest de l'Europe. Ces régions représentaient 82% de la consommation énergétique des centres de données en 2018. Cette proportion atteindra 87% à l'horizon 2025. La consommation énergétique en Europe du Nord spécifiquement imputable aux centres de données devrait enregistrer une forte hausse (de 28%) pour passer de 26,3 à 38,9 TWh/an entre 2018 et 2025. L'éventail des perspectives envisageables en Europe est large. Cependant, si tous les potentiels sont exploités, il sera possible de réduire la consommation énergétique des centres de données à des niveaux inférieurs à ceux de 2010.

Le principal facteur d'amélioration du ratio capacité informatique/consommation énergétique au cours des dernières décennies a été la constante amélioration des performances informatiques suivant ce qu'il est convenu d'appeler « la loi de Moore ». La demande de capacité informatique n'ayant cessé de croître, la demande totale en énergie des équipements des TIC a également augmenté mais à un rythme comparativement bien inférieur. La question de savoir si les contraintes physiques permettront de continuer à générer des gains d'efficacité selon la loi de Moore est sujette à controverse.

L'efficacité des infrastructures et l'indicateur d'efficacité énergétique des centres de données se sont améliorés ces dernières années. Les potentiels d'amélioration de l'efficacité énergétique s'amenuisent à mesure que la technologie s'approche de ses limites physiques. Parallèlement, les potentiels restants sont de plus en plus difficiles à exploiter. Le développement de logiciels sobres en énergie joue un rôle important dans l'efficacité énergétique de l'informatique en nuage, notamment pour les applications nécessitant une forte puissance de calcul comme le minage de cryptomonnaies et l'IA. L'énergie consommée pour la transmission d'un Go de données sur les réseaux baisse, mais la consommation d'énergie totale devrait continuer d'augmenter du fait de l'augmentation du nombre de réseaux. Le déploiement de nouveaux réseaux d'accès (5G, FTTH par exemple) est très rapide et les objectifs affichés sont ambitieux. Il est impossible d'abandonner par ailleurs les anciennes technologies de réseaux du fait des stocks d'équipements existants. Cela peut conduire à de nouvelles augmentations de la consommation d'énergie, notamment sur les réseaux mobiles.

La fourniture de ressources en TIC par le biais de l'informatique en nuage public (cloud public) ou en périphérie de réseau offre plusieurs possibilités d'augmenter l'efficacité énergétique par rapport aux centres de données classiques. Une meilleure exploitation des capacités de calcul, un renouvellement permanent de matériels sur mesure et les avantages des services professionnels offerts par les fournisseurs de services informatiques en nuage peut conduire à une amélioration de l'efficacité énergétique. L'informatique en nuage comporte toutefois parallèlement un risque élevé d'effet de rebond, qui tient à sa considérable extensibilité et à la faible barrière financière à l'entrée. La solution technologique la plus simple pour améliorer l'efficacité énergétique est identifiée et décrite dans le cadre de la tâche 2.

Dans l'UE, la demande sans cesse croissante en capacités informatiques centralisées, liée à la transformation numérique en cours, requiert d'importants gains d'efficacité pour empêcher une augmentation rapide de la consommation d'énergie. D'autres potentiels technologiques d'amélioration de l'efficacité existent d'ores et déjà. Pouvoir les exploiter, et les exploiter rapidement, nécessite une politique de RDT adaptée. Un dialogue soutenu avec les fournisseurs de services informatiques en nuage, les opérateurs de centres de données, les cabinets de consultants, les experts en informatique et en énergie et les établissements universitaires a fait ressortir un large consensus sur les domaines technologiques clés, les potentiels d'économie d'énergie pour l'informatique en nuage, les pistes de réflexion pour d'autres améliorations et les leviers d'action envisageables en matière de RDT.

Sept recommandations sommaires pour une politique de RDT adaptée ont été formulées sur la base de l'analyse technologique et d'une vaste consultation des parties intéressées, qui a consisté en une enquête en ligne, des entretiens téléphoniques et un atelier de validation. En résumé, ces recommandations sont les suivantes:

- Formuler des exigences de transparence et promouvoir des indicateurs uniformes permettant de mesurer l'efficacité énergétique;
- Promouvoir, pour l'informatique en nuage, l'utilisation d'outils d'optimisation développés nativement pour le nuage;
- Soutenir l'innovation technologique pour des problématiques spécifiques;
- Améliorer l'efficacité des logiciels;
- Exploiter le potentiel des PME et préparer ces dernières à l'informatique en nuage;
- Mettre l'accent sur la recherche sur les tendances émergentes;
- Intégrer la problématique de l'efficacité énergétique des services d'informatique en nuage dans d'autres programmes de RDT.

Les moyens d'action et des exemples de bonnes pratiques sur les marchés privés et publics ont été examinés afin d'identifier les pratiques actuelles, mais aussi de définir dans quelle mesure les Marchés publics écologiques (MPE) peuvent influer sur la fourniture, en Europe, de services d'informatique en nuage efficaces sur le plan énergétique. Au total, 195 sources d'informations pertinentes sur l'approvisionnement, les Marchés publics écologiques et l'informatique en nuage efficace sur le plan énergétique ont été identifiées et étudiées au niveau de l'UE et des États membres.

S'agissant des MPE, l'enquête a produit les résultats suivants :

Les marchés publics représentent une part importante du PIB de l'Europe. L'UE a déjà mis en place plusieurs actions visant à assurer l'intégration des principes des MPE dans les pratiques de passation de marché, notamment des actions volontaires telles que des plateformes et des réseaux de passation de marchés (ICLEI, GPP2020, Procura +, par exemple), des lignes directrices pour les MPE, des critères, des outils ainsi que des normes, des projets de recherche, etc. Les actions de l'UE relatives aux marchés publics mettent constamment l'accent sur l'efficacité énergétique dans les domaines de la construction, des infrastructures et des produits informatiques – des appareils destinés aux utilisateurs finals dans la vaste majorité des cas. À l'heure actuelle, l'UE ne dispose pas d'un cadre spécifique pour la passation de marchés relatifs à l'informatique en nuage, ce qui signifie que la passation de marchés de services d'informatique en nuage est soumise à la même procédure que n'importe quel autre service. En règle générale, la thématique de l'efficacité énergétique de l'informatique en nuage n'est pas tellement présente dans les MPE.

La Commission européenne a établi des critères applicables aux Marchés publics écologiques (critères MPE) quant à l'efficacité énergétique dans les centres de données, dans un document qui est en cours de finalisation à l'heure de la rédaction du présent rapport. Elle est également à l'origine du Code of Conduct on Data Centre Energy efficiency (Code de conduite de l'UE pour des centres de données efficaces sur le plan énergétique).

Comme le révèle l'analyse, l'intégration et l'application de ces critères au niveau des États membres, notamment dans des plans d'action nationaux ou dans les MPE, ont pris du retard. Les groupes et plateformes dédiés aux MPE sont peu sensibilisés à la question de l'efficacité énergétique des services d'informatique en nuage. Il semble exister un déficit de connaissances dans les groupes MPE (centres de compétence MPE et groupes consultatifs MPE) en matière d'informatique en nuage efficace sur le plan énergétique. De plus, les membres de ces groupes ne sont généralement pas en charge des achats de services d'informatique en nuage. La thématique de l'informatique en nuage efficace en énergie est devenu un sujet prioritaire sur l'agenda politique de l'UE et d'important documents ont été adoptés telles que la stratégie numérique de l'UE (Commission européenne, 2020a) et le pacte vert pour l'Europe (Commission européenne, 2019e). L'examen des plans d'action nationaux des États membres de l'UE et des MPE a révélé que la thématique « efficacité énergétique des services d'informatique en nuage et des centres de données » n'a été reprise dans aucun de ces plans d'action nationaux ni dans aucun des ensembles de critères examinés. Il existe donc manifestement des lacunes au niveau des États membres quant à l'inclusion, dans les plans d'action nationaux, de critères MPE pour une informatique en nuage efficace sur le plan énergétique, et notamment pour les centres de données et les salles de serveurs.

L'analyse a également révélé qu'il demeure de forts potentiels non exploités pour que les MPE débouchent sur des services d'informatique en nuage efficaces sur le plan énergétique. Il faut notamment profiter de la demande croissante de services numériques dans le secteur public pour promouvoir l'inclusion des critères MPE au niveau national et leur mise en œuvre au niveau régional. La première étape doit en effet consister en la mise en œuvre des critères de la Commission au niveau national.

L'analyse a également permis d'identifier en Europe quelques bonnes pratiques quant à l'informatique en nuage efficace sur le plan énergétique, et notamment quant aux centres de données. Les bonnes pratiques en matière de centres de données et de salles de serveurs efficaces sur le plan énergétique incluent diverses approches, dans les marchés publics comme dans les marchés privés. Les approches les plus courantes sont:

- Systèmes de refroidissement plus efficaces;
- Réutilisation de la chaleur, notamment pour le chauffage urbain;
- Virtualisation de logiciels, utilisation optimale de la capacité des serveurs;
- Génomique efficace sur le plan énergétique;
- Écoconception pour l'efficacité des infrastructures;
- Utilisation d'énergies renouvelables pour l'alimentation des centres de données;
- Construction de centres de données dans des régions au climat froid.

Si les exemples de centres de données efficaces sur le plan énergétique sont nombreux, il n'existe guère de preuves de l'existence de services d'informatique en nuage efficaces sur le plan énergétique pour les réseaux et pour la transmission et le codage de données. Les seuls exemples trouvés étaient à l'état de recherche, mais ils n'ont jamais été commercialisés.

Comme le montre l'analyse, certains États membres de l'UE élaborent leur propre feuille de route pour le numérique (l'Autriche, le Royaume-Uni, la Slovaquie ou l'Italie par exemple), mais sans prendre en compte les aspects environnementaux. Ces feuilles de route tendent à privilégier des aspects tels que « la préparation d'un avenir numérique » et l'accessibilité de l'internet, en couvrant les thématiques de la sécurité des données, de la transmission de données et de la construction d'infrastructures, eu égard notamment à la transformation numérique attendue dans les prochaines années. Les plans numériques nationaux devraient par conséquent inclure à l'avenir des critères d'efficacité énergétique pour les services d'informatique en nuage, afin de faire de cet aspect important une priorité politique.

Pour la plupart des moyens d'action analysés relatifs aux marchés publics et privés, on ne dispose d'aucune évaluation de leur faisabilité ni d'aucune mesure de leur caractère opérant en matière d'amélioration de l'efficacité énergétique. Mais même si les évaluations indiquaient des effets sur l'efficacité énergétique, il serait possible que ces améliorations résultent au moins en partie d'autres facteurs tels que des tendances économiques ou des évolutions technologiques indépendantes, et ne soient pas uniquement le fait d'un moyen d'action mis en œuvre.

L'étude révèle qu'en raison de la nature de l'informatique en nuage et de la diversité des fournisseurs de services d'informatique en nuage, on ne dispose d'aucun projet de moyen d'action ou de combinaison de moyens d'action visant à promouvoir une informatique en nuage efficace sur le plan énergétique. La possibilité de transférer les résultats obtenus avec les moyens d'action utilisés en matière de TIC ou de centres de données vers des moyens d'action spécifiques à l'informatique en nuage est limitée. Les moyens d'action existants peuvent toutefois – à des degrés divers – servir de base à l'élaboration de moyens d'action adaptés ou tout au moins en inspirer de nouveaux. Un exemple d'un tel instrument est le code de conduite de l'UE sur l'efficacité énergétique des centres de données qui peut être utilisé comme une base pour le développement étape par étape d'un code de conduite pour l'informatique en nuage. À l'instar des recommandations formulées pour la politique de RDT (élaborées pour la partie « technologie » de cette étude), des recommandations relatives aux moyens d'action en faveur d'une informatique en nuage efficace sur le plan énergétique ont été présentées lors d'un atelier réunissant les parties intéressées. Elles incluent les types de moyens d'action suivants:

- mesures d'information et de sensibilisation;
- mesures visant à améliorer la transparence;
- lignes directrices pour une informatique en nuage efficace sur le plan énergétique;
- schémas de certification;
- labels;
- incitations;
- normes;
- adaptations du cadre législatif;
- propositions permettant de favoriser une informatique en nuage efficace sur le plan énergétique dans les MPE;
- sensibilisation à la politique menée;
- mesures en faveur du développement et de l'innovation.

Lors de l'atelier, les recommandations ont été classées par les participants. Le résultat de l'atelier consiste donc en une série de recommandations, validées et classées par ordre de priorité, en faveur d'une informatique en nuage efficace sur le plan énergétique au sein de l'UE. Une mesure seule ne produira pas une amélioration suffisante de l'efficacité énergétique dans le domaine de l'informatique en nuage. Il faudra la compléter par quelques recommandations et moyens d'action issus des travaux de R&D (tâche 4), soit pour des actions complémentaires soit pour servir de base à certaines des recommandations citées dans le cadre de la tâche 6. De meilleurs indicateurs peuvent, par exemple, fournir des informations importantes pour le développement d'un calculateur d'empreinte écologique pour l'informatique en nuage ou d'un système de mesure virtuel intelligent (voir recommandation no 3).

Alors que l'étude était en cours, l'Union européenne a défini d'importantes orientations et stratégies, qui se rapportent également en partie à l'informatique en nuage efficace sur le plan énergétique, notamment le Pacte vert (Commission européenne, 2019e) et la stratégie européenne en matière de données (Commission européenne, 2020a). Il est souhaitable que les recommandations formulées dans l'étude soient reprises dans un cadre propre au secteur numérique de type Pacte vert. Dans le cadre du Pacte vert, la Commission envisagera également des mesures visant à améliorer l'efficacité énergétique et les performances en matière d'économie circulaire du secteur numérique lui-même, depuis les réseaux à haut débit jusqu'aux centres de données et aux dispositifs des TIC. La Commission évaluera également la nécessité d'une plus grande transparence quant à l'impact environnemental des services de communication électronique, ainsi que de mesures plus strictes lors du déploiement de nouveaux réseaux (Commission européenne, 2019e). Les conditions d'encadrement de l'informatique en nuage sont également une thématique mentionnée dans la communication Une stratégie européenne pour les données (Commission européenne, 2020a). Comme précisé dans ce document (Commission européenne, 2020a), la Commission européenne prévoit de mettre en place d'ici 2020 un cadre cohérent rassemblant les différentes règles applicables (y compris l'autorégulation) aux services en nuage, sous la forme d'un « recueil réglementaire de l'UE pour l'(auto)régulation de l'informatique en nuage ». Ce « recueil réglementaire » comprendra tout d'abord un recueil des codes de conduite et des certifications existants pour l'informatique en nuage en ce qui concerne la sécurité, l'efficacité énergétique, la qualité des services, la protection des données et la portabilité des données. Une action plus précoce sera envisagée dans le domaine de l'efficacité énergétique (Commission européenne, 2020a).

5. INTRODUCTION

Rationale & scope

The present study examines the demand for electrical energy caused by cloud computing, the decisive factors which influence this electricity consumption and how electricity consumption can be expected to develop in the future.

Cloud computing

Based on the most commonly used definition of Cloud Computing by the National Institute of Standards and Technology (NIST) (Mell & Grance, 2011), this document refers to a theoretical model for providing IT resources in different service and provisioning models, with the requirement to enable certain characteristics.

Based on the NIST definition, the power consumption of cloud computing can therefore be regarded as part of the power consumed by typical applications of information and communication technology (such as data centres and communication networks). The power consumption of cloud computing includes the consumption of IT resources that are used directly (e.g. servers) or indirectly (e.g. access networks) for the provision of cloud products. In addition, the energy consumption of secondary infrastructure such as cooling or power supply is taken into account.

For the analysis of power consumption and energy-efficiency, direct components such as servers or storage are taken into account, as are indirectly used components such as the access network of local telecommunications or mobile communications providers.

Energy-efficiency

According to the definition of the EU Parliament, energy-efficiency represents "the ratio of output of performance, service, goods or energy, to input of energy" (Gregor Erbach, 2015). This definition can also be applied to cloud computing, bearing in mind that an increase in energy-efficiency in the ICT sector does not automatically lead to a reduction in absolute energy consumption, but is often compensated or even overcompensated by a growth or rebound effect. If this definition of energy-efficiency is applied to cloud computing, the output depends on the service model. For IaaS and PaaS, output can be represented in terms of usable virtual resources, such as the number of virtual machines or vCPUs, or the amount of virtual storage (file, block, or object storage). However, some further criteria (RAM, network connection, etc.) have to be considered in order to assess the output objectively.

The output of SaaS products is much more versatile and, accordingly, more heterogeneous, since the output is strongly dependent on the individual application. A cross-application comparison of "output per energy consumed" is not possible here. Output can at most be application-specific for different products/providers. However, especially in the area of cloud computing, there are more and more products that combine elements from different cloud environments and possibly also on premise systems, making it very difficult to assign a cloud application to a specific physical ICT or its power consumption.

In addition, the administration and management software of cloud providers is also highly relevant for energy-efficiency. This includes, for example, the algorithms that are responsible for the distribution and scaling of virtual machines, automatic backups of cloud storage, or the control of physical hardware.

The range of resources used for cloud computing

Especially some of the indirectly used ICT components are also used for other purposes at the same time, which makes a direct assignment of components and their energy consumption to cloud computing very difficult. A good example are networks that are also used for other services such as classic online services (e.g. peer-to-peer) or telephony etc., which, according to the NIST definition, cannot be described as cloud services.

A distinction between different components is relevant if total cloud energy consumption is to be determined at EU27 level and if the energy consumption of the large number of physical components is to be assigned to cloud computing. However, to analyse and describe the individual physical components and their specific energy consumption and to calculate their potential for energy saving, the differentiation is of little importance. All compo-nents that are relevant for the provision of cloud computing can be examined, regardless of whether they are also used in other contexts. The same applies to the various software components, for example for virtualisation, scaling or the geographical distribution/provision of cloud services.

Related research

In existing studies, for example, it was investigated what savings cloud computing can achieve compared to the traditional provision of IT resources or online services such as e-mail (Masanet et al., 2014). The results of these studies can be considered qualitatively, but cannot be applied to the entire range of cloud products, as these would not be possible without the concept of cloud computing.

Another scientific field investigates the indirect energy savings through the enabling effects of ICT (GeSI & Accenture Strategy, 2015). The present study focuses on the energy consumption of cloud computing through the application of various technologies; external effects of the usage of cloud applications are not considered.

In light of this, the European Commission's Directorate General for Communications Networks, Content & Technology (DG CONNECT) launched in December 2018 a study on "Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market" for a period of 16 months. This study is jointly carried out by Umweltbundesamt GmbH and Borderstep Institute in order to analyse the current and future energy consumption of cloud computing services in Europe, to develop a roadmap for RTD in the area of energy-efficient cloud computing and ICT and to develop policy measures for driving the cloud market towards energy-efficiency.

6. USE OF CLOUD COMPUTING - CURRENT SITUATION AND FRAMEWORK SCENARIO

Current situation

Cloud computing is changing the way IT is used. While in the 2000s the operation of IT hardware and software ("on premise") was still the norm for companies and other organizations, cloud services are increasingly becoming the dominant form of IT use in the current decade. Advantages such as flexibility, scalability, lower administration costs or no investment costs mean that more and more organizations are opting to use cloud services. Cloud services are also becoming increasingly popular in the private sector - often in the form of free offers or as a flat rate service.

The trend towards more cloud computing is also having a positive effect on the economy as a whole, as confirmed by a study conducted by IDC on behalf of the European Commission - DG Communications Networks (IDC, 2015). In the baseline scenario, the GDP in the EU is expected to rise by €103 billion by 2020. That corresponds to 0.71% of the GDP. This economic growth would be linked to over 300,000 new businesses and almost 1.6 million new jobs in the EU (IDC, 2015) (Figure 1).

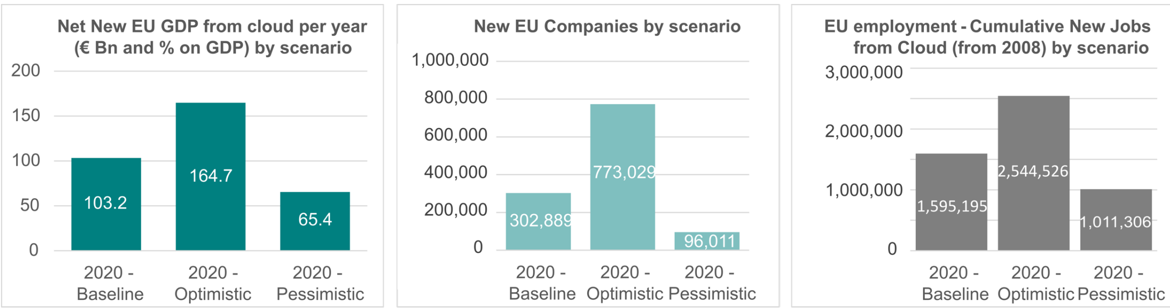

Figure 1 - EU: New GDP, companies and employment from the Cloud (Source IDC 2014)

For the above mentioned IDC study, a total of 1651 companies with 10 or more employees, in France, German, Italy, Spain and the UK, were interviewed during October 2013. About 70% of these companies used at least one public cloud service in 2015; 48% used a private cloud service. This means that the number of cloud users in the IDC survey is significantly higher than the number of cloud users in the EU calculated by Eurostat[2]. According to Eurostat, a total of 26% of the enterprises in the EU28 use cloud services; 18% use public cloud services and 11% private cloud services. Cloud use by enterprises is particularly high in Finland, Sweden and Denmark, while relatively few cloud services are used in Poland, Romania and Bulgaria (Figure 2). For the Eurostat survey, 158,000 enterprises with more than 10 employees were surveyed in all EU28 countries (Eurostat, 2018). There are only assumptions as to how the deviations in the results of the IDC survey from the Eurostat survey can be explained. It could be that IDC surveyed more of the relatively large companies. According to the Eurostat survey, 56% of the large enterprises use cloud

[2] Other studies - such as the annual Cloud Monitor used by KPMG/Bitkom in Germany (KPMG & Bitkom, 2018b) or the annual Cloud Computing Whitepaper published by the Cloud Industry Forum in the UK (CIF, 2017) - also arrive at significantly higher cloud usage rates than the Eurostat study. While the Cloud Monitor for Germany states that 66% of companies used cloud services in 2017, Eurostat assumes that the usage rate was only 22% in 2018. CIF indicates that 88% of the companies in the UK used cloud services in 2017, while the usage rate according to Eurostat was only 41.9% in 2018.

services, while only 25% of the small and medium-sized enterprises use cloud services. It is also possible that IDC, a company active in ICT market research, has increasingly reached ICT savvy companies in its survey, companies that use more cloud services than the average business.

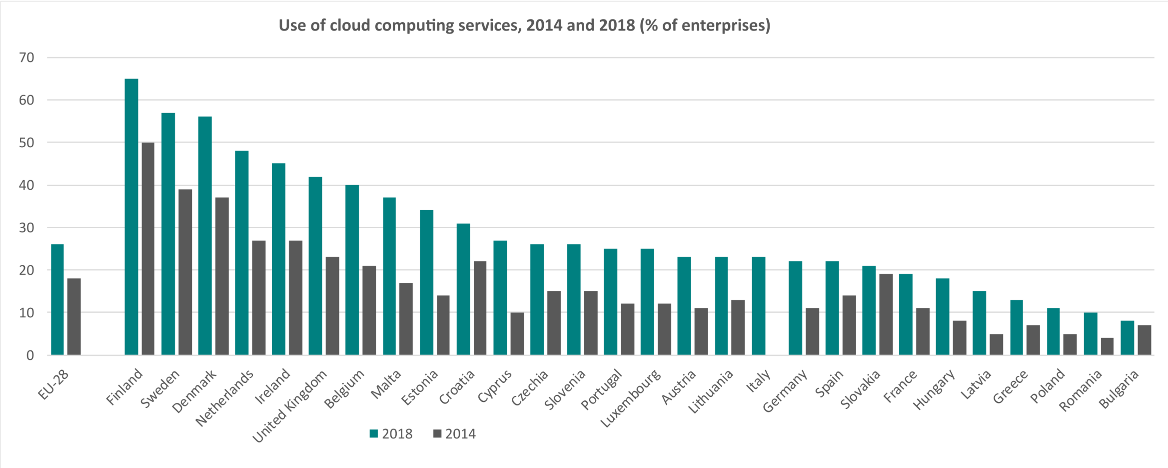

Figure 2 - Use of cloud computing services in enterprises (Eurostat, 2018)

Irrespective of the current level of the percentage of cloud users, both IDC and Eurostat conclude that the use of cloud services in enterprises is increasing significantly and that cloud use is becoming the mainstream in the EU (Eurostat, 2018; IDC, 2015). This trend is also confirmed by further studies on European markets, e.g. by Cisco (Cisco, 2018a), Bitkom/KPMG (KPMG & Bitkom, 2018b), the Dutch Data Centre Association (Dutch Data Centre Association, 2017), the Cloud Industry Forum (CIF, 2017).

The use of cloud services is also increasing in the private sector. In the EU28 countries, 56% of individuals aged 16 to 74 used the internet for social networking in 2018 (Eurostat, 2019). In the United Kingdom, Sweden, Belgium and Denmark 70 to 80% of individuals use social networks. In the three EU Member States Slovenia France and Italy, the use of social media is under 50% (Figure 3). According to Cisco, consumer applications are responsible for about 25% of workloads and compute instances in data centres worldwide. Of these, the cloud applications search, social networking and video streaming account for about 2/3 (Cisco, 2018a).

According to Cisco, the use of cloud services by enterprises and private households is already responsible for the majority of data processing, storage and transmission in data centres and networks. By 2019, nearly 90% of the workloads and compute instances[3] in data centres in Western Europe will be cloud workloads and only 10% traditional workloads. Measured in terms of the number of servers, this means that 70% of servers in Western Europe are operated as cloud servers. Measured by data centre IP traffic, cloud computing will be responsible for 93% of the traffic in Western Europe in 2019 (Cisco, 2018a).

[3] Cisco defines workload and compute instance as follows: “A server workload and compute instance is defined as a virtual or physical set of computer resources, including storage, that are assigned to run a specific application or provide computing services for one to many users.” (Cisco, 2018a)

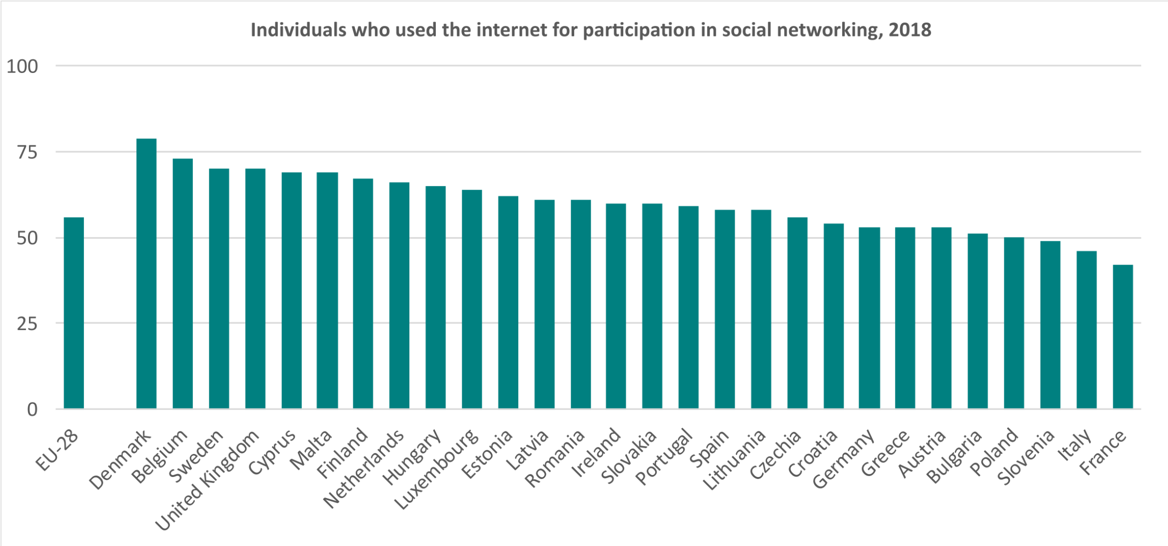

Figure 3 - Individuals who used the internet for participation in social networking, 2017 (Source: Eurostat 2018)

Cisco also provides information on how the workloads and compute instances of the cloud data centres are divided between private and public cloud services. According to these figures, around 30% of the world's cloud workloads and compute instances will be private by 2019 and 70% will be public cloud workloads and compute instances. The trend towards more public cloud services is accompanied by an increase in the number of cloud hyperscale data centres. Cisco has identified 24 cloud companies that generate billions of dollars in revenue from cloud services. The data centres operated by these companies are considered hyperscale data centres. Cisco expects the number of these data centres worldwide to increase from 338 to 628 between 2016 and 2021.According to Cisco, 53% of all data centre servers will be operated in hyperscale data centres by 2021 and 55% of data centre IP traffic will be caused by hyperscale data centres (Cisco, 2018a). The United States Data Centre Energy Usage Report assumes somewhat more conservatively that by 2020 about 40% of servers in the USA will be operated in hyperscale data centres (Shehabi et al., 2016).

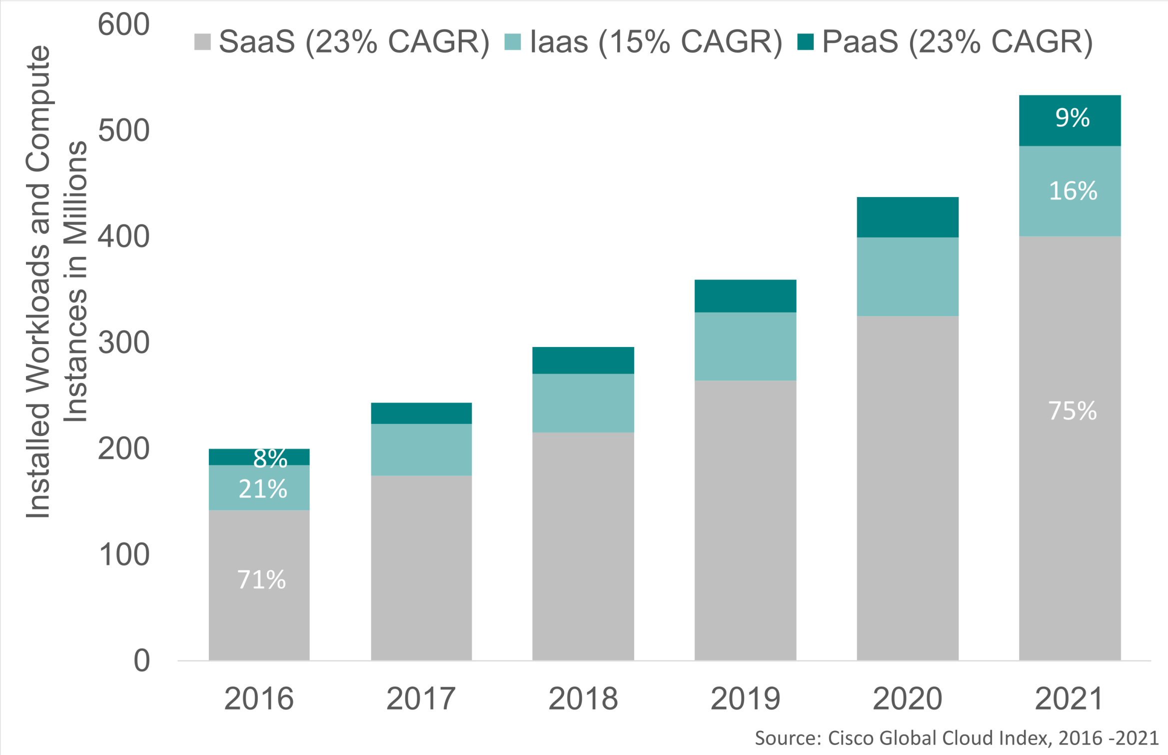

Figure 4 - Deployed global cloud services from 2016 to 2021 (Source: Cisco 2018)

If one distinguishes between the provisioning models IaaS, PaaS and SaaS, SaaS dominates in cloud services. According to Cisco, SaaS accounts for over 70% of workloads and compute instances in cloud data centres (Figure 4). This dominance of SaaS as a delivery model is confirmed by IDC's Smart 2013 study, according to which the SaaS market in the EU with a volume of € 8,477 million will account for around 75% of the total market for cloud services in 2015 (IDC, 2015).

According to Eurostat (Eurostat, 2018), companies use e-mail, storage of files and office software (Figure 5) particularly frequently as cloud services. According to IDC's Smart 2013 study, cloud services are particularly common in office collaboration; 20.1% of the companies surveyed use or plan to use cloud services. Other frequent areas of application include customer relationship management (CRM) (17%), storage (16.4%), database as a service (16.2%), security (15.4%), unified communications (15.2%) and enterprise resource planning (ERP) (14.8%) (IDC, 2015).

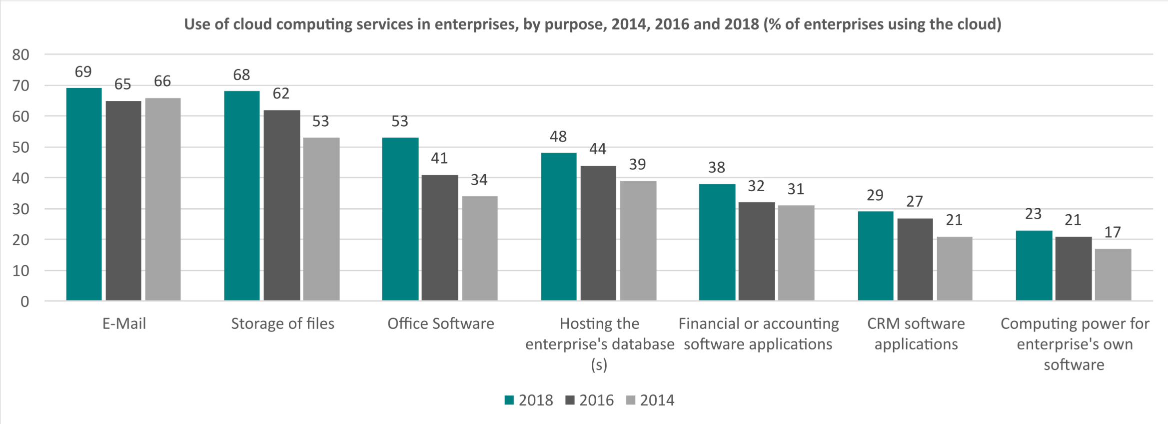

Figure 5 - Use of cloud computing services in enterprises, by purpose, 2014, 2016 and 2018 (% of enterprises using the cloud) (Source: Eurostat 2018)

In terms of industries, companies from the finance, telecommunications, media and distribution sectors in the EU make above-average use of public cloud services (Figure 6). The use of cloud services in the manufacturing sector is below average. Healthcare/education companies frequently use private cloud services (IDC, 2015).

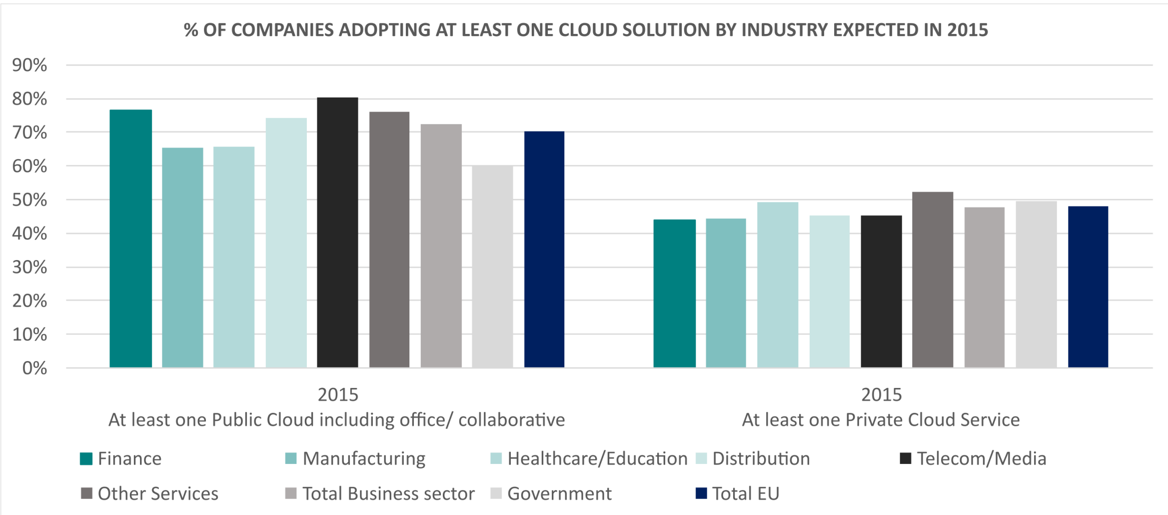

Figure 6 - Use of cloud computing by industries in 2015 (Source: IDC 2015)

Estimation of energy consumption of cloud computing

The significant increase in the use of cloud services is also leading to an increase in the energy consumption of cloud computing. However, it is very difficult to quantify exactly how much energy is needed for cloud computing. This is due to the fact that it is difficult to distinguish energy requirements from cloud services and other - traditional - services running on ICT infrastructures (Prakash et al., 2014). Determining the energy demand of cloud computing also depends on how cloud services are precisely defined. There are some studies that deal with the energy needs of cloud computing, but there is little information on how much energy cloud services require overall in data centres and networks. For example, there is a study by the Centre for Energy-Efficient Telecommunication on the energy demand of wireless cloud solutions (CEET, 2013). This study comes to the conclusion that for wireless cloud solutions 90% of the energy required arises in wireless networks and only 9% in data centres. In a case study for the USA, Masanet et al., identify energy-saving potentials through the use of cloud services. The authors estimate a technical savings potential of 87% in energy consumption if typical office applications are shifted to the cloud (Masanet et al., 2014).

In some studies and publications, the energy demand of cloud computing is simply equated with the energy demand of the entire internet (Cook, 2012; Cook et al., 2014; Hintemann & Clausen, 2016; Mills, 2013). Such an analysis provides at least an overview of the impact of cloud computing on energy demand, as cloud workloads and cloud traffic - as shown above - account for a high proportion of the overall performance of the internet. In addition, the current growth of IT infrastructures is mainly due to the growth of cloud services (Hintemann, 2018; Shehabi et al., 2016).

Several scientific studies examine the current energy consumption of data centres and networks. In the following, the results of some studies dealing with the energy requirements of data centres and network infrastructures are presented in a short overview.

Energy consumption of data centres worldwide

A study on the development of the energy demand of ICT solutions comes from Andrae und Edler (Andrae/Edler, 2015). The results of this paper have received a relatively high level of attention in the discussion about the energy consumption of data centres (Belkhir & Elmeligi, 2018; Jones, 2018; Malmodin & Lundén, 2016, 2018; Pohl & Finkbeiner, 2017). This is certainly due to the fact that Andrae/Edler forecast a strong increase in energy consumption, especially in the next decade. According to their calculations, data centres worldwide will need around 480 terawatt hours per year (TWh/a) in the expected scenario in 2018. Figure 7 shows the results of various current studies on the development of the energy demand of data centres worldwide in the years 2010 to 2018. As the figure shows, it is currently impossible to speak of a reliable state of knowledge on the development and level of the energy demand of data centres worldwide. According to the studies considered, the annual energy demand of data centres worldwide in 2018 was between 200 and 800 TWh/a.

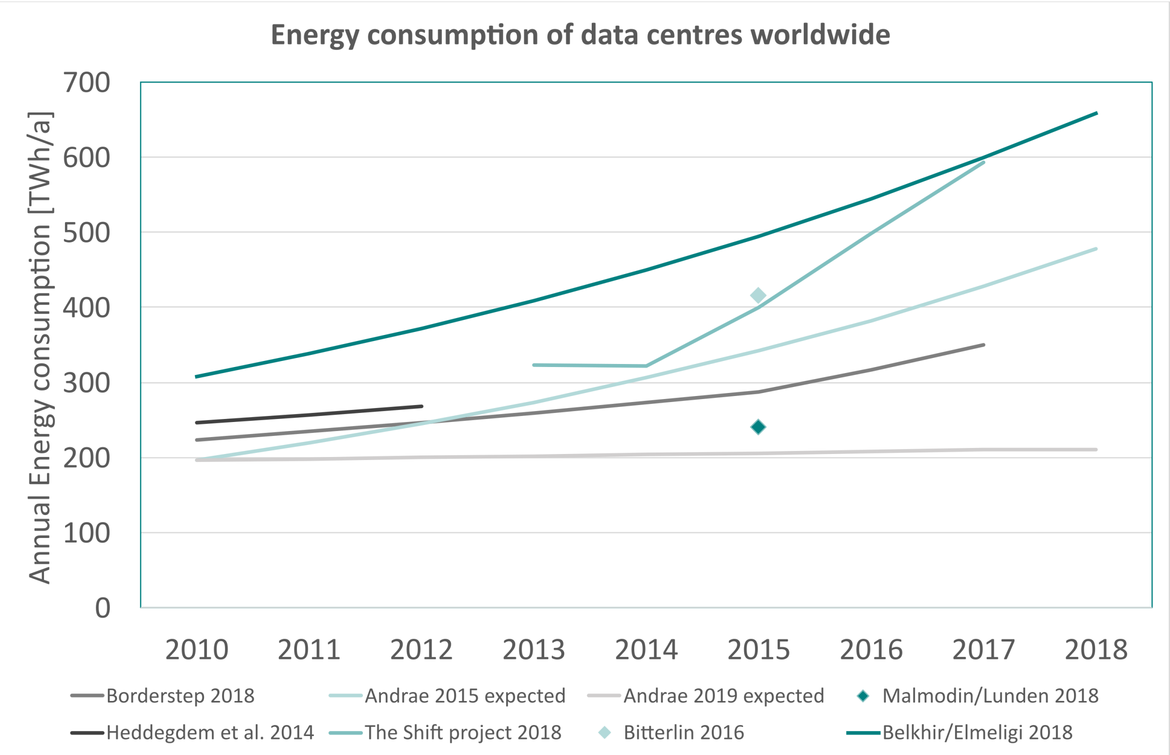

Figure 7 - Overview of studies on the current energy requirements of data centres

Energy consumption of data centres in Europe

In contrast to the global situation, the results of various studies on the energy consumption of data centres in Europe are much closer together. The preliminary Ecodesign study on enterprise servers and data devices identifies an energy consumption of 78 billion kWh for data centres in Europe by 2015 (Bio by Deloitte & Fraunhofer IZM, 2016). In a study on the practical application of the new framework methodology for measuring the environmental impact of ICT, Prakash et al., calculate an energy consumption in the EU27 of 52 billion kWh for 2011 and forecast an increase to 70 billion kWh by 2020 (Prakash et al., 2014). In 2018, Borderstep Institute estimated the development of the energy demand of data centres in Western Europe based on the development of workloads and server numbers. According to this estimate, energy consumption rose by a good 30% from 56 billion kWh in 2010 to 73 billion kWh in 2017 (Hintemann, 2018).

Energy consumption of networks

Even for the development of the energy demand of network infrastructures worldwide, it cannot be said that the available studies come to similar results. The range of results is similar to that for data centres (Figure 8). The Andrae/Edler study mentioned above calculates an annual energy demand of 600 TWh/a for fixed and mobile radio networks in 2018. In 2019, Andrae presented an update of his own calculations in which he calculated an energy demand of only 362 TWh/a per year (Andrae, 2019b). This clear difference in the calculations carried out by one individual author is a symbol of the uncertainty currently present in the calculations. A current study for the ‘shift project’ calculates an energy demand of 478 TWh/a for the year 2017 (The Shift Project, 2019). Investigations by Malmodin/Lunden (Malmodin & Lundén, 2018) and van Heddeghem et al., (Van Heddeghem et al., 2014) arrive at energy requirements between 200 and 300 TWh/a.

A rough Borderstep Institute estimation of the energy demand of network infrastructures leads to even lower energy requirements (Hintemann & Clausen, 2016). In this estimate, the energy demand of mobile and fixed networks per terminal device is determined on the basis of a study for Germany and these values are multiplied by the number of terminal devices worldwide. Since Germany is relatively well equipped with a high density of ICT devices, it seems plausible that this estimate is nearer the lower limit of the energy demand of networks worldwide.

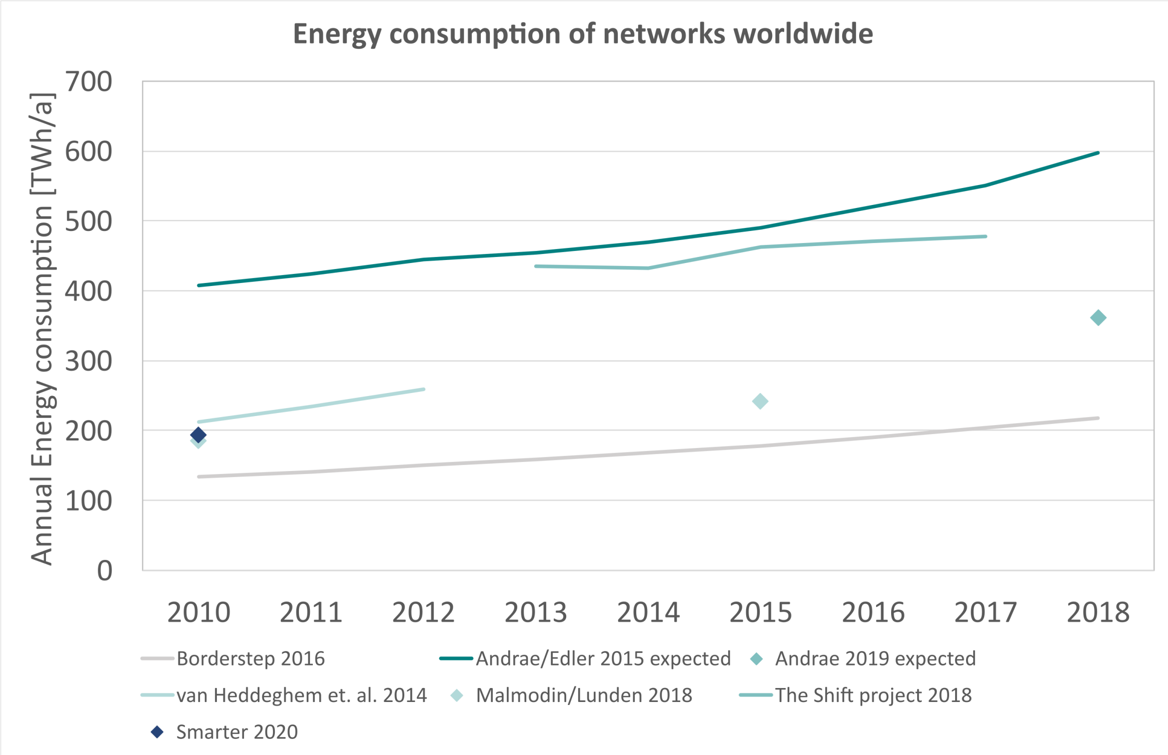

Figure 8 - Comparison of studies on the current energy demand of network infrastructures

For the EU27, Prakash et al., calculated an energy demand of 20.5 TWh/a for mobile and fixed networks in 2011 and forecast an increase to 50 TWh/a by 2020 (Prakash et al., 2014). From today's perspective and taking into account available studies on the worldwide energy demand of telecommunications networks, it can be assumed that the current energy consumption of telecommunications networks in the EU28 is between 60 and 80 TWh/a. This is comparable to the energy consumption of data centres.

Framework scenario of cloud computing services

Overview

This section presents a framework scenario concerning the development of digital technologies for the next 5-10 years, based on the information available in existing studies.

Many studies predict that digitalisation, namely the development of a number of key technologies ranging from the IoT, Artificial Intelligence, Big Data Analysis, etc. (key technologies are identified in the next chapter), will completely disrupt the way traditional sectors are conceived. Basically all sectors, from housing to energy, transport, healthcare, education, banking, industry and entertainment will radically change thanks to a combination of different digital technologies which will strongly rely on the cloud, and specifically on the interactions of traditional and cloud data centres (the core), enterprise-hardened infrastructure like cell towers, and endpoints such as PCs, smart phones, and IoT devices (IDC 2018b).

Hence, the digitalisation process will transform entire economic sectors, and in order to do so it will strongly rely on cloud computing. However, it is often argued that the overall directionality of the ICT sector as it is used is unsustainable. Without dramatic increases in efficiency, the ICT industry could use up to 20% of all electricity and emit up to 5.5% of the world's carbon emissions by 2025. This would be more than any country except the US, China and India (Morley et.al. 2017).

In order to pave the way for policy making, green public procurement and R&T development, and especially in order to steer the process towards more energy-efficient cloud services, it is important to identify the key economic sectors and the digital technologies which will require more cloud computing and therefore affect energy consumption.

In this chapter, the following topics are covered:

- Economic sector trends in relation to key digital technologies
- Digital technological trends. In particular, trends related to the rapid development and uptake of certain technologies (e.g. AI, Blockchain, IoT) which are likely to happen and will impact the use of cloud computing, are identified.
- Future development of cloud computing
- Future energy demand of cloud computing
- Future energy demand of cloud computing

Information on data generation, on the effects on cloud computing and energy consumption is assessed to the extent possible.

On this basis, assumptions regarding the future energy demand of cloud computing – i.e. a reference scenario - can be formulated for the purposes of this study.

Economic sectors in a digitalised future

Cloud services can have a significant impact on the development of various industries. In the following paragraphs the healthcare, industry and manufacturing, housing, finance and e-banking, transport, and the media and entertainment sectors are presented in order to identify the digital technologies used in these sectors, and to assess the potential effects on cloud computing.

Nevertheless, whether certain digital technologies can be fully deployed depends on different factors. Economic aspects such as market demand, costs, and the speed of innovation will be decisive for certain technologies and whether they are taken up. Similarly, IT related aspects such as data security, data privacy, operability, and availability will also be a decisive factor for the uptake of certain technologies.

Healthcare

The healthcare sector is already experiencing a transformation into an information centred industry, with cloud computing playing a central role.

At first, smart devices such as wearable watches or mobile phone devices will constantly monitor health-related parameters, so that patients will be able to monitor, store, transmit and process data on their personal health situation and history through smartphone apps (GeSI & Accenture Strategy. 2015). Secondly, DNA sequencing (also known as genomics) is gaining momentum (Langmead & Nellore, 2018). Public archives for the raw sequencing data have double in size every 18 months, and the costs of DNA and pathogen sequencing are expected to drop significantly by 2030. This, combined with access to a large database securely storing the data, will enable doctors to use data analytics to arrive quickly at precise diagnoses and to tailor treatments accordingly. Thirdly, augmented reality, which provides assistance during surgery and can help improve medical training, might also become a trend in medical healthcare, e.g. to perform remote diagnostic and tele-surgery (SMART

2030), thanks to the reliability and accessibility of real-time data, which relies itself on the availability of strong networks, such as the 5G.

Data generation and big data analytics are the key technologies enabling automatic processing and the interpretation of large amounts of data. This process is already partially facilitated by open standards which enable collaboration (through workflows and information sharing) between hospitals, medical practices, insurance companies and research institutes (Langmead & Nellore, 2018). As a matter of fact, cloud computing provides the necessary system environment that makes it easy for healthcare organizations to provide easy access to computing power with a lower initial investment than previously required for purchasing or long-term licensing. In addition, cloud environments are lowering the barriers for innovation and modernisation of IT systems and applications.

The demand for health care will continue to rise, mainly due to aging and the growth of the world population, but also due to the increasing interest of people in health care. In terms of data generation, the healthcare sector is predicted to grow fast, namely from 2 zettabytes in 2019 up to 10 zettabytes in 2025. Out of this, about 8.5 zettabytes will be stored, and about 6 zettabytes will be generated in real time (IDC, 2018b). Nevertheless, some factors will be crucial in ensuring the broad diffusion of digital options across the healthcare sector, such as an increased investment in technologies, the relocation of established processes in healthcare via data integration and comparative analysis, and the development of skills combining medical knowledge and data analytics (Cloud Standards Customer Council (2017). Ensuring data privacy, data security and reliability are also two critical factors for the uptake of digital technologies in the healthcare sector.

Industry & manufacturing

The intense use of digital technologies within the industrial sector of the future is also known as Industry 4.0 or as the Industrial Internet of Things (IIOT).

Smart sensors and devices connected to each other constitute the IoT, which continuously generates data that is collected, processed and analysed in cloud environments, either at the edge or centralized in order to increase productivity and quality while reducing energy and other resource usages. Innovations like virtual manufacturing, customercentric production, 3D printing and virtual production networks are also new trends reshaping industrial production.

The key technologies which will enable Industry 4.0 are mostly the Industrial Internet of Things and Machine to Machine communication, which will strongly rely on edge computing, data analytics & cloud computing.

Data generation in the industry sector is already the biggest of all sectors considered, accounting for about 5 zettabytes in 2019, which is expected to grow up to 23 zettabytes in 2025. Data for storage will grow from 3 zettabytes in 2019 up to 18 zettabytes in 2025. Noteworthy is the amount of generated real-time data. Companies are increasing the capture and use of real-time data to include data from IoT and actual product use, tracking everything from engine location to performance. Predictive maintenance and asset performance management are becoming massive data generation engines that are driving the adoption of data management and analytics strategies focused on operational excellence. As a result, real-time data will grow from about 1 zettabyte in 2019 to 10 zettabytes in 2019 (IDC, 2018b).

Since no industry is fully optimised, even in its advanced state, there is room for improvement. This is especially true for investment in Blockchain and artificial intelligence. A timeline of 5 to 10 years for Industry 4.0 to become fully integrated across operations and industries has been estimated (GeSI, & Accenture Strategy, 2015).

Housing

The house of the future will be smart. Automation systems and sensors will be integrated into smart grids via smart meters, which can perform energy use analytics, forecasting and optimisation. Sensors will allow continuous monitoring of temperature, lighting and other parameters in real-time. Data collected via smart meters and other smart home solutions are controlled via smart devices, allowing users to monitor energy use and control building functions via remote technology. This transformation is already happening: the number of household appliances that are connected to communication networks, ranging from televisions and washing machines to doorbells and security cameras, has seen a sharp rise in recent years.

A combination of smart devices, Internet of Things and data analytic tools, e.g. for predictive maintenance, will make smart housing possible, as well as machine automation and pattern recognition, e.g. by employing Artificial Intelligence algorithms.

Estimations of future data generation on smart homes are difficult to find in the literature, although it suggests that the amount of data will grow considerably. Some questions, which still need to be fully addressed, will shape the effects of smart homes on cloud energy consumption. At first, there is the question of which data are to be stored and where, e.g. for data analytics purposes (Bouchard et.al. 2016). A computing task can be either executed on the IoT and smart home devices or outsourced to the cloud. Where to compute depends on overhead trade-offs, data availability, data dependency, the amount of data transportation, communications dependency and security (Menachem 2019). Data generation will also vary among different smart devices: sending 10 to 15 queries to a virtual assistant each day would require about 30MB (NBNCO.com 2019) a month, whereas a security camera average of 60 GB of data per month at the mid-range setting, rocketing to 140 GB for high resolution. With a subscription to Nest Aware − the paid cloud service that saves Nest Cam’s video stream into history files, the average use will be 120 GB of data a month at that same mid-range setting and up to 400 GB per month for high resolution and advance features, e.g. if facial recognition is activated (Viasat.com, 2018). Another difficult point to predict is how many devices a smart home will have on average. Recent studies have evidenced that in the US, in each house at least one connected device is present, with 26% owning more than three. Typologies of devices range from smart appliances (smart TV, washing machine etc.), to devices for utility management (smart thermostat, light regulators, etc.), to home entertaining and security (such as video-streaming devices) (McKinsey (2019). Recently, in Austria a smart building was constructed employing about 800 sensors such as smart LED sensors for light regulation, which should also lead to energy savings (Computerwelt.at, 2019). Hence, the adoption of smart devices in each home can vary significantly. In the future, the most influential factor will be the amount of new smart homes that will be built and equipped with such a high number of sensors and devices. However, it is predicted that by 2040, 50% of the household electricity demand for appliances will come from connected devices (IEA, 2017).

Finance & E-Banking

The financial and e-banking sectors are already in the process of being shaped by digital technologies.

Through e-banking, banking products and services are delivered through electronic channels like the internet or mobile banking to millions of additional people, who are now able to operate in the financial system and to perform complex banking operations from everywhere. Electronic payment systems will eventually make cash redundant. In retail, more transactions are now carried out online and retail e-commerce sales worldwide reached $1.2 trillion in 2013, which equals a growth rate of nearly 20%, with the majority of growth coming from emerging markets. Finally, cryptocurrencies such as Bitcoin and Ethereum saw a tremendous uptake in the past 10 years.

The digital technologies which will enable e-banking and e-commerce will mostly be online platforms, where data security and data protection are decisive factors. The adoption of cryptocurrencies based on Blockchain technologies also seems to be a field that interests many banks.

Data generation in the financial services is expected to exceed 10 zettabytes by 2025, out of which 9 will need to be secured and 3.5 zettabytes are real-time data (IDC, 2018b).

Transport

The digitalisation of transport, also known as smart transport, will improve system operations, safety, efficiency and service, as well as lower the costs. The control and optimisation of traffic are facilitated through connected smart sensors, location-based applications and intelligent infrastructure, all working together to make traffic, driving and parking more efficient. Through connected private transportation people and vehicles having similar origins or destinations are connected. For example, smartphone enabled car-sharing or car-pool platforms can help travellers meet at designated spots to travel together. Smart logistics will connect vehicles, products and load units, thereby improving route and load optimisation and reducing the amount of waste in the system. A technology that seems promising, although it is still in its experimental phase, is autonomous driving (GeSI & Accenture Strategy, 2015).

Smart transport will take huge advantages from the deployment of sensors for data collection, communications technologies to enable remote control, and advanced data analytics to calculate the most efficient paths in real time. Autonomous driving, on the other hand, will strongly rely on real-time information gathering and data analytics, as well as on the 5G network infrastructure.

Increased connectivity of new mobility sharing services combined with advances in vehicle automation and electrification could result in substantial but uncertain energy and emissions impacts. Over the longer term, road transport energy use could either drop by about half or more than double, depending on the interplay between technology, policy and behaviour. As transport becomes increasingly digitalized, questions about vehicle and software certification, liability, cybersecurity, data privacy, and employment will also play an important role in the uptake of digital technologies in the transport sector (IEA, 2017).

Media & Entertainment

Media and entertainment are conducted via smart devices and broadband internet. As highlighted in the current scenario chapter, consumer applications are responsible for a consistent amount of worldwide data workloads and compute instances, accounting for about 25% (Cisco, 2018a).

TV/video and social networking are the two main app types and services that generate engagement and data traffic. The combination of apps for TV/video services and social networking accounts for more than half of the traffic, while gaming generates disproportionately low data traffic.

Key technological solutions such as open community platforms, gamification and virtual reality have the potential to create personalized ecosystems that will be increasingly affordable and engaging, and will rely more and more on large broadband connections such as the 5G, e.g. for streaming sophisticated media contents such as online games. For instance, in 2019 YouTube released Stadia, a cloud gaming on-demand service streamed through the cloud which can be used on any portable device. Among the different media and entertainment options, video streaming is by far the most environmentally unfriendly. A recent study showed that video streaming is far from being green: it accounted for 63% - 71% (Greenpeace, 2017; Cisco, 2019) of global internet traffic in 2015, and it is projected to reach about 80% by 2020, leaving the remaining share to software downloads, audio, social networking and web browsing. Every second, nearly a million minutes of video content will cross the network by 2020. Also, social platforms such as Facebook and Twitter are providing real-time video streaming services, meaning data will grow even more in the near future in this sector (Greenpeace, 2017).

Hence, the cloud market for media and entertainment will keep growing. Key areas for further developments in the media and entertainment industry will be online community platforms, video streaming, videoconferencing, augmented reality and virtual reality, and gaming. Those services that are particularly data and energy-intensive are the video streaming processes. Media and entertainment data growth is expected to exceed 6 zettabytes in 2025, compared to 1 zettabyte in 2019 (IDC, 2018b).

Technology trends

Digitalisation is described as a new megatrend that will make use of disruptive technologies to transform the way most economic sectors are traditionally conceived, as highlighted in the previous paragraph.

Nevertheless, for all key digital technologies, data is at the heart of digital transformation. The demand for cloud services will happen in response to a growing demand for data storage, management and transmission.

In this chapter, key digital technologies are identified based on a literature review, and their significance for the development of cloud computing over the next 5 to 10 years is also reviewed. The key digital technologies considered are namely:

- Smart sensors and the IoT
- Big Data Analysis
- Blockchain
- 5G & satellites
- Artificial Intelligence, Deep Learning

Nonetheless, not all key digital technologies are at the same stage of development. According to existing studies (Sitra Accenture Strategy 2018), the IoT, Big Data and Machine Learning are already at a mature stage, which could reach a scale–up stage in the next few years, and might deserve special attention as they are the most impactful technologies. Blockchain is still at the stage of being improved, as it is currently massively employed for cryptocurrencies, but still immature for applications in other fields, as explained in a separate paragraph below. Deep Learning is still in the early stages of its development as an emerging technology, although the pace of its development is fast.

Smart sensors and the IoT

As evidenced in the previous paragraph, smart sensors and devices connected to the cloud to store, share and analyse data for monitoring and optimisation purposes – the so–called Internet of Things, will be a predominant trend in the future and especially in the manufacturing, housing, transport and healthcare sectors.

Over the longer term, it is conceivable that most electrical devices – and even some consumer items such as clothing – could become connected IoT devices, using energy to collect, process, store, transmit and receive data. The number of connected IoT devices is expected to increase from about 6 billion in 2016 to 20 – 30 billion by 2020. As already highlighted, the devices will need mains electricity and tap into the energy used by data centres and network services. Different studies estimate that gains in energy-efficiency could keep energy demand growth largely in check for data centres and networks over the next five years (IEA 2017; GeSI & Accenture Strategy 2015). In the longer term for instance, industry estimates suggest that by 2030 smarter systems could save 10 times the carbon emissions they generate.

The energy consumption due to data generation, analysis and transmission of smart sensors and the IoT alone is already remarkable. According to estimates, 2.5 to 5 quintillion bytes of data are already produced every day (GeSI & Accenture Strategy, 2015; Sivarajah et.al., 2017), and data traffic and energy consumption due to the IoT is predicted to skyrocket in the next years, and produce 3.5% of the global emissions by 2025 and 14% by 2040 (Andrae, 2017).

Anyway, the energy demand varies according to the typology of smart devices and sensors. Mini devices that require little interaction will produce minimal data and cause very low bandwidth costs. Remote devices to turn on and off appliances such as light bulbs or a thermostat are very simplistic. Devices that will need to send data to and from the internet regularly as well as monitoring devices (such as health smart devices or GPS tracking devic-es), or devices that are never turned off, will have a medium usage and electricity consumption. As soon as an IoT device begins sending or receiving data that is not simply text or numbers, higher bandwidth usage is needed. This is especially true for video data: global computing power demand from internet-connected devices including high resolution video streaming, surveillance cameras and a new generation of smart TVs, was consuming roughly 3-5% of the world's electricity in 2015 and is increasing at a rate of 20% each year. Extreme bandwidth usage will occur due to IoT devices which are not typically available yet for standard residential use by the average citizen, but could soon be widely applied. These are generally more complex devices that track a huge amount of data and transmit it to the cloud in real-time, as will occur with connected cars, which are expected to generate data traffic to the cloud up to 25GB per driving hour.

Concerning mains electricity consumption of connected devices, standby power consumption is a particular concern. Inefficient networked standby could waste around 740 TWh per year by 2025, equivalent to the current annual electricity consumption of France and the United Kingdom combined. The standby power consumption of IoT devices that are plugged in (excluding televisions and computers) is projected to grow to 46 TWh by 2025, with 36 TWh coming from home automation (IEA, 2014). Nevertheless, economies of scale and product improvement are expected to halve the energy intensity of active control devices over the next 25 years, from an average of around 2 kWh per square metre (m2) per year in 2010 to 1 kWh/m2 /year in 2040. Globally, active control devices are projected to consume 275 TWh in 2040 (IEA, 2017b, and Ismail, 2017).

That is to say, direct energy use in the long run will continue to be a battle between data demand growth versus the continuation of efficiency improvements of smart devices and sensors.

Big data analysis (advanced data analytics, big data analysis)

Big data analytics is the use of advanced analytic techniques against very large, diverse data sets that include structured, semi-structured and unstructured data, from different sources, and in different sizes from terabytes to zettabytes. Big data comes from sensors, devices, video/audio, networks, log files, transactional applications, web, and social media much of it generated in real time and on a very large scale. Artificial intelligence (AI), mobile, social and the Internet of Things (IoT) are driving data complexity through new forms and sources of data (IBM.com, 2019).

Big data analysis finds and will find its application in many economic sectors, since it makes use of the information generated by smart sensors and the IoT, allows DNA sequencing, makes it possible to optimise the performance of smart appliances and smart homes, and so forth. In general, big data analysis can be used for descriptive analysis (to tell what happens in a certain system), predictive analysis (to tell what might happen in a certain system), or prescriptive analysis (to tell what is desired to happen in a certain system, such as when one defines a certain objective).

The employment of big data analytics is already huge and will be massive in the upcoming years, to the point that the issue is described as a "tsunami of data". It is estimated that out of the 2.5 – 5 quintillion bytes of data the world produces every day, 90% of this is unstructured (Sivarajah et.al, 2017). The massive amount of data needs to be analysed in an iterative, as well as in a time sensitive manner, with the availability of advanced Big Data analysing technologies (e.g. NoSQL Databases, BigQuery, MapReduce, Hadoop, WibiData and Skytree).

Other than assuming that it will be considerable, it is difficult to predict how much energy will be required to compute this amount of data. This will depend on the amount and typology of data generated, on the path and speed of data transmission, on the efficiency of the analytic tools employed for the analysis as well on the abilities of the physical compute infrastructure.

Blockchain

Blockchain made its first appearance in 2008 as a technology for the development of cryptocurrencies (Nakamoto, 2008).

A Blockchain is a growing list of records, called blocks, which are linked using cryptography. Each block contains a cryptographic hash of the previous block, a timestamp, and transaction data. Thanks to this protocol, Blockchain allows parties to co-create a permanent, unchangeable and transparent record of exchange and processing, without having to rely on a central authority (central ledger). Simply put, a Blockchain is about the exchange of value and how to make it instant and trustworthy.

This trust enables distributed account management, which is a great advantage for the use of cryptocurrencies. For current cryptocurrencies, the transparent record of the exchange and processing of Blockchain is ensured through the validation of transactions via the resolution of an encrypted algorithm. In exchange, those validating the transaction receive a token (e.g. the Bitcoins, or other forms of credit). But the machines need huge amounts of energy for validating the transactions for current cryptocurrencies: it has been widely reported that the Bitcoin mining network now consumes more electricity than 159 countries of the world together. According to the Digiconomist Bitcoin Energy Consumption Index (Digiconomist.net 2019), it is estimated that the annual energy consumption of Bitcoin and Ethereum combined accounts for about 40 to 70 TWh, which is more than the annual energy consumption of an entire small country.

A crucial question is nevertheless if and how Blockchain technology can be applied in the future in a way which does not dramatically affect energy consumption, and in fields other than cryptocurrencies. Blockchains has the potential to improve traceability, reduce or totally eliminate the need for a trusted middleman in many operations, be it a supply of certified renewable electricity coming from distributed energy generation, the verification of legal provisions, the establishment of a patent, or a simple payment (UNIDO, 2017). Rewards can be fungible (tradable for other cryptocurrencies) or non-fungible (identity-based reputation tokens). Examples of such purpose-driven tokens include proof of CO2 emission reduction (i.e. Solar Coin, Electric Chain, Sun Exchange), proof of energy consumption reduction: Energy Mine, Electron), proof of trees planted, recycling, etc. (Plastic Bank, Earth Dollar, Bit Seeds, Eco Coin, Earth Token, Recycle To Coin). Although the technology is still in its early stages, with many technological, legal and network effect challenges ahead, the potentials for future developments are huge (Bitkom, 2019).

5G & Satellites

5G is the successor to 4G, and it is much more than just a new wireless standard. 5G is a key enabler for disruptive communication technologies. The extremely powerful mobile communication technology makes the promises of Industry 4.0 and autonomous driving possible. It will greatly simplify the dynamic design and operation of communication networks and the secure networking of things and people, and will contribute to all economic sectors. New business models will emerge in vertical markets.

The data packets sent via 5G not only have to be transferred quickly. They also have to be processed close to their origin. This requires computing capacity, storage space and intelligent algorithms that are integrated into the networks. This is why the researchers are expanding the 5G systems with cloud concepts. In the future data sent by sensors, components, robots or machines (for instance in the Smart Industry) can be processed in the cloud. If a company sets up its own local cloud and the servers are located on the premises, even very low latencies can be achieved. One advantage of this is that the computing capacities in the cloud are easily scalable. Edge computing also helps speed up traffic. Data is already being processed at new base stations or special gateways and data centres at the edge of the networks.

Communication service providers (CSPs) have therefore great expectations - both for the higher capacity and for the new services and innovations. 5G, in combination with the Internet of Things and Edge Computing, offers opportunities that were unimaginable a few years ago. 5G can be described as a convergence of underlying technologies that undergo multi-dimensional acceleration, including the unification of fixed and mobile networks, private and public (hybrid), communications provider, and edge cloud. Also, the 5G technology makes it possible to equip virtually every component with a sensor and an ID. During production, the resulting products continuously collect data on their processing. These can then be stored as a kind of individual protocol for each component with all relevant production data. The innovative Massive MIMO (multiple-input multiple outputs) technology delivers increased ranges and energy-efficient, directional transmission. Especially at high frequencies in the millimetre-wave range, for example the recently defined 26 GHz band (European Commission, 2019), these antennas feature a compact design and a high bundle gain. A prerequisite for the high data transmission rates is the extension of the frequency spectrum. While the previous 4G mobile (LTE) is used in the range between 700 megahertz (MHz) and 2.7 GHz, the spectrum in which 5G is operated is significantly larger.

In order to increase the reliability of data transmission, identical data packets are sent simultaneously via several base stations and in different directions, so that their arrival is guaranteed. This is known as redundancy, which obviously increases data traffic and hence the energy consumption of data transmission.

Satellites play an important role in the development of 5G. At 5G, satellite communications and terrestrial radio communications will converge. The definition of the 5G standard takes into account the technical characteristics of the satellites. The LEO (Low Earth Orbit) satellites, which orbit around the earth at a relatively low altitude between 500 and 2,000 kilometres, will play a special role. For example, the LEOs are necessary for open-air IoT applications where thousands of sensors transmit data from measurement stations. Here, especially in environmental protection and agriculture, applications are conceivable. Agricultural machines are already using GPS technology to keep harvesting and mowing machines exactly on track by determining their position.

In addition, GPS and 5G complement each other perfectly. Particularly where GPS reaches its limits, such as in innercity areas or in buildings, a high density of 5G nodes could efficiently complement GPS in the future.

The proposed fifth generation of mobile telecommunications, succeeding in the current 4G standard is expected to be deployed from 2020 onwards (IEA, 2017). In particular, 21% of the operators were expected to roll out 5G services in 2019, and an additional 86 % expect to be delivering 5G services by 2021. However, the majority of telecom operators do not expect to achieve total 5G coverage until 2028, while only 4% expect to have total coverage by 2025 (Vertiv, 2019).

Concerning electricity consumption of 5G, estimates found that although there was optimism about the services and the interplay with edge computing enabled by 5G, there are significant concerns about rising costs. The move to 5G is likely to increase total network energy consumption by 150 to 170 % by 2026. The largest cost increases will be in macro, node and network data centres. (Vertiv, 2019)

Other studies based on simulations reveal that more than 50% of the energy is consumed by the computation power at 5G small cell base stations. Moreover, the computation power of a 5G small cell base station can approach 800 Watts when the massive MIMO (e.g. 128 antennas) is deployed to transmit high volume traffic. This clearly indicates that computation power optimisation can play a major role in the energy-efficiency of small cell networks (Xiaohu & Yang et.al, 2017), but also that the deployment of 5G poses additional burdens on the overall energy consumption of the cloud.

AI, Deep Learning, Deep Mind

In general terms, AI refers to a broad field of science concerned with getting computers to do tasks that would normally require human intelligence, hence to some kind of ability to plan, reason and learn, sense and build some kind of perception of knowledge, and communicate in natural language. An AI system combines and utilises mainly machine learning and other types of data analytics methods and computational algorithms to achieve artificial intelligence capabilities (Deloitte.com, 2019).

Currently, there are some fields of application with promising developments in the upcoming future: image and speech recognition, translations, Q&A and games. But the fields of applications might be much wider, and once the technology is mature it will find applications in almost any field from autonomous driving to predictive maintenance, smart housing, healthcare, etc.

AI models need to be trained, in order to be able to “learn” how to perform a certain task. One very promising field for instance concerns Generative Adversarial Networks, where two computational models compete against each other to achieve a certain objective (Goodfellow et.al, 2014). While doing so, they compute and analyse an extremely high amount of data. The model is promising (and currently also ethically controversial since it is the one used, for instance, to generate so-called deep fakes), but it requires days of continuous computation before it can reach satisfactory results. Similarly, the model training process for natural-language processing (NLP), the subfield of AI that focuses on teaching machines to handle human language, has reached several noteworthy performance milestones in machine translation, sentence completion, up to writing convincing fake news articles (the Open-AI’ GPT-2 model). Again, training the models requires a considerable amount of computation – hence, electrical power.

Studies performed a life cycle assessment for training several common large AI models (the Transformer, ELMo, BERT, and GPT-2) and found that the most computationally intensive process can emit from 26 (for the Transformer 65Mparameters model) up to 626,000 pounds of carbon dioxide equivalent (Strubell et.al, 2019), which is nearly five times the lifetime emissions of the average American car (and that includes the manufacture of the car itself), and equals the carbon footprint emitted by an average American for 17 years.

Needless to say, the carbon footprint of natural language processing is computationally expensive and highly energy intensive. The significance of those figures is huge, especially when considering current trends in AI research.

Future Development of Cloud Computing

As described in the previous section, the demand for cloud computing services is expected to rise further in the future. There are numerous studies on the future development of cloud computing. All forecasts assume a strong growth of the cloud computing market, but the level of growth varies. This section briefly presents and compares some indicators of the predicted growth of cloud computing. The possibilities created by simplified management through cloud computing for large and distributed ICT capacities offer a wide scope for new applications such as scientific simulation with over 100 vCores distributed over 40 000 cloud instances (AWS and HPC-wire, 2018) (Barr, 2019).

Figure 9 illustrates market forecasts for Public Cloud Computing from IDC, Gartner and Wikibon Research. The IDC and Gartner figures are inter/extrapolated from the previous average compound annual growth rate (CAGR).

Gartner, IDC and Wikibon Research predict growth rates in the range of 16% to 22.5% of the CAGR for global revenue from public cloud computing over the next five years. While Gartner and IDC expect growth to be relatively constant until 2022, Wikibon forecasts go up to 2027, levelling off towards the end.

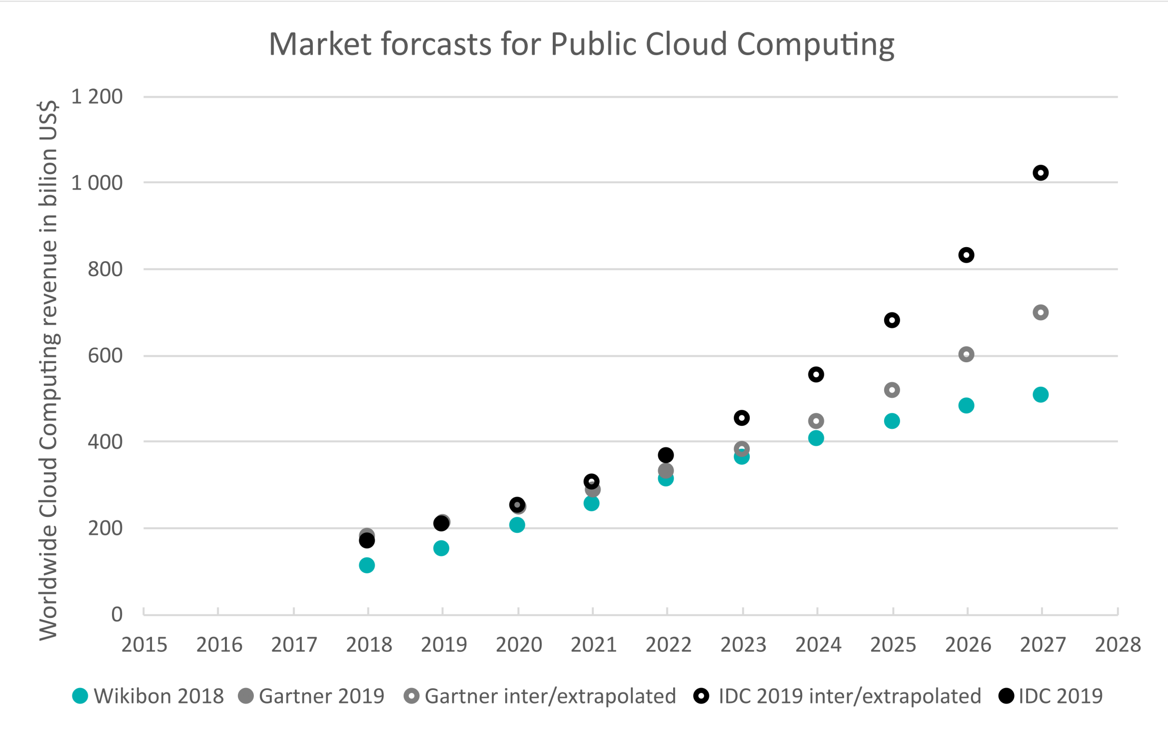

Figure 9 -Comparison of market forecasts for public Cloud Computing, Sources: (IDC, 2019a), (Gartner, 2019), (Wikibon Research, 2018), own inter- and extrapolation based on average CAGR

A forecast for the future of cloud computing is fraught with too much uncertainty due to the high dynamics in the ICT market, but it is certain that the demand for computing power, memory and communications technology will continue to rise in the future and drive growth in cloud computing. Gartner has published a forecast about the revenues for specific cloud service models, which is shown in Figure 10.

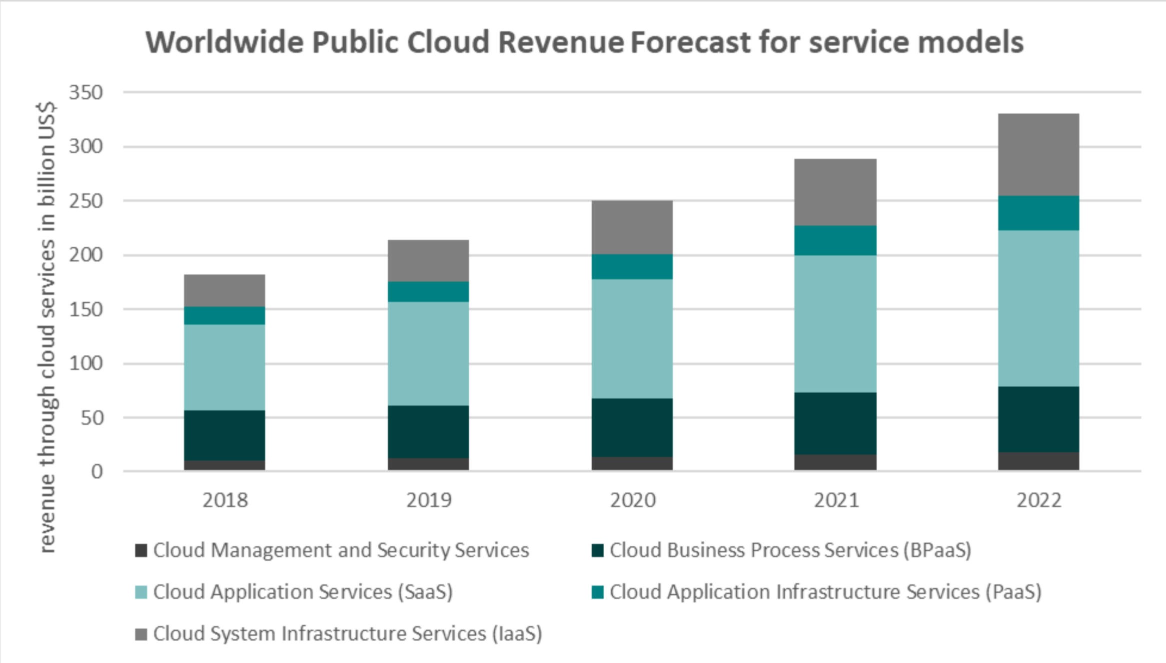

Figure 10 - Cloud growth by service model (Gartner, 2019)

In addition to the three classic service models (IaaS, PaaS SaaS), Gartner also forecasts Business Process as a Service, and Cloud Management and Security Services. The strongest growth is expected for IaaS (five-year average CAGR ~20%) and SaaS (five-year average CAGR ~15.3%).

Trends in different sectors of cloud computing

Total spending on IT infrastructure for cloud computing (public cloud and private cloud) is predicted to grow at a yearly rate of 10.9% of the CAGR for the period of the next five years, reaching 99.9 billion US$ in 2023. Figure 11 shows IT infrastructure spending divided into public cloud computing and private cloud computing. The strongest growth is expected for IaaS (five-year average CAGR ~20%) and SaaS (five-year average CAGR ~15.3%).

For public cloud services it is estimated that spending on IT infrastructure will reach around 68 billion US$ in 2023 at an average CAGR of 10.9%. Spending on private cloud services is projected to reach around 32 billion US$ within the same period at an average CAGR of 12.0%.

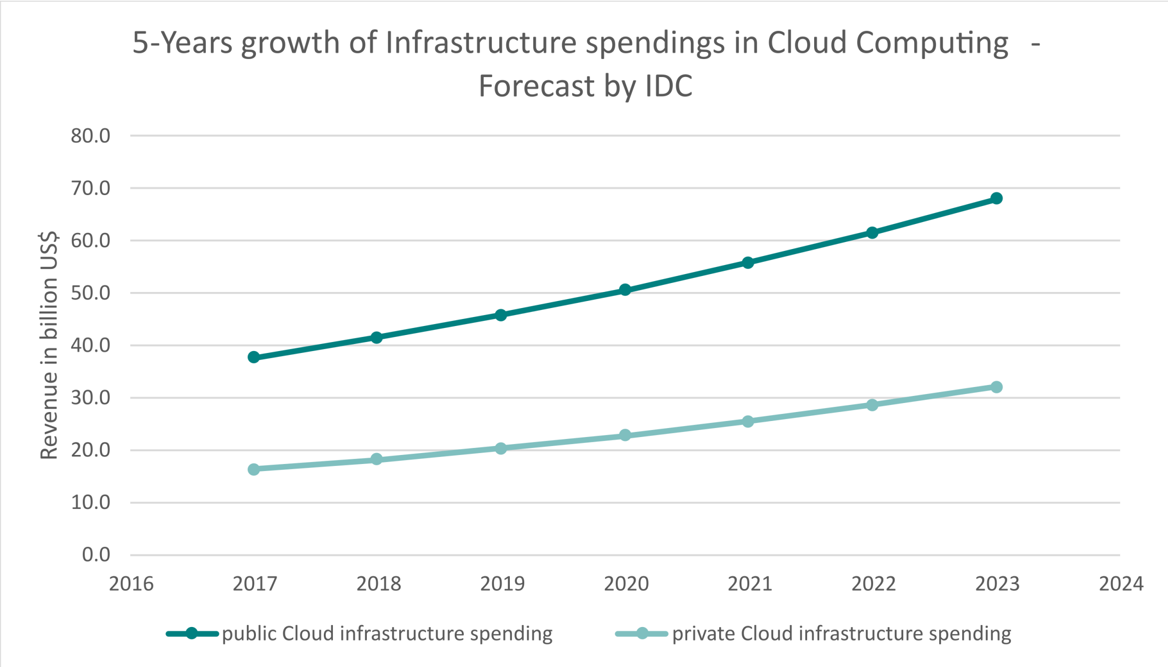

Figure 11 - 5-year forecast for worldwide IT-infrastructure spending (IDC, 2019a)

Separating cloud computing from traditional IT provision

It is expected that total (data centre) spending on IT infrastructure will gradually shift towards cloud computing over the next few years, and that spending on traditional IT operations will increase slowly (~4-5% CAGR), but will become less important overall than cloud computing. Between 2018 and 2022 total IT infrastructure spending is expected to rise from 131 billion US$ to 158 billion US$ (own calculations based on (IDC, 2019b)).

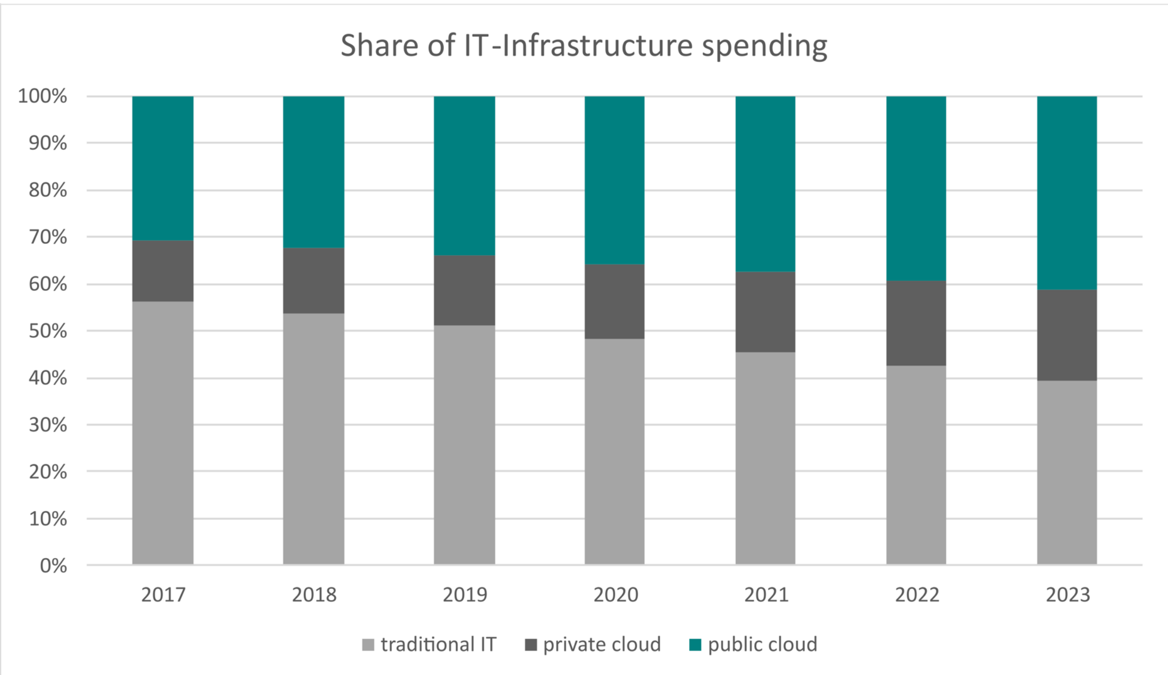

Figure 12 - IT infrastructure spending split into traditional IT, public cloud and private cloud. (IDC, 2019b)

Future Energy Demand of Cloud Computing

As the forecasts show, the significant growth of cloud computing in this area is expected to continue. It is likely that this will also increase the energy demand of cloud computing in the future. This section provides an overview of the current state of research in this area.

The present study focuses on energy-efficiency in cloud computing and thus on the energy demand of cloud infrastructures. The study does not focus on the energy-saving potentials of cloud-based solutions in other areas of life and industries. These potentials are undoubtedly very high, as the studies of the Global eSustainability Initiative (GeSI) on the possibilities of reducing greenhouse gas emissions through smart ICT solutions show (Climate Group & GeSI, 2008; GeSI & Accenture Strategy, 2015; GeSI & The Boston Consulting Group, 2012). According to GeSI, smart ICT solutions can save eight to ten times more greenhouse gases than caused by the entire ICT itself. Cloud services can support many of these ICT-related savings potentials. Figure 9 provides an overview of the CO2 saving potentials in the various economic sectors identified in the #smarter 2030 study. However, these potentials are not self-evident, but require a multitude of supporting measures, as the studies emphasise.

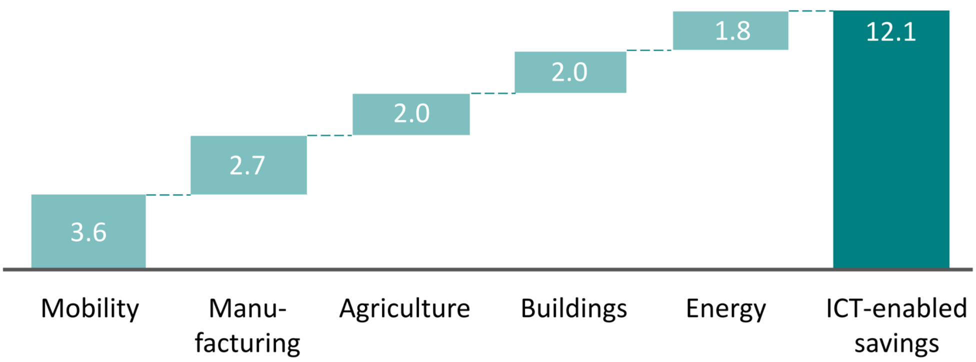

Figure 13 - Environment – CO2e abatement potential by sector (2030) (Source: #Smarter 2030 (GeSI & Accenture Strategy, 2015))

In the following, the focus of the analysis will be on the energy requirements of cloud computing. As mentioned in Section 1.1, the results of other studies on the energy requirements of data centres and network infrastructures worldwide have been considered.

Most studies on the development of the energy demand of data centres assume that this demand will continue to rise significantly in the future (Figure 14). The forecasts range widely. The reason for the increase in energy consumption is the expected sharp rise in the demand for computing and storage capacity in data centres. Trends such as IoT, artificial intelligence, big data applications, video streaming and edge computing are expected to lead to an ever-increasing demand for data centre performance.

The forecasts shown below for the worldwide energy consumption of data centres in the year 2030 range from 500 TWh/a to 3,000 TWh/a. The differences in the predicted energy requirements are due in particular to different assumptions about the development of the computing and storage capacity of the data centres and to different assumptions about the development of energy-efficiency.

If it is possible to increase the energy-efficiency in data centres significantly, the increase in global energy demand will be much lower than with an only slightly improved energy-efficiency.

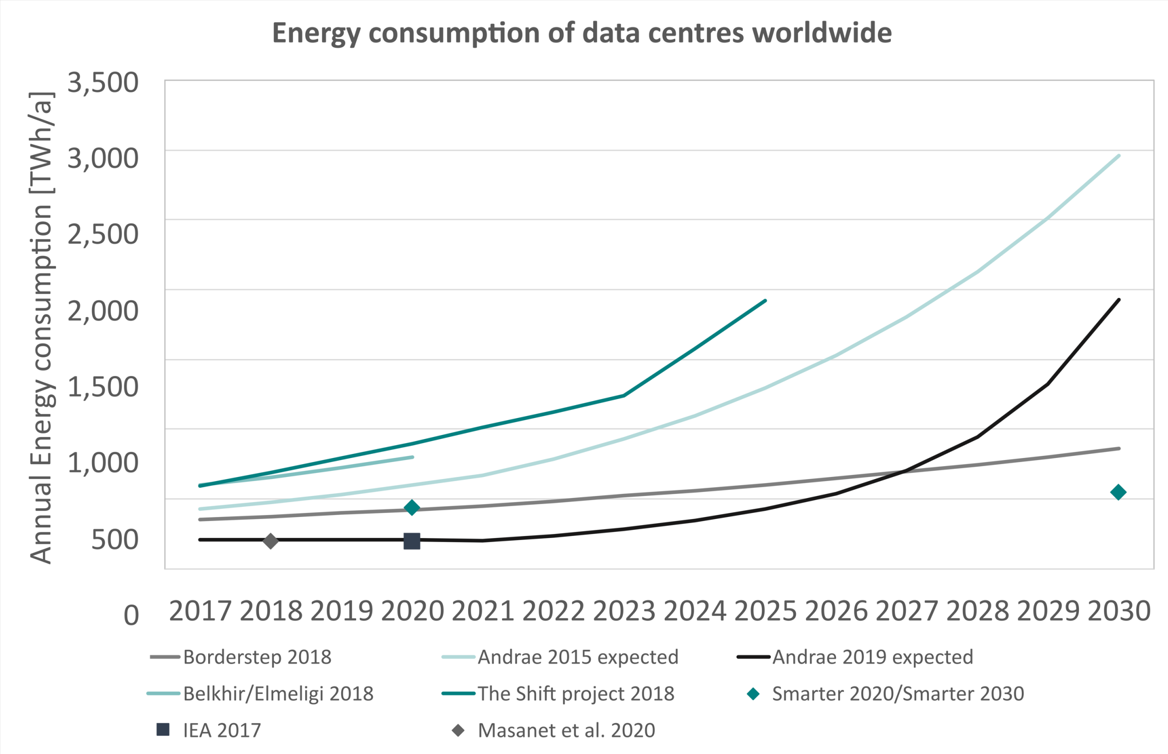

Figure 14 - Overview of studies on the energy demand of data centres worldwide up to the year 2030

The available forecasts for the development of the energy demand of network infrastructures differ widely in some cases (Figure 15). The 2015 forecast by Andrae/Edler calculates the highest energy demand for the year 2030 at over 3,700 TWh/a worldwide (Andrae & Edler, 2015). In his 2019 update, Andrae calculates an energy demand that will only rise to just under 2,000 TWh/a in 2030 (Andrae, 2019b). In both forecasts, it is particularly the second half of the next decade that is expected to see a significant increase. With almost 2,000 TWh/a, the 'shift project' is expected to have the highest forecast energy demand of network infrastructure by the year 2025 (The Shift Project, 2019). In contrast, the #smarter 2030 study assumes that the energy demand of network infrastructure will remain largely constant in the future despite significantly increasing data transmission rates (GeSI & Accenture Strategy, 2015). Even the Borderstep Institute estimate (Hintemann & Clausen, 2016), which is rather conservative (as shown above), shows only a slight increase in the energy demand of network infrastructures.

As with the data centres, the analysis of the various forecasts shows that a future increase in the energy-efficiency of network infrastructures is of very high importance.

Assuming that in 2030 the energy demand of data centres and network infrastructures will be caused almost exclusively by cloud services; the energy demand of cloud computing infrastructures can be estimated at between approx. 1,000 TWh/a and 7,500 TWh, according to the forecasts presented in this report. Depending on the energy-efficiency achieved, the energy requirements of cloud computing infrastructures could thus range from 2.5% to 19% of the global electricity requirements.

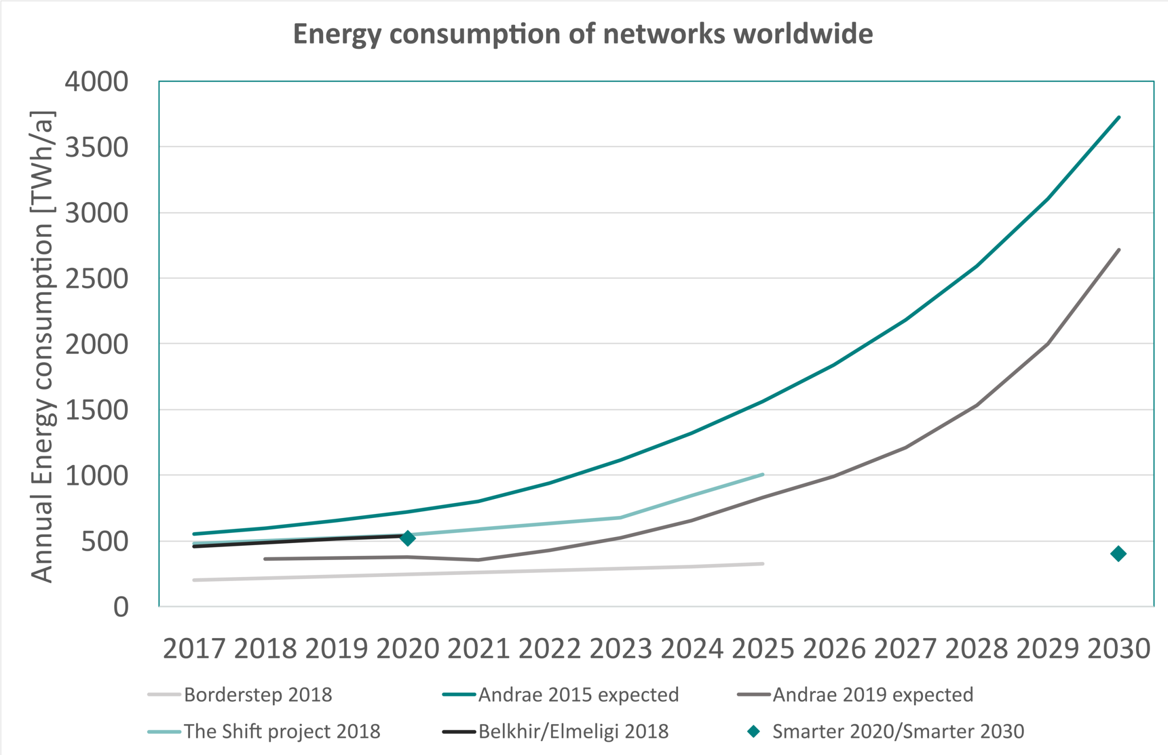

Figure 15 - Overview of studies on the energy demand of network infrastructures worldwide up to the year 2030

7. TASK 1 - ANALYSIS AND MODELLING ACROSS THE EU28

Introduction

The increasing digitalisation of the economy and society is associated with a strong expansion of digital infrastructures. While the expansion of telecommunications infrastructures such as mobile communications and fibre optics is the subject of intense public debate, the growth of computing capacities in data centres has received less attention. Above all, the increasing demand for cloud services for companies and private individuals is leading to the construction of more and sometimes very large data centres.

These data centres need more and more energy. A very large data centre can consume over 500 million kWh/a, more than a city of approx. 100,000. No official statistics exist on the development of the energy consumption of data centres. Unfortunately, the results of the available studies differ considerably (see below). Hardly any data are available for Europe and in particular for the regional distribution of the energy consumption of data centres in Europe. Also, there are few answers to the question about the role of the ever-increasing expansion of cloud computing in the development of the energy consumption of data centres.

Increasing data volumes and the development of 5G mobile networks are also likely to boost the demand for decentralised computing capacities in edge data centres. From today's perspective, however, it is still very difficult to assess what role these edge data centres will play in the overall energy consumption of data centres.

The purpose of this chapter is to contribute to answering the questions raised here on the development of the energy consumption of data centres in Europe:

- How has the energy consumption of data centres in the EU28 developed in recent years?
- What is the share of cloud data centres in the energy demand of all data centres?
- What impact can the trend towards edge computing have on data centre power consumption?
- What is the regional distribution of the energy consumption of data centres in Europe?
- How will the energy demand of data centres in the EU develop in the future?

Key findings

1 **The energy consumption of data centres in the EU28 increased from 53.9 TWh/a to 76.8 TWh/a between 2010 and 2018 . This means that in 2018, data centres accounted for 2.7% of the electricity demand in the EU28**. Ongoing digitalisation and especially the increasing availability of cloud services are leading to significant growth in data centre capacities. This growth is so strong that it has more than offset the significant efficiency gains achieved at all levels (hardware, software, data centre infrastructure), and the total energy consumption of data centres in Europe has risen.

2 **Compared to 2018, the energy consumption of data centres is expected to increase by 21% to 92.6 TWh/a by 2025.** While the share of cloud data centres accounted for 10% of data centre energy consumption in 2010, it increased to 35% in 2018 and is expected to rise to 60% in 2025.

3 **The share of edge data centres will also increase significantly in the future.** By 2025, edge data centres are expected to account for 12% of data centre energy consumption in EU28.

4 **Regionally, the majority of data centre capacity is located in Northern and Western Europe. These regions were responsible for 82 % of the energy consumption of data centres in 2018.** By the year 2025 this proportion will rise to 87%. Especially for the energy consumption of data centres in Northern Europe a strong increase of 48% from 26.3 to 38.9 TWh/a is predicted for the period 2018 to 2025.

5 **The range of possible future developments of the energy consumption of data centres in Europe is wide.** It can be assumed that the digitisation of the economy and society as a whole will lead to a further increase in the energy consumption of data centres. In the trend case, data centres in Europe will consume 98.5 TWh/a in 2030. If all technical potentials are exploited, however, it will even be possible to reduce their energy consumption to the 2010 level.

State of research on the energy consumption of data centres

The issue of the future development of the energy consumption of data centres has attracted increasing public and media attention, especially since 2018. In addition to specialist journals and media, the topic is now increasingly being taken up by leading media outlets such as Forbes, the Guardian and the Frankfurter Allgemeine Zeitung (Danilak, 2017; Harris, 2018; Janović, 2019). An article in the scientific journal Nature entitled "How to stop data centres from gobbling up the world´s electricity" (Jones, 2018) was surely a trigger for the increased media interest. The article referred to a 2015 study by Huawei researchers Andrae and Edler in which they predicted that the energy consumption of data centres would increase dramatically by 2030. In the expected scenario, the energy consumption of data centres would increase from approx. 200 terawatt hours (TWh) per year (≙ 200 billion kWh/a) in 2010 to almost 3,000 TWh/a in 2030. In that case, data centres would account for about 8% of global electricity consumption by 2030. In this scenario, the energy consumption of global data centres in 2018 was predicted to be 478 TWh/a. In more recent publications, Andrae assumed significantly lower energy consumption for data centres, namely around 200 TWh/a in 2018 (Andrae, 2019a, 2019b). Andrae has also significantly revised his forecasts for the next decade. In the spring of 2019 he still assumed energy consumption to be 1,929 TWh/a in 2030 (Andrae, 2019b). In a publication in autumn 2019, his forecasts in various scenarios range from 163 to 1,495 TWh/a (Andrae, 2019a).

Other studies have also predicted a sharp increase in data centre power consumption worldwide. Belkhir and Elmeligi, for example, anticipated an annual increase of 10% in data centre energy consumption by 2020 (Belkhir & Elmeligi, 2018). This growth rate was based on data from the market research company Technavio (Technavio, 2015). Based on this assumption the energy consumption of data centres worldwide would be 797 TWh/a in 2020.

The French non-profit think tank "Shift Project" expected an increase in the energy consumption of data centres worldwide from 323 TWh/a in 2013 to 1,918 TWh/a in 2025. For 2018, the study calculated energy consumption of about 700 TWh/a (The Shift Project, 2019).

However, some studies have assumed that the energy requirements of data centres will not increase, or only marginally. In an article recently published in the journal Science, a US research group presented calculations according to which the energy consumption of data centres worldwide increased only slightly (from 194 to 205 TWh/a) between 2010 and 2018. According to this study, cloud data centres were already responsible for two-thirds of the energy requirements of all data centres worldwide in 2018 (Masanet et al., 2020). Based on the results of this research group, the International Energy Agency (IEA, 2017) and a new ITU Recommendation (ITU-T, L.1470) also assumed that the energy requirements of data centres had been near constant. In the United States Data Center Energy Usage Report, the same US research group found that there was only a small increase in data centre energy consumption of 4% to 70 TWh/a in the US between 2010 and 2015. The study even showed a clear potential for reducing the future energy consumption of data centres (Shehabi et al., 2016). This is remarkable because the study predicted that the number of physical servers in the US would increase by more than 60% from approximately 11 million in 2006 to over 18 million in 2020. The main assumptions made in the publications of the US researchers for increasing energy efficiency in data centres are comprehensible. The present report also assumes significant increases in the number of workloads of data centres and the energy efficiency of servers. In the authors' view, it is unlikely that these increases in efficiency will compensate the growing demand for computing power and that the energy consumption of data centres worldwide remains almost constant between 2010 and 2018. Several reasons speak against this assumption, such as the proven high energy demand of Bitcoin mining, the increase in the energy demand of data centres in China (Greenpeace & North China Electric Power University, 2019) and the fact that the use of traditional data centres is still widespread in Europe (Hintemann, 2020).

Malmodin/Lundén of the telecommunication companies Ericsson and Telia calculated the worldwide energy consumption of data centres for 2015 to be 240 TWh/a (Malmodin & Lundén, 2018).

Some studies have dealt with the energy consumption of data centres in Europe. The Ecodesign Preparatory Study on Enterprise Servers and Data Equipment calculated the energy consumption of data centres in Europe to be 78 TWh/a in 2015 (Bio by Deloitte & Fraunhofer IZM, 2016). In a study on the practical application of a new framework methodology for measuring the environmental impact of ICT, Prakash et al. calculated the energy consumption of data centres in the EU28 at 52 TWh/a for 2011 and forecast an increase to 70 TWh/a by 2020 in the scenario ‘high data traffic’. In the high-efficiency scenario, just under 50 TWh/a were expected for 2020 (Prakash et al., 2014). According to estimates by the author of the present study, the energy consumption of data centres in Western Europe also rose significantly between 2010 and 2017. Based on data from the IT company Cisco on the development of workloads and the numbers of servers in data centres (Cisco, 2015, 2016), I assumed that energy consumption increased by a good 30% from 56 TWh/a in 2010 to 73 TWh/a in 2017 (Hintemann, 2018). Further estimates by Bertoldi, Koomey and Whitehead (quoted by Avgerinou, Bertoldi, & Castellazzi, 2017) came to similar conclusions.

Methodology

In this study, data centres are defined as all enclosed spatial units such as server cabinets, server rooms, parts of buildings or entire buildings in which at least three physical servers are installed. The energy consumption of data centres in the EU28 is determined using a calculation model developed by Borderstep Institute. The calculation model is based on a structured and optimised quantitative survey of the equipment used in data centres. Energy-relevant technology and usage parameters are assigned to the various devices used. These parameters are used to calculate the resulting electrical power consumption (Fichter & Hintemann, 2014; Hintemann et al., 2010; Hintemann, 2017b, 2018; Hintemann & Hinterholzer, 2019; Stobbe et al., 2015).

This model has been developed and adapted annually since 2010. It describes the equipment of data centres of different size classes with different server types, storage systems and network infrastructures. The age structure of the servers and the energy consumption of the different server types in different operating modes are also taken into account. In addition, data centre infrastructures such as air conditioning, uninterrupted power supply (UPS), etc. are modelled for different size and redundancy classes. The development of the data centre capacities is calculated in particular on the basis of the server equipment in the data centres. Large data centres for Bitcoin mining are also in operation, particularly in Northern Europe (Rauchs et al., 2018). However, these are not operated with standard servers, but with specially developed hardware. The energy consumption of these data centres was also taken into account in the model[4].

The following sources in particular were used as input for the model:

- Study „Entwicklung des IKT-bedingten Strombedarfs in Deutschland“ (Development of ICT-related electricity demand in Germany) – Study by Fraunhofer IZM and Borderstep Institute on behalf of the Federal Ministry of Economics and Energy (Stobbe et al., 2015).
- Current results by analysts and researchers on the development of the data centre market (Andrae, 2019a; Belkhir & Elmeligi, 2018; CBRE, 2018; CBRE Global Corporate Services, 2017; Cisco, 2015, 2016; Hintemann, 2014, 2017a; Hintemann et al., 2014; Hintemann & Clausen, 2018a, 2018b; Howard-Healy, 2018; Malmodin & Lundén, 2018; Masanet et al., 2020; Shehabi et al., 2016)
- Data from the market research institute Techconsult on market development for servers, storage and network components in Germany (eanalyser) (Techconsult, 2014, 2015, 2016)
- Data of the market research institutes IDC and EITO on the market development of servers in Europe (EITO, 2014, 2019; IDC, 2018)
- Ecodesign Preparatory Study on Enterprise Servers and Data Equipment (Bio by Deloitte & Fraunhofer IZM, 2016)
- Scientific literature on the energy consumption of data centres (Andrae, 2019a, 2019c, 2019b; Andrae & Edler, 2015; Avgerinou et al., 2017; Belkhir & Elmeligi, 2018; Koomey & Taylor, 2015; Shehabi et al., 2016, 2018; The Shift Project, 2019; Van Heddeghem et al., 2014)
- Manufacturer information on the power requirements of servers, storage and network products
- Data on energy consumption of data centres for bitcoin mining (Digiconomist, 2019; Kamiya, 2019; Rauchs et al., 2018)

Figure 16 shows an overview of the structure of the adapted calculation model. The energy demand per year and EU region is calculated for servers, storage and networks of the data centres. This is done on the basis of available figures for shipments in a specific year, the determined average energy requirements of the components, typical load profiles and the average usage time spent using the devices. For the different EU regions, the energy consumption of cooling/air conditioning, uninterruptible power supply and other infrastructure elements is determined using assumptions for partial PUE values[5]. The sum

[4] Based on the information from Rauchs et al., (2018), it was assumed that Bitcoin mining in Northern Europe required around 3 TWh/a in 2018.

[5] The PUE (Power Usage Effectiveness) value indicates the ratio of the energy consumption of a data centre to the energy consumption of IT components. It is a measure of the energy efficiency of a data centre's infrastructure. When calculating a partial PUE (pPUE) only a part of the data centre (e.g. cooling) is considered.

of the individual elements then indicates the energy demand of the data centres in the regions and the energy demand of the data centres in the EU28.

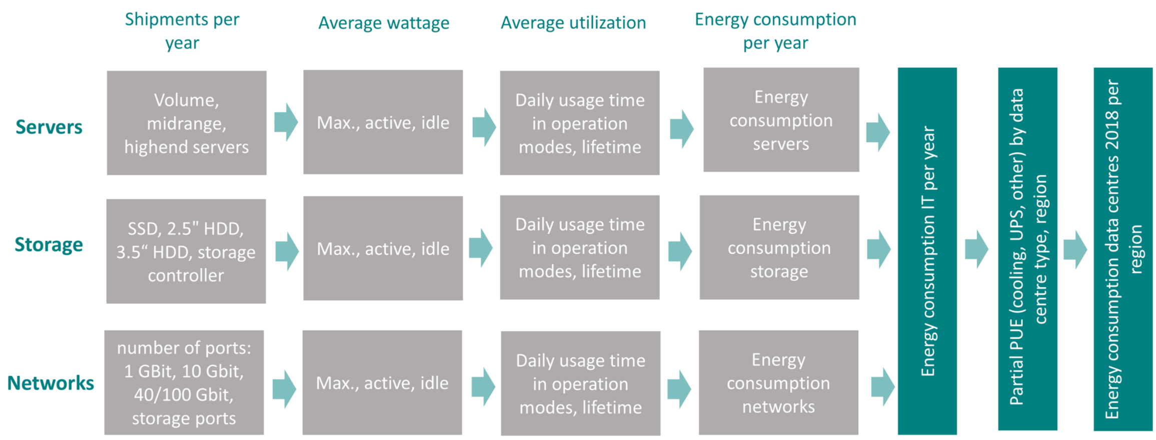

Figure 16 - Schematic illustration of the Borderstep Institute calculation model for the energy consumption of data centres in the EU28

The energy consumption of data centres is calculated in TWh/a. The model is used to calculate the current energy demand of the data centres, and it is also suitable for forecasting the future development of energy consumption.

One focus of the energy consumption calculations in this chapter is on regional distribution within Europe. The following four regions are distinguished:

- Eastern Europe: Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia,
- Northern Europe: Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Sweden,
- Southern Europe: Croatia, Greece, Italy, Malta, Portugal, Slovenia, Spain,
- Western Europe: Austria, Belgium/Luxembourg, France, Germany, Netherlands

Another focus of this chapter is the energy consumption of cloud data centres. To determine how much cloud computing accounts for in the energy consumption of all data centres, it is first necessary to define how cloud data centres can be distinguished from other data centres. Cloud computing is a technical approach to providing IT resources. This approach is used both in data centres built specifically for this purpose and increasingly in data centres of companies and public authorities, e.g. as a private cloud service.

There are several ways to differentiate the energy consumption of cloud data centres from the energy consumption of other data centres. In principle, the following approaches are available:

- The energy consumption of cloud computing data centres is assumed to be that of hyperscale cloud data centres.
- The energy consumption of cloud computing data centres is assumed to be the amount of energy required by hyperscale cloud data centres plus an estimate for other data centres used exclusively for cloud services.

- The energy consumption of cloud computing data centres is estimated using estimates of the use of public and private cloud services as compared to other IT services.
- The energy consumption of cloud computing data centres is estimated using available data from Cisco on the proportion of cloud workloads in all data centres in Western Europe.
- The total energy consumption of data centres is attributed to cloud computing.

Depending on the approach, cloud data centres account for 30 to 100% of total energy consumption of data centres. In the future, with the predicted further increase in the use of cloud services, the range is likely to narrow significantly. Cisco assumes, for example, that in 2021 more than half of all servers will be operated in just 600 very large hyperscale cloud data centres.

This chapter uses the second approach described above.

Researchers calculating the energy requirements of edge data centres also face the methodological challenge of defining exactly what is meant by an edge data centre. In this chapter, we define an edge data centre as a small data centre (up to a maximum of 10 server racks) operated remotely.

Energy consumption of data centres in the EU28

Figure 17 shows the evolution of the energy demand of data centres in the EU28 from 2010 to 2018, calculated using the Borderstep Institute model described above. This energy consumption increased from 53.9 TWh/a to 76.8 TWh/a over the period. This means that in 2018, data centres accounted for 2.7% of the electricity demand in the EU28. It is not possible to determine their exact share of greenhouse gas emissions, as reliable data on CO2 emissions (from the electrical energy mix used in the data centres) is not available. A rough estimate puts the data centre share of EU28 greenhouse gas emissions for the year 2018 at 0.4 to 0.6%. These greenhouse gas emissions could be reduced if data centres in the EU become climate neutral by 2030, as called for in the Digital Strategy "Shaping Europe's digital future", (COM(2020) 67 final) (European Commission, 2020c).

Figure 17 also distinguishes between the energy consumption of the IT components (server, storage, network) and the infrastructure (cooling, UPS, other). The energy consumption of the IT components increased by 65% from 26.5 TWh/a to 43.8 TWh/a in the period under review.

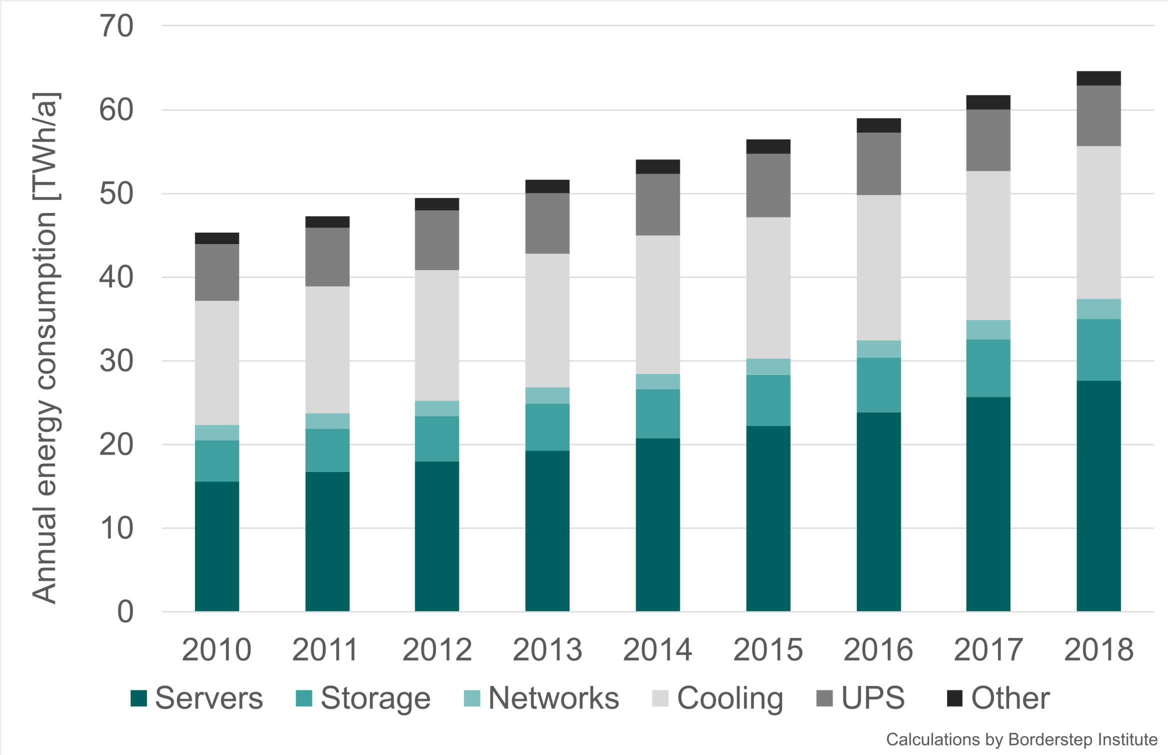

Figure 17 - Development of the energy consumption of data centres in the EU28 in the years 2010 to 2018

By contrast, the energy consumption of the infrastructures increased by only 20%, from 27.3 to 33.0 TWh/a. The efficiency of the infrastructures has therefore improved. This development is reflected in an improvement in the average PUE value in the EU28 from 2.03 in 2010 to 1.75 in 2018.

The data centre market in Europe is particularly concentrated in Germany, UK, France and the Netherlands (Hintemann, 2015). Together, the data centres in these countries accounted for 56% of the energy consumption of data centres in the EU28 in 2018. Figure 18 shows the distribution of data centre energy demand between these four countries and the rest of the EU28.

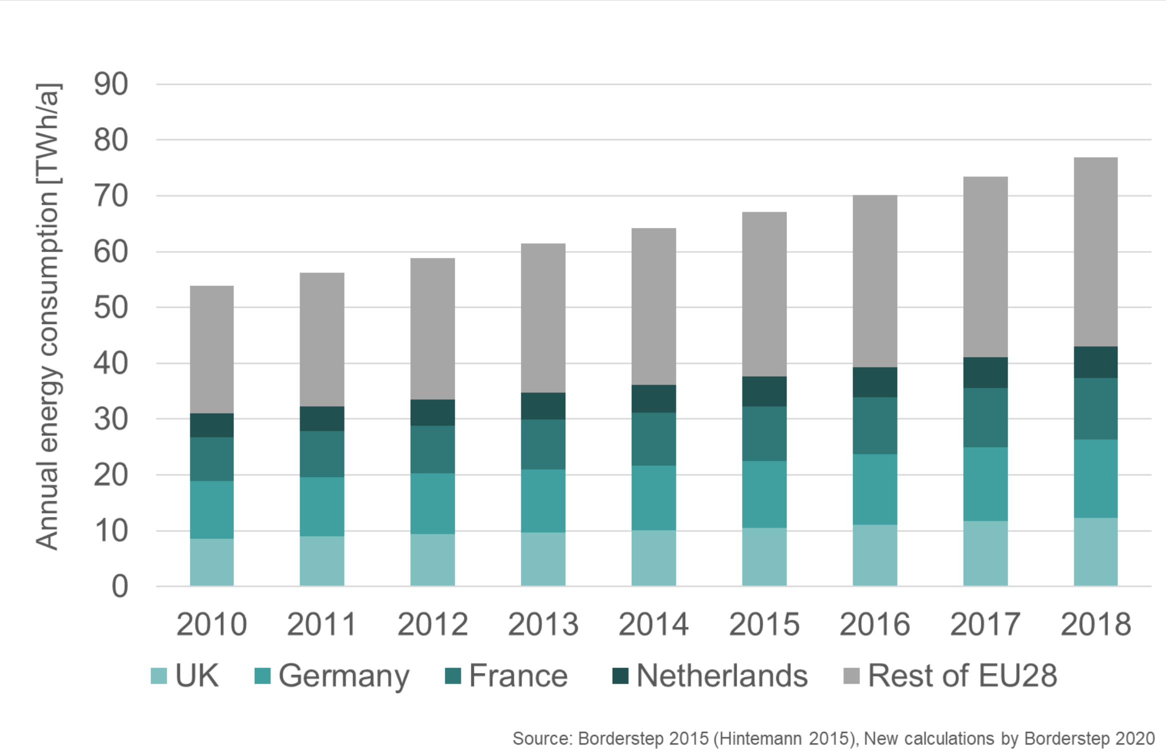

Figure 18 - Development of the energy consumption of data centres in the EU28 and distribution between Germany, UK, France, Netherlands and the rest of the EU28 in the years 2010 to 2018

Cloud computing drives growth of data centres in Europe

A major driver of the increase in the energy consumption of data centres is the construction of more and often very large cloud data centres. Cloud computing offers great potential for providing and using IT resources efficiently. At the same time, however, cloud computing is also driving economic growth, leading to the development of more and larger ICT infrastructures. While in the 2000s the operation of IT hardware and software 'on premise' was still the norm for companies and other organisations, cloud services are increasingly becoming the dominant form of IT use in the current decade (Gartner, 2019; IDC, 2012, 2015, 2019a; KPMG & Bitkom, 2018a). Advantages such as flexibility, scalability, lower administration costs and no investment costs mean that more and more organisations are opting to use cloud services. Cloud services are also becoming increasingly popular in the private sector – often in the form of free offers or as a flat service.

According to a 2018 forecast by Cisco, the use of cloud services by enterprises and private households is already responsible for the majority of data processing, storage and transmission in data centres and networks. Cisco predicted that by 2019, nearly 90% of the workloads and compute instances in data centres in Western Europe would be cloud workloads and only 10% traditional workloads. Measured in terms of the number of servers, this means that 70% of servers in Western Europe would be operated as cloud servers. Cloud computing was expected to be responsible for 93% of data centre IP traffic in Western Europe in 2019 (Cisco, 2018a).

Decentralised data processing is becoming even more important because of increasing digitalisation and the associated need to capture, transfer and process more and more data. It is expected that the need for regionally distributed computing capacity will lead to strong growth of edge data centres, a decentralised type of data centre (Bittman, 2017; Cohen et al., 2018; Reinsel et al., 2018; van der Meulen, 2019). These data centres are located at the edge of communication networks for improving signal latency between an end user and a physical cloud.

Edge data centres may operate less efficiently than large cloud data centres due to their size and architecture. Because of the expected high number of such data centres – Vertiv expects the number of Edge sites to more than triple by 2025 (Vertiv, 2019) – they can therefore become highly relevant for the overall power consumption of data centres. Even though edge data centres can be a part of cloud offerings, their energy consumption is shown separately in this paper due to their particular relevance.

Figure 19 shows how the energy consumption of cloud data centres developed in the years 2010 to 2018 and how it is expected to continue to develop until 2025. While the share of cloud data centres accounted for 10% of data centre energy consumption in 2010, it increased to 35% in 2018.This share is expected to rise to 60% in 2025. Edge data centres currently still play a minor role in the energy consumption of data centres. According to our calculations, their share was 2% in 2018. Predictions for the future development of edge computing and edge data centres are fraught with uncertainty. As shown above, many analysts assume that edge computing will develop rapidly. A report by Transparency Market Research (TMR) predicts growth rates of over 20% per annum up to 2025 and a global market volume of micro data centres of around US$15 billion in 2025 (SBWire, 2018). Taking into account the available information and studies on the development of edge data centres (Vertiv, 2019, van der Meulen 2019, Bittman 2017), such growth seems plausible. It is therefore assumed that edge data centres will account for around 10% of the server capacity installed in the EU28 in 2025. By 2025, edge data centres are expected to account for 12% of the energy demand of all data centres in the EU28.

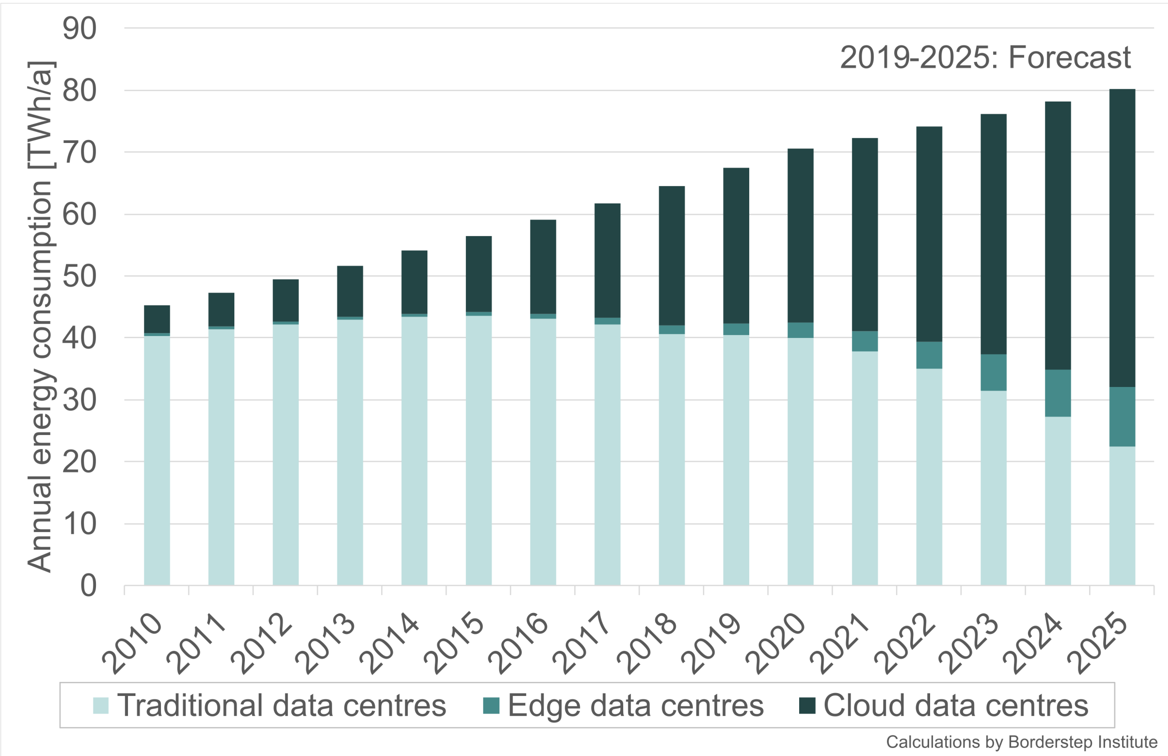

Figure 19 - Development of the energy consumption of data centres in the EU28 in the years 2010 to 2018 and forecast up to 2025 with the share of cloud and edge data centres

As already mentioned above, there is a clear trend towards operating servers in very large hyperscale data centres in the future (Cisco, 2018a). The trend towards large cloud data centres is also reflected in the regional distribution of data centre energy consumption. International hyperscale cloud providers often build their large data centres in Northern

Europe (Borbe, 2013; Microsoft News Centre, 2017; Mortensen, 2019; Quandt, 2014; Windeck, 2013). The reasons for this decision include low costs for cooling, low electricity prices and the availability of renewable electricity (Hintemann & Clausen, 2018a). This development has increased the energy consumption of data centres in Europe, especially in Northern Europe (Figure 20). In the coming years, this trend is likely to become even more significant. The share of data centre capacity in Southern and Eastern Europe is relatively small. According to Borderstep Institute calculations, only 18% of all servers installed in the EU28 were operated in these regions in 2018. Accordingly, the share of Southern and Eastern Europe in the energy consumption of data centres in the EU28 is low.

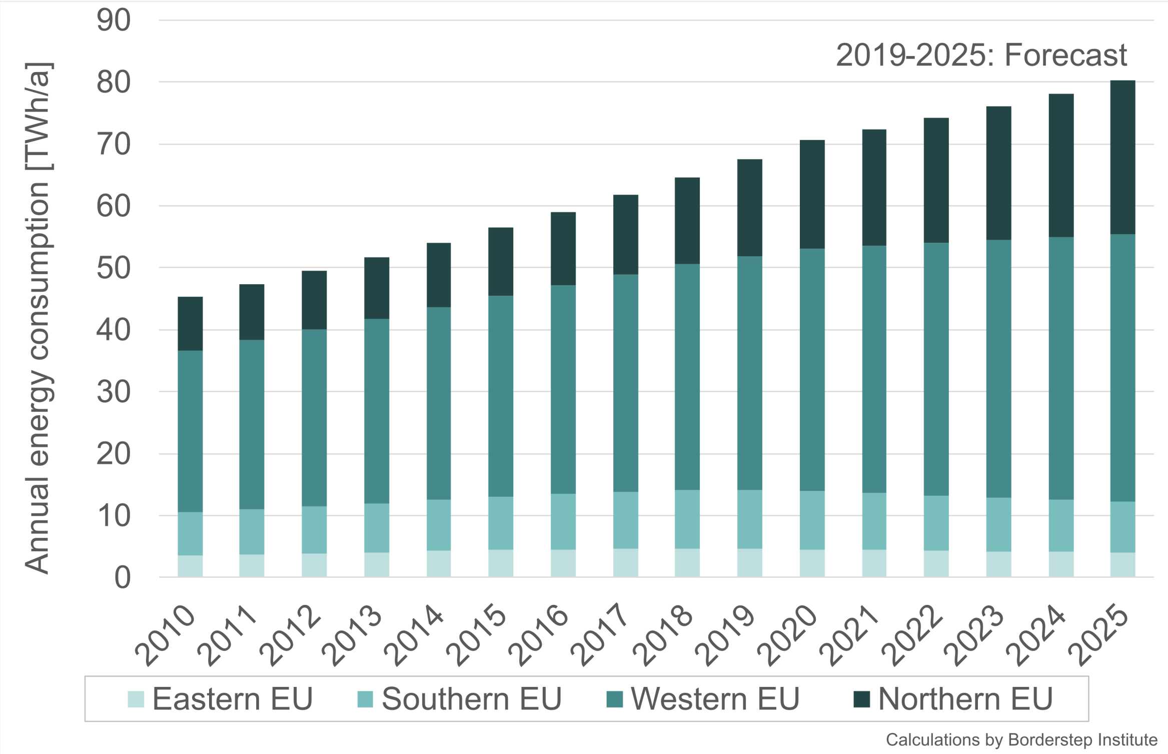

Figure 20 - Development of the energy consumption of data centres in the EU28 in the years 2010 to 2018 and forecast up to 2025 - breakdown by EU regions[6]

Outlook on the development of the energy demand of data centres in Europe up to the year 2030

A further increase in the energy consumption of data centres in the EU28 is also to be expected in the future. In order to illustrate the range of possible developments, four scenarios were created which are briefly described below:

Trend scenario: the trend scenario describes the development if hardware sales and efficiency increases in IT hardware and data centre infrastructure continue to develop as they did in the years 2010 to 2018. It is assumed that in 2025, 20% of the total server capacity available in data centres will be installed in edge data centres. In the trend

[6] As commissioned, this study examines the development of the energy demand of data centres in the EU28 – also for the future. It is difficult to estimate how the data centre market in the UK will develop from a current perspective because the effects of Brexit are still uncertain; this is not the subject of this study. In order to be able to assess the significance of the UK data centre market in the present forecast, the predicted energy consumption of data centres in the UK in 2020 and 2025 should be mentioned here: 13.0 TWh/a in 2020, 12.3 TWh/a in 2025. This calculation is based on the forecasts of server sales figures prepared before the decision for Brexit was taken.

scenario, the energy consumption of data centres will increase to 98.5 TWh/a by 2030 (Figure 21).

Expanding Edge data centres: for this scenario, it is assumed that the trend towards edge computing will be much more pronounced than in the trend scenario and that additional edge data centres will be built. For the year 2030, it is assumed that edge data centres will account for 40% of the total server capacity. Since an increase in edge computing is likely to be accompanied by a significant increase in the total amount of data to be processed, the energy consumption calculated in this scenario is higher than in the trend scenario. Such a development is not unlikely. With the expansion of 5G mobile networks and high-tech developments such as industry 4.0 and autonomous driving, the demand for small decentralised edge computing centres could see a massive increase. In this case, the energy consumption of all data centres in the EU28 could rise to approx. 120 TWh/a. If efficiently built edge data centres are used primarily to replace data processing in large cloud data centres, a sharp increase in edge data centres may be possible even without an increase in the power consumption of data centres overall.

Taking into account the energy demand of data transmission, an improvement in the energy efficiency of the entire ICT infrastructure is also possible.

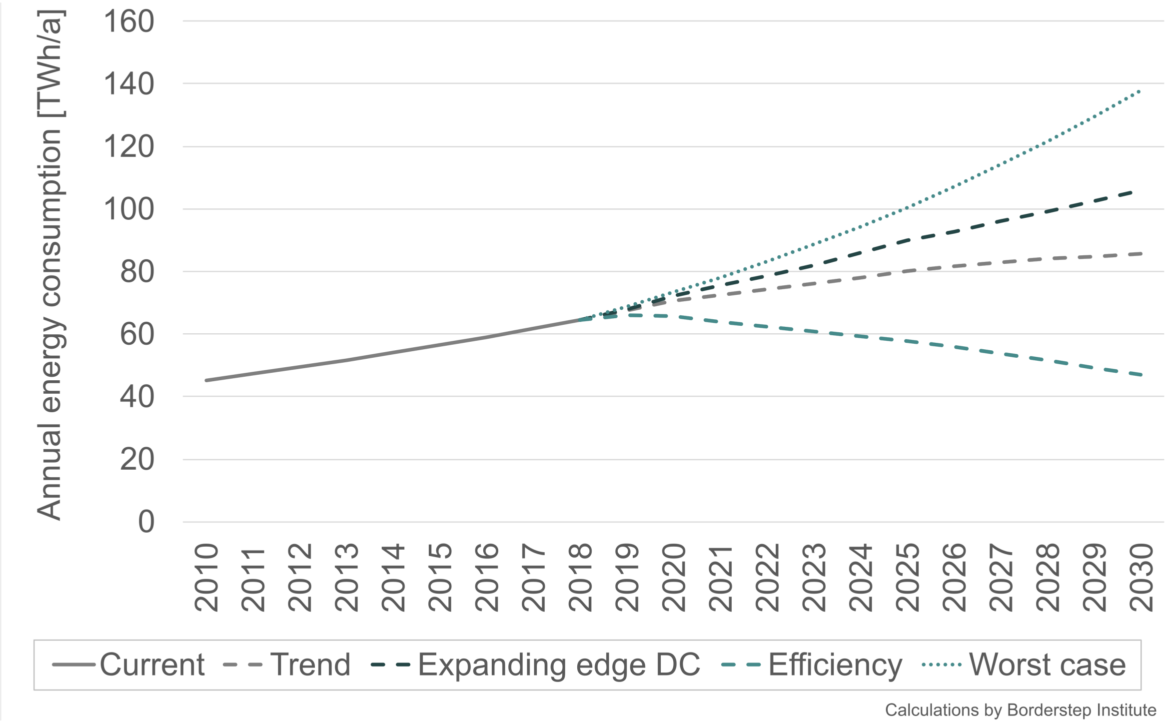

Figure 21 - Possible scenarios for the development of the energy demand of data centres in the EU28 until 2030

Efficiency: in the efficiency scenario, the expansion of data centres is assumed to be slightly lower. The growth rate for hardware equipment in data centres is expected to be 10% lower than in the trend scenario. The technological potential for increasing the energy efficiency of data centre infrastructures, IT hardware and especially management and architectures is assumed to have been largely exhausted. Edge data centres are used primarily to improve the efficiency of the entire ICT infrastructure. Once all available efficiency potentials have been exploited, it will be possible for the energy consumption of data centres in Europe to fall and be back at the level of 2010 (52 TWh/a). However, such a development is unlikely to come about unless it is massively promoted by government incentives and regulations. However, while the location of computing power can be flexible at least to some extent, the design of any measures in the EU should attempt to ensure that computing centres are not moved outside the EU area. Setting incentives for energy-efficient cloud services, e.g. in the context of public procurement, and promoting transparency as regards the total actual resource requirements are promising starting points here.

Worst case: in the worst case scenario it is assumed that current growth will accelerate even further and that data centre capacities in the EU28 will be expanded more than in the trend scenario. The growth rate for hardware equipment in data centres is assumed to be 10% higher than in the trend scenario. It is also assumed that there may be lower efficiency gains. Such a development is not unlikely, as further efficiency increases could become increasingly difficult due to the limits to miniaturisation of the semiconductor technology that is commonly used today, and is a trend that has been referred to as the end of Moore's Law (Waldrop, 2016). In the worst-case scenario, an increase in data centre energy consumption up to 160 TWh/a in 2030 is possible.

Figure 22 shows data centre energy consumption as a proportion of final electrical energy demand in the EU28 for the years 2010 to 2030. The energy requirements of the data centres based on the trend scenario are used here for predictions of the future energy consumption. While the percentage of data centres stood at 1.9% of final electrical energy demand in 2010, it could rise to 3.2% by 2030 in this scenario.

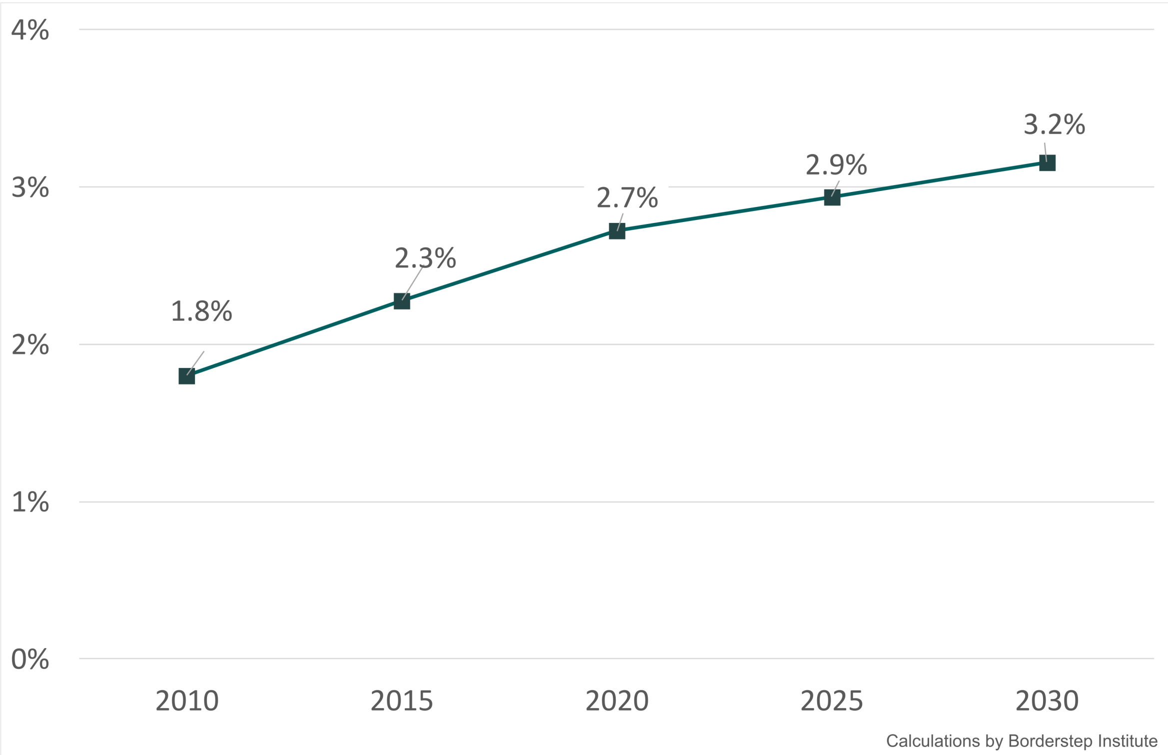

Figure 22 - Energy consumption of data centres between 2010 and 2030 (trend scenario), as a proportion of EU28 final electrical energy demand (Source EU28 electric energy demand: report of the modelling scenario EUCO32325 (European Commission, 2019)

Summary and conclusion

As this chapter has shown, the energy consumption of data centres in the EU28 has been rising steadily for years. Although cloud computing itself is in many cases an (energy-) efficient way of providing IT resources, the strong growth of cloud data centres is a major reason for this overall increase. The convenient, flexible and often cost-effective usage options lead to a significant increase in the demand for cloud services and thus to an increase in the energy consumption of data centres.

The analyses presented in this study also show that the range of possible developments in the future is wide. It can be assumed that the digitalisation of the economy and society as a whole will lead to a further increase in the energy consumption of data centres in the future. How high this increase will be and whether it can possibly even be prevented depends on the development of the technical and regulatory framework conditions.

8. TASK 2 - TECHNOLGICAL ANALYSIS

Introduction

Background & Context

Cloud computing is a delivery model for ICT resources such as storage or compute resources, but also for finished user products such as online applications, which have seen growth rates of around 30 % per year in previous years (Synergy-Research, 2018). In order to provide these services, far-reaching technological infrastructure is necessary, which also leads to increases in energy consumption as the demand for cloud products increases.

This working paper is intended to describe the current state of technology and the physical basis of underlying infrastructure and to analyse it in terms of its characteristic energy consumption. Further factors will be investigated, such as the management practices and generic services that are commonly used to deliver these services. This paper presents the ongoing discussion and the results of the SMART 2018/0028 study which was commissioned by the European Union.

Objective

Technological analysis: compile and analyse the spectrum of technologies for providing the full range of cloud computing services - from edge computing, intermediate networking and processing to cloud data centres - to determine typical and representative energy consumption patterns, the state of the art of energy-efficiency and the scope for further technological developments to improve energy-efficiency. This analysis should include relevant technologies, edge devices, networking, software, hardware, Blockchain as well as architectures and management approaches.

Scope

This paper describes the relevant components that are needed for cloud computing - from the edge of the networks to the central data centres - in terms of the energy consumption of individual services and specific energy consumption patterns within their use phase, including the relevant factors for management and software. Current technology trends that affect energy-efficiency are discussed and future potentials described.

Not within the Scope

The energy consumption of manufacturing, transport or recycling/disposal is not analysed in this paper, but taken into account in the discussion on recommendations. Also, this paper does not analyse the renewable power production of cloud providers or the purchase of green power certificates, as it focuses solely on the reduction of energy consumption. Neither does it compare the provision of products through public cloud providers with self-operated ICT infrastructures on company level.

Research question and scientific approach

Problem

The extent to which physical and software technologies enable cloud computing services is very versatile and highly complex in terms of their interdependency. A one-to-one assignment of physical devices or energy consumption to specific cloud applications is not possible (today) due to the high layers of abstraction and the sharing of resources in cloud architectures. Only components or component groups can be systematically captured and described with regard to their role in the provision of cloud services and the corresponding impact on the energy demand for these services.

To discuss the energy-efficiency of cloud computing, a separate analysis of individual components is helpful the gain a better insight into the technologies and their effects. But at the end, a comprehensive understanding of the functional relationships in the provision of cloud products is necessary for a discussion of appropriate measures; otherwise, there is a high risk of contradictory effects.

This paper therefore aims to describe the essential physical components, the software as well as the management tools that are used in cloud computing and their impact on energy consumption or energy-efficiency.

Methodology

In order to carry out such an analysis, information on the corresponding technologies is compiled on the basis of a comprehensive review. The following sources are used, based on the authors' selection:

- Scientific publications focusing on the fields of cloud computing, data centres and communication networks, with reference to energy consumption and energy-efficiency.
- Data sheets from manufacturers
- Available presentations and interviews with providers of public cloud services

It is primarily the responsibility of the authors to evaluate the correctness and completeness of the research. In addition to the research, various stakeholders are asked in an online consulting session about the completeness and correctness of previously determined values for cloud computing, and any gaps or questionable issues are revised or marked as controversial where necessary.

The results of the expert survey are presented in blue boxes in the respective sections of the document.

Key findings

1 Moore's Law has been the main driver for improving the ratio of computing power per energy consumption over the past decades. As the demand for computing capacity has steadily increased, the energy requirements of ICT have grown as well, but at a much slower rate in relative terms. Whether the fundamental physical conditions will allow Moore's Law to continue to provide further efficiency gains is a subject of controversy.

2 Infrastructure efficiency and the PUE of data centres improved over the past few years. The remaining energy-efficiency potentials are getting smaller as technology is moving closer towards the physical limits. At the same time, unlocking the remaining potentials is getting more complicated.

3 Energy-aware software development plays a major role for efficiency in cloud computing, especially when it comes to compute-intensive applications like Bitcoin mining and AI. There are carbon footprints that are fundamentally different, depending on the different software-based approaches used to realise the actual task.

4 Transmission in data networks is becoming more efficient in terms of energy consumption per GB, but total energy consumption is expected to further increase due to additional networks. The rollout of new access networks (e.g. 5G, FTTH) is very fast and the goals are ambitious. At the same time, old network technologies cannot be phased out because of existing equipment inventories. This can lead to further increases in energy consumption, especially in mobile networks.

5 The provision of ICT resources through public cloud computing offers several opportunities to increase energy-efficiency, compared to traditional data centres. High utilisation of compute resources, continuous renewal of custom-made hardware and advantages of professional operations through cloud computing providers can lead to an improved energy-efficiency. At the same time, however, cloud computing has a high risk of rebound effects due to its fast scalability and low financial entry barrier.

Characterisation of cloud services

Definition and basic characteristics of cloud computing

In this paper, the term cloud computing is used according to the following definition of the National Institute of Standards and Technology (NIST):

[Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This cloud model is composed of five essential characteristics, three service models, and four deployment models.] (Mell & Grance, 2011)

According to the NIST definition, cloud services can be described by the following five essential characteristics:

- On-demand self-service
- Broad network access
- Resource pooling
- Rapid elasticity
- Measured service

Cloud deployment models and typical cloud products

The various cloud services can be categorized according to their deployment model. Accordingly, the categories are referred to as XaaS, where X describes the scope or type of service. According to Mell & Grance (2011) the following three models represent the characteristic types of cloud computing:

- Infrastructure as a Service (IaaS)
- Platform as a Service (PaaS) and
- Software as a Service (SaaS)

In addition, there are other XaaS services which, as the authors understand it, can be assigned to the respective three characteristic cloud deployment models.

The understanding of cloud infrastructure

A common understanding of the cloud infrastructure is crucial for the further understanding of the document. In the NIST definition, cloud infrastructure is defined as follows:

[A cloud infrastructure is the collection of hardware and software that enables the five essential characteristics of cloud computing. The cloud infrastructure can be viewed as containing both a physical layer and an abstraction layer.

The physical layer consists of the hardware resources that are necessary to support the cloud services being provided, and typically includes server, storage and network components. The abstraction layer consists of the software deployed across the physical layer, which manifests the essential cloud characteristics. Conceptually the abstraction layer sits above the physical layer] (Mell & Grance, 2011).

Cloud energy-efficiency model

Based on the definition of NIST, cloud computing thus represents a model for the provision of ICT resources. Cloud computing products range from the provision of infrastructure products to turnkey online applications including all underlying components.

With regard to energy-efficiency, which can be understood as [...ratio of output of performance, service, goods or energy, to input of energy...] (Gregor Erbach, 2015), the factors that have an influence on this ratio must therefore be determined. Behind this, however, lies a high degree of complexity, since the respective factors have very different influences on energy-efficiency and cannot be evaluated with a common metric.

That is why a model has been developed to map the relevant areas of cloud computing and to describe and cluster the relevant factors for the energy-efficiency of cloud computing. The basic theory behind the model is to capture all relevant elements for providing the three cloud service models (IaaS, PaaS and SaaS) in terms of their energy-efficiency. The particular categories are:

Cloud computing physical elements

The physical elements that are needed to provide cloud computing services, from edge devices and networks to highly centralized data centres. Efficiency can be described as the relation of ICT workload (calculations, data storage, data throughput etc.) to the energy that is consumed.

Cloud computing software elements

The software layers according to the NIST Cloud definition that provide virtualized hardware, platform services or ready-to-use software applications. These software elements should have a low footprint in IT-resource usage (CPU-time/RAM/Storage/etc.).

The management elements to control the above-mentioned elements

The tools that help to coordinate the usage of widely distributed and heterogenous ICT infrastructures, performing efficiency-related tasks like scheduling, scaling or load balancing.

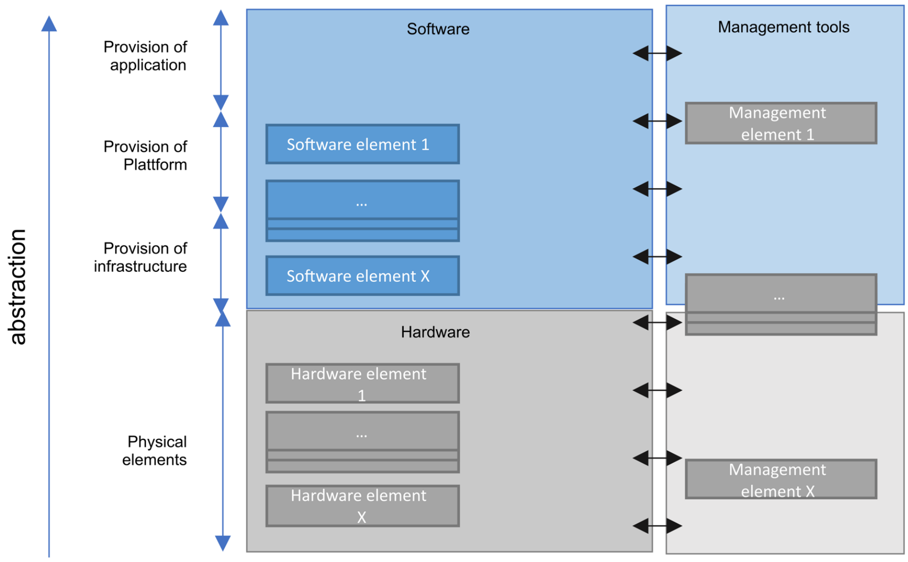

Figure 23 - The three basic areas Hardware + Software + Management tools for energy-efficiency in cloud computing

There are physical factors (hardware energy-efficiency), virtualisation related factors (e.g. hypervisor overhead), platform-related factors (OS overhead, runtime environment) and the actual efficiency of the application software. While the upper layers (light blue) induce the demand for virtualized ICT resources (compute/storage/network), virtualisation is responsible for the efficient provision of theses virtual resources on top of physical ICT hardware. The physical layers represent the hardware elements that physically consume energy and are relevant for the physical efficiency for providing IT-Equipment and the IT-Environments (e.g. cooling, uninterruptible power supply). Each layer and its elements are thus responsible for the energy demand of the cloud product in the end. To what extent this applies to different cloud products mainly depends on the respective cloud service model, e.g. the scope of SaaS products is bigger than that of IaaS products.

In addition to the functional (vertical) structure of the stack, an efficient provision of cloud products also depends heavily on the management of the different levels. For example, the mechanisms for up- and downscaling can strongly influence IT resource usage and are thus also relevant for energy-efficiency. A model with identified factors that are relevant for energy consumption and energy-efficiency in cloud computing is presented in Figure 24.

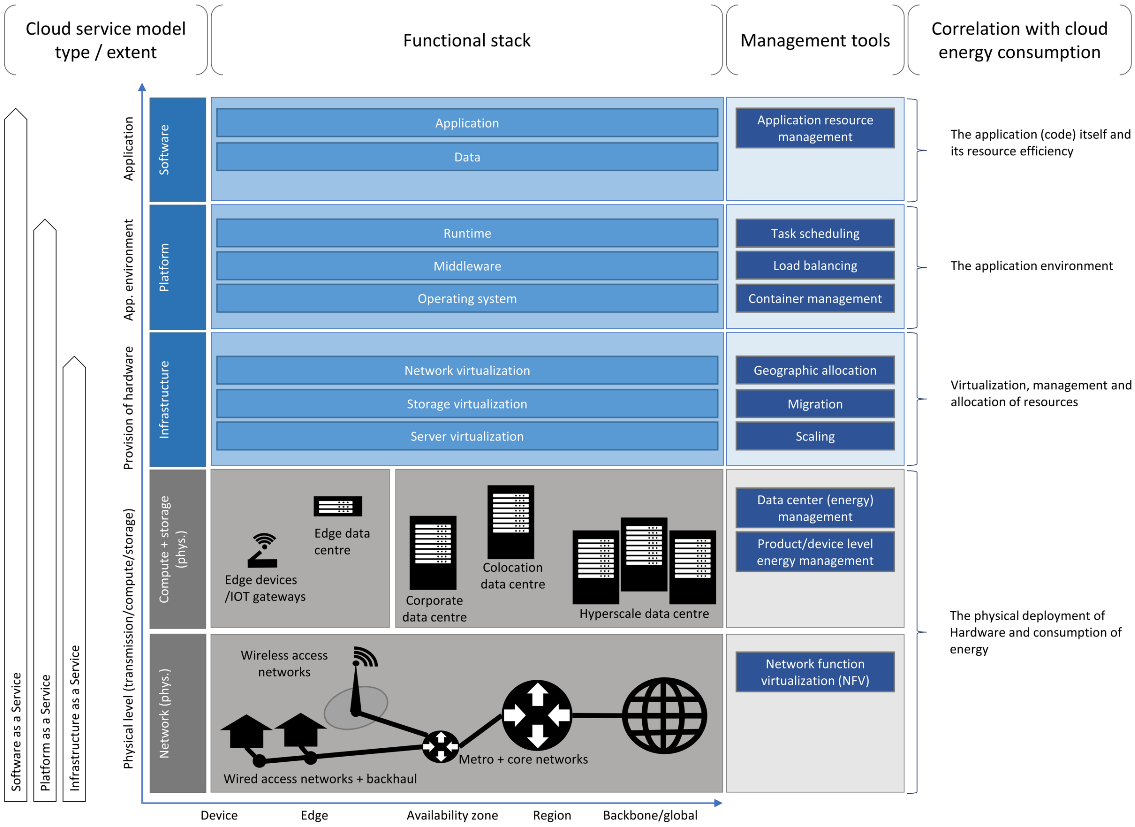

Figure 24 - Model with identified components relevant for energy-efficiency in cloud computing

The physical elements of cloud computing

The following chapter will describe briefly the spectrum of physical elements used for providing full cloud computing services.

Data centres

Role and relevance for cloud computing

Centralized IT components are typically housed in so-called data centres. Data centres are buildings, rooms or cabinets designed specifically for the operation of IT hardware. The operation of ICT hardware is subject to very specific requirements regarding security, access protection, fire protection, the thermal environment etc., which are to be met by the data centres and their integrated technological infrastructure.

For the provision of cloud services, data centres fulfil a key function, operating the fundamental physical IT resources of the cloud in a centralized manner. A high level of centralization facilitates a maximum degree of automation (e.g. replacement of a server by a robot) as well as continuous support and maintenance by satisfying economic criteria. Each data centre is an individual unit: even if data centre operators fulfil the same tasks, there might be variations in the age, the local ambient conditions or other factors. But there are characteristic types of data centres according to which most of them can be grouped. Some relevant data centre types for cloud computing are briefly described below.

Hyperscale data centre

The name hyperscale data centre originates from the term "hyperscale computing", an architectural approach that is intended to enable IT resources to be adapted to the needs of a business, i.e. to scale continuously and virtually indefinitely (Reegan Barnett, 2018). To provide the typical scalability for various kinds of workload, hyperscale data centres are equipped with multipurpose IT resources. These physical resources provide their capabilities (e.g. computing, storage or network) through virtualisation technology to a huge virtual resource pool, where automatic allocation satisfies the current demand of users.

According to Cisco, there were 386 hyperscale data centres operated by 24 companies at the end of 2017 (Cisco, 2018a). The worldwide capex of hyperscale date centres was almost 120 bn Dollar in 2018, a plus of 43 % compared to 2017 (Synergy-Research, 2019b).

Colocation data centre

With colocation data centres, a professional provider provides the space, infrastructure (electricity, network connection, fire protection, access control, lighting, etc.), while the IT hardware is provided by individual operators. Depending on the space and infrastructure required, the operator has to pay a fee for using a colocation data centre.

Corporate data centre

Many enterprises increasingly use cloud technologies to provide ICT resources. A complete migration of all processes to an externally operated cloud (public/private cloud) is currently still rejected by enterprises for various reasons. Frequently, self-powered cloud infrastructures can be extended with the much larger elastic resources of a cloud provider using standardized APIs.

Edge data centre

Currently there are huge expectations that a need for regionally distributed computing capacity will lead to a strong growth of a decentralised type of data centre, located at the edge of communication networks for improving signal latency between an end-user and physical cloud ICT.

Energy consumption and relevance

Data centres as buildings are highly individually designed and the existing components can vary greatly depending on the requirements. A simplified model is used for the consideration and analysis of energy-efficiency, which considers the most important components and clusters them into the following areas:

- IT equipment (server, storage, network)
- power supply (power transformation, uninterruptable supply batter-ies, distribution)
- Air conditioning/cooling (chiller, ventilation, pumps, humidifier, etc.)

Besides those areas, there are usually some other electrical components installed in data centres, but these are of less relevance for the total energy consumption of data centres or cloud computing.

More detailed information can be found in Task 1.

State of the art of energy-efficiency

Data centre play a major role in optimising the energy-efficiency in ICT. Integrated planning for energy-efficiency is needed including ICT, power supply, cooling and ventilation, the building, and also the local surroundings (potential heat sinks/waste heat customers). During operation, constant optimisation needs to be ensured, on the one hand to allocate changing workloads to the most efficient physical devices (dynamic resource allocation), but also to constantly adjust the infrastructure to the needs of the ICT equipment. Further details on the energy-efficiency of the data centre infrastructure (e.g. cooling and ventilation) can be found in the following section.

Server

Role and relevance for cloud computing

Servers are responsible for some of the core functionalities in data centres – these are the main physical devices that provide the necessary processing and computation resources. There are very different physical server types with regard to their (vertical) performance; or, on the other hand, they are adapted to the type of task (e.g. computing intense, memory intense or network intense). Large public cloud operators order customized servers or even produce their own servers and CPUs, which is reflected, among other things, in an ever-increasing ODM/direct sale of servers. (IDC's Quarterly Server Tracker 2018, 2018)

Some essential performance indicators for servers are:

- CPU architecture, model and number of CPUs/Cores/Threads
- Number of RAM and type
- Storage size and type
- Graphic Card(s), GPU model and number
- Network bitrate and redundancy

By varying these indicators and changing the ratios (for example the number of CPU threads to main memory) the server can be optimised for the respective workload.

The performance required in each category depends heavily on the application, so cloud data centres typically use different server types. The existing physical infrastructure of the servers is reflected in part by the compute products in the IaaS area, where many of these products (compute instances) use only a portion of the physical server resources and physical hardware is often shared by multiple virtual instances (section Server Virtualisation).

Energy consumption and relevance

Since there are big differences in the equipment of servers, their power consumption is also very different. In addition, current consumption depends on the respective load. The power consumption of commercially available server ranges from a few Watts for ARM based micro servers to two-digit kW for mainframe servers or GPU accelerated servers.

In between there is a wide range with different characteristics. For example:

- Compute optimised systems with high CPU performance (high core count)
- Ram-optimised systems with higher memory-per-core ratio

- Network optimised systems with high transfer rates or memory optimised systems that offer a higher capacity of integrated memory.

Further very specific servers are for example GPU supported systems or special CPU architectures (e.g. FPGA) for high performance applications or artificial intelligence. The spectrum of physical servers is reflected in the instance types of IaaS service providers, for example in the EC2 management console (AWS, 2019).

Standard servers are designed to optimally serve a wide range of cloud services from an economic point of view. It can therefore be assumed that this economically optimised multi-purpose segment also accounts for the largest share of physical servers. Large IaaS vendors have custom servers manufactured to achieve optimal economic conditions (James Hamilton, 2016).

More information about the total energy consumption of servers in cloud data centres can be found in the results of Task 1.

Energy-efficiency state of the art

The performance advantages in microelectronics (Moore's Law) have previously been the main factor for increasing the efficiency of servers, considering the relation between consumption and workload. This enables newer severs to handle a higher workload with comparable or even lower power consumption. The energy that is saved through server replacement after (typically) 3-5 years can easily pay back the necessary energy used for the creation of new server products over a life cycle.

One big factor for the energy-efficiency of servers is power consumption when in idle mode. As the utilization in data centres is often quite low, idle power consumption represents a loss of energy, as servers typically run 24/7 even if there is no workload. Highly virtualized cloud servers have the advantage that they are used for multiple purposes, and higher utilization rates (compared to a single purpose server with fluctuating workloads) are theoretically possible through smoothing peaks. Some cloud operators offer a spot market to incentivize the usage of cloud instances at times of low demand (Jeff Barr, 2015).

In the early years of cloud computing some research was published about the under-utilization of servers in cloud environments (Huan Liu, 2011). More recent data is not available. But there might be some circumstances that could still cause low utilization:

- avoiding noisy neighbour effects on shared TDP per CPU or other shared hardware (e.g. network or hard disk)
- bad configuration of the scaling mechanisms by the user
- bad instance for workload decisions

No current data on low utilization is available.

Technological trends and further gains for energy-efficiency

This development of new chip technology has a major impact on the energy-efficiency of the ICT devices that are affected by these technological innovations. As previously described, the main factor for improving the relation between workload and power consumption for servers (or instructions per watt on CPU level) is based on the technological performance increase in microelectronics. Reducing the performance density in CMOS technology would also reduce the continuous increase in energy-efficiency. At present, it is impossible to predict when such effects will occur. Chip manufacturers have previously found various workarounds, but currently there are delays (Feldman, 2019).

The CPU thermal design power (TDP) is an indicator of how much electrical power is drawn at 100 % utilization. Intel introduced in April 2019 a second generation of XEON scalable CPUs (focus on enterprise and Cloud) that has an TDP of up to 400 watts, a level much higher than previous generations (Intel, 2019). This can lead to a massive densification of the power-per-server and power-per-rack indicators in the future. It is not necessarily an indicator of how energy-efficient those servers compute a certain workload (instructions per watt) but enables fast growth without increasing the amount of energy per server or energy per floor space in a data centre.

Strong efforts are being made to further advance technology development by the industry. In the EU, a project called European Processor Initiative is aimed at developing an ARM-based general-purpose processor. According to the project website, promising approaches will be chosen to make the chip as energy-efficient as possible. This chip, manufactured in the EU, is to be used in individual high-performance computing applications from 2021 on, in the long term also for general purposes, i.e. also in the area of cloud computing.

Effects of regulatory requirements

Regarding the idle energy consumption of servers, it can be expected that the 2019 Commission Regulation for servers and data storage products will further improve the energy-efficiency of servers with an estimated annual reduction of 2.4 TWh within the EU28 in 2030 (Bio by Deloitte & Fraunhofer IZM, 2016).

Storage

Role and relevance for cloud computing

The physical storage in data centres can be provided through different technologies and organized in different architectures. A variety of factors are relevant for providing storage for the specific needs of a cloud application. Some of the main factors are:

- storage size
- Input/output per second (IOPS) and throughput (MBPS)
- latency, security (durability)
- security (access control/encryption)

There are different technologies used for the physical storage of the data. Traditional rotating hard disks are gradually disappearing and being replaced by flash storage – Solid State Drive (SSD). In many performance indicators, SSDs score better than HDDs. Storage drives can be operated, organized and physically provided for the different applications in various ways:

- internal drive of a Compute Server
- external enclosure (e.g. JBOD)
- external Direct attached storage (DAS)
- external storage that is provided on the network (storage area network-SAN)

A highly parallel operation of disks is used for different applications, mainly to accumulate high amounts of storage, to allow local data backup or to improve input/output rates.

Energy consumption and relevance

Big public cloud providers operate their own designed storage arrays, for example whole racks that contain more than 1000 disks (Hamilton, 2016). Like for servers, the power used by hard discs can be categorized through static (idle) and dynamic power consumption, depending the access; so efficiency is also a question of utilization.

Based on an ASHRAE Whitepaper, the energy consumption of HHDs and SSDs commonly used for enterprise applications can be estimated to range between 4.3 and 16.6 watts per disk, depending on various factors. Only drives with other shapes and connections that deviate from the usual form factors (2.5", 3.5"), such as PCIe or M.2 designs, have other power characteristics but often also offer other performance advantages like high input/output rates or a low energy consumption for mobile appliances (ASHRAE, 2015).

Energy-efficiency state of the art

The energy-efficiency of storage devices was examined in detail in Task 4 of the Preparatory Study for Ecodesign of Enterprise Servers and Data Equipment (Bio by Deloitte & Fraunhofer IZM, 2015).

Besides the product specific energy-efficiency, the energy-efficiency in operation depends heavily on how the data in the storage is organized and provided to applications and how management tools are used. Some important factors and approaches to provide energy-efficient storage are automatic provisioning, optimised compression strategies, and deduplication of unnecessary redundant files.

Technological trends and further gains for energy-efficiency

As cloud storage is more and more provided by SSDs, this reduces the energy consumption in the operation considerably, especially for I/O intense tasks provided through multiple parallel operation of rotating disks. Here, also the 3D XPoint technology from Intel (brand name “optane”) promises further advantages.

Network (data centre)

Role and relevance for cloud computing

The network in data centres provides the functionality of exchanging information within data centres and outside. A network mainly consists of network ports in storage and server devices, switches, routers and gateways and passive elements like cables (electrical/optical).

Networks employ different architectures while the expected vertical traffic (Up/Downlink) as well as the horizontal traffic within a data centre also plays a major role. At the rack level, all servers or storage devices are typically linked to a local switch that provides Up-/Downlink capabilities. Further aggregation then centralizes the traffic to the higher levels, from where data can be routed to external connections or other destinations within the data centre. The most typical data centre network topologies are three-tier and fat-tree (Popoola & Pranggono, 2018). In most data centres, network virtualisation is used to improve performance, reliability, flexibility, scalability, and security. Network virtualisation is particularly effective for networks that are subject to sudden, large and unforeseen load peaks. Examples are the Virtual Private Network (VPN) and Software-defined Networking (SDN).

Some big data centre operators have developed their own network architectures and even their own network devices like switches. Some cloud providers apply and promote specific standards (e.g. 25G networking) that are promising for their business needs (Amazon Web Services’ Secret Weapon, 2017).

Energy consumption and relevance

Switches and routers within data centres have very different performance requirements with a connectivity between 1 Gbit and 100 Gbit and up to 196 ports. Depending on the performance of the switches, the number and type of the ports (copper/fibre) and the technology factors (e.g. the routing functionalities on different Layers of the OSI model), the energy consumption of the switches varies heavily.

Also, the architecture of data centre networks play a major role for energy-efficiency (Popoola & Pranggono, 2018). Besides switches, the data centre network needs other components such as gateways or load balancers, but these are assumed to consume only small amounts of electricity overall.

Energy-efficiency state of the art

As with the other components, higher network performance components consume more energy than comparable components with lower performance; but the specific energy consumption per Gbit is typically lower. This leads to a steady efficiency increase in the energy consumption per transmitted GB but not in the energy consumption per network port. Data centres have different concepts of network architectures with tradeoffs between redundancy, performance on the one hand and energy-efficiency on the other.

Technological trends and further gains for energy-efficiency

The typically customized equipment used in big public cloud data centres can be assumed to be highly optimised for a particular purpose and thus can be considered as highly energy-efficient. Similar to backbone and core networks, software defined networking (SDN) has potentials to improve the data centre networks in terms of energy-efficiency.

Cooling and ventilation

Role and relevance for cloud computing

The electricity consumption of the ICT equipment in data centres is transformed into sensible heat, which needs to be removed to guarantee suitable operational conditions. Ventilation and cooling equipment cause an additional consumption of energy which leads to bad efficiency results for the provision of cloud products.

The removal of heat in data centres can be achieved in various ways: through air cooled systems, liquid cooled systems and hybrid cooling. Depending on the climatic conditions (especially maximum outside temperatures, humidity), active refrigeration is needed to guarantee the right operational parameters (ASHRAE, 2015).

Energy consumption and relevance

Energy consumption for cooling and ventilation can be divided into energy used for ventilation (pumping etc.) and energy used for refrigeration. Cooling is part of the data centre equipment and thus very important for power usage efficiency (PUE), an important KPI for rating the overall energy-efficiency of data centres.

Depending on the data centre technology, the operating parameters and the climatic conditions, a cooling system can consume huge amounts of energy, up to the amount of energy consumed by the ICT itself or even more.

Energy-efficiency state of the art

Self-reported figures of data centre operators within the European Code of Conduct on Data Centre Energy efficiency indicate that the average PUEs over the years have declined which could indicate that more efficient data centre equipment like cooling is applied (Avgerinou et al., 2017).

As cooling is only a supporting technology in the provision of the thermal operational conditions, it is one of the lowest hanging fruits in the attempt to reduce the overall energy of data centres. Efficient cooling technologies like liquid cooling and free cooling have proven to be appropriate and trustworthy for data centre cooling (Daraghmeh & Wang, 2016), (Yevgeniy Sverdlik, 2018).

Related to cooling, waste heat recovery is a relevant field. Although it does not directly reduce the energy consumption of data centres, it can be used to heat buildings or to provide other heat consumers in the neighbourhood of data centres. But there are many barriers to waste heat recovery, depending on the relevant data centre, the local regulations for district heating and the possible customers.

Technological trends and further gains for energy-efficiency

There are various approaches and technologies that provide efficient cooling solutions for data centre equipment.

There is ongoing technological optimisation with new technology concepts, for example:

- Airflow management and design
- Cooling management
- Temperature and humidity settings
- Free cooling

(Acton et al., 2018)

Especially for new data centres, the feasibility of using waste heat should always be considered and, if necessary, the cooling concept should be adapted accordingly. Further potentials for improving the energy-efficiency of cooling can be unlocked by research and through technology transfer from other industries. Since security and reliability have a high priority in IT environments, it is necessary (especially in the area of critical components such as cooling) that appropriate demonstrations by pilots exist to achieve a high market penetration.

Communications Networks

Role and relevance for cloud computing

By definition (NIST), communication connectivity and high-quality data transmission are essential elements for cloud computing. On the physical level, this communication can be realised using different technologies. The technologies for data transmission basically distinguish between wired transmission and wireless transmission.

The most contemporary networks can be categorized into access and aggregation layers, the core network and interconnections to Internet exchange points (IXPs) or Tier 1 Internet service providers. The European Union has ambitious targets regarding broadband internet access EU-wide. Until 2025 all schools, transport hubs and main providers of public services should have at least 1Gbps internet connection; all households a transmission speed (download) of at least 100 Mbps (European Commission, 2016b). Often power consumption and performance requirements are contradictory goals, which is why a tradeoff between them must be found.

Worldwide network energy consumption was estimated at between 200 to 500 TWh annually (Andrae, 2019b; Mills, 2013). Even though the specific energy per transmitted data (kWh/GB) in the network is decreasing fast (Aslan et al., 2017), a growth in total energy consumption can be expected as the data traffic has increased in an exponential manner in the past. (Andrae, 2019b) expects a 6-fold increase within the next 10 years.

Fixed access networks

Role and relevance for cloud computing

Fixed access networks play a major role for individual access to the internet as well for private households but also for any institution in terms of data traffic (including Wi-Fi connections at the home gateway) (Cisco, 2018b). Fixed access networks mainly consist of different variants of DSL connections (ADSL, VDSL, etc.) via copper lines, the coaxial TV cable network (DOCSIS) as well as direct fibre optic connections (FTTH/B).

Most of the old technologies of the telephone network (PSTN, ISDN) and their corresponding switching and transmission technologies have already been largely dismantled and are not playing a role in cloud computing, which is why they are not further discussed here. In (European Commission, DG COMM, 2019) the current market of fixed broadband subscriptions is presented by listing the different technologies. The share for each fixed broadband subscriber technology in July 2018 was:

- 61% DSL
- 19% Cable
- 16% FTTH/B
- 3.6 % Other

On average, access via glass fibre has seen the strongest growth (+34% on average per year) over the last five years, ahead of Cable (+7.3% on average per year) (calculated on the basis of European Commission, DG COMM, 2019).

Energy consumption and relevance

Fixed access energy consumption is mainly caused by enduser Routrs/Modems of which it can be estimated that they consume 3 watts each, but also by the aggregation switches of the internet service provider. An estimate by (Andrae, 2019b) assumes an energy consumption of around 69 TWh for the global fixed access networks in 2019; on an EU28 scale with ~180 million subscribers in July 2018 (European Commission, DG COMM, 2019) this would equal to around 6.2 TWh.

Energy-efficiency state of the art

The energy consumption of different access technologies for wired access networks varies quite strongly (Baliga et al., 2011). But, the customer premise equipment, mainly consisting of modems and wifi-routers (or integrated access devices) can be estimated to play the major role for the total energy consumption in access networks. The Ecodesign regulation privilege routers, gateways and access points compared to other networked devices as “High network availability functionality enabled networked device “(HiNA)-devices that is given more leeway in terms of standby energy consumption. (Coroama et al., 2014)

Technological trends and further gains for energy-efficiency

The specific energy consumption per transmitted GB in access networks can be estimated to be constantly decreasing, mainly through higher bandwith and increased data transmission while the consumption per subscriber remains constant. The total number of subscribers within the EU28 can be estimated to be further increasing (European Commission, DG COMM, 2019), so the total energy consumption of access networks might further increase.

Radio access networks

Role and relevance for cloud computing

Radio access networks (RAN) enable wireless access to the internet with a combination of various technologies. The existing radio access networks consist of a wide variety of heterogeneous technological components which differ in their functions, their age and energy-efficiency.

The fifth generation of mobile networks (5G) is a combination of various technologies aimed at improving mobile communications. The European Union has defined ambitious targets for the implementation of 5G Networks within the 5G Action Plan. For example, a fully-fledged service should already be available in at least one city in each EU Member State in 2020 (European Commission, 2016a, 2016b). 5G brings new completely new wireless trans-mission bands for public use like the millimetre wave above 30 GHz especially for small cells, but it also integrates existing macro cells (3G and 4G) to achieve a wide geographic coverage. The radio technologies will be enhanced with new multiple input-multiple output (MIMO) antennas, referred to as massive MIMO or full dimension MIMO. These antennas will provide advantages such as a larger number of parallel connections and an enhanced data rate through high spectral efficiency and improved beamforming. Besides new antennas, a wide range of IT components are needed to enable these network features with devices that have direct functions for network operation like complex precoding for MIMO optimisation.

5G brings new technological features that will enable further applications that are closely linked with cloud computing and will enable new services.

Energy consumption and relevance

Broadband equipment is estimated to consume around 15 % of the ICT sector's overall energy consumption. In 2015 it was responsible for at least 50 TWh annually in the EU 28 (Ari Sorsaniemi, 2017).

Technological trends and further gains for energy-efficiency

The fifth generation of the mobile network 5G brings promising opportunities through new technologies that improve energy-efficiency. On the one hand within the RAN, the data volume transferred per energy consumed can be improved through high data transmission rates, which allow more data to be transmitted from a single transmitter with comparable power consumption. On the other hand, 5G brings other possibilities like small cell offloading and mobile edge caching (Yan et al., 2019) that can reduce the overall energy consumption of cloud application. Manufacturer of mobile network equipment aim to reduce the energy intensity of mobile data transmission (kWh/GB) by the factor 10 until 2022 compared to 2017. Looking at the total energy consumption of mobile networks, these efficiency gains can be reduced or even erased by heavily increasing data transmission through the mobile networks.

Backbone and core networks

Role and relevance for cloud computing

Backbone or core networks are responsible for the far-distance and complex routing functions at the centralised infrastructure of the networks. These networks are highly important for the provision of typical cloud services, because IT resources are consolidated in big data centres for economic reasons. The bigger public cloud providers operate their own backbone network that connects their cloud regions all over the wold.

Energy consumption and relevance

As in data centre ICT equipment, the energy consumption of backbone and core networks consists of a static (idle) energy consumption plus a dynamic consumption that depends on the network activity. (Schien et al., 2014) modelled the core network of the internet and estimates a specific energy consumption for core networks of 0.052 kWh per transmitted GB for the year 2014.

Energy-efficiency state of the art

Like in other domains, the energy-efficiency depends highly on the utilization rate of the networking equipment. The virtualisation of network infrastructure can help to navigate traffic through the most energy-efficient routes and to enable “power-off” for not required equipment during times of low network traffic.

Technological trends and further gains for energy-efficiency

The energy intensity in kWh/GB of the average transmission network energy consumption is estimated to be reduced by half every two years, which means the efficiency savings double. These efficiency gains are comparable to the efficiency gains in CMOS-based microelectronics, which is not surprising as many network technologies also use these or similar technologies (Aslan et al., 2017). But energy consumption estimates are based on many assumptions that vary greatly from study to study.

Edge computing

Role and relevance for cloud computing

Edge computing is a decentralised way of providing various services in a decentralised manner at the edge of the networks. It enables additional services where the decentralised location of the hardware brings advantages in various ways.

“Edge computing” can be understood in very different ways, sometimes even as the opposite of cloud computing, namely as the decentralised edge vs. the central cloud. But the NIST cloud computing definition (Mell & Grance, 2011) is not limited to centralized infrastructure; instead, it generally describes the provision of ICT infrastructure, which in many cases would include edge devices.

It is expected that services will increasingly be operated on the edge on the basis of ICT components; this will also have major effects on energy consumption in cloud computing. There are many different approaches and trends that are related to the edge computing paradigm. Popular examples are cloudlet, fog computing, mobile edge computing (MEC), nebula, FemtoCloud, EdgeCloud and many more. The aims of these approaches often overlap or are even similar but may also differ fundamentally and the technologies used and their functionalities can also vary widely (J. Pan & J. McElhannon, 2018). A popular example to the heterogeneous edge computing infrastructure are smart/self-driving cars, where edge resources need to be located inside the car to enable the local computation of a huge amount of sensor data; but edge resources are also needed within the mobile network (MEC) that processes and provides data very quickly about the surrounding traffic.

Edge devices can have quite different technological functions depending on the relevant use case, but often multipurpose hardware is used, to enable a wide range of applications. Examples of edge devices are edge routers (giving further devices access to the network, or giving latency challenging data, computing resources or specific communication access to IoT applications). But they can also be the centralized controller within a car or ship that pre-processes data from subcontrollers to enable cloud services even in regions with a bad internet connection or under challenging operating conditions.

Energy consumption and relevance

The following sections give a short overview on how the different edge computing trends and the huge variety of so-called edge applications can be described in regard to their effects on energy consumption and energy-efficiency. Edge computing services can be divided into three characteristic clusters in terms of their impact on energy consumption/efficiency:

Edge computing-enabled (new) applications/services

The provision of services/applications via edge resources has many motivations, but some services are only made possible by the presence of IT resources at the edge. These are services or applications that are at least partly dependent on edge typical specifications, for example close-by processing or low latency signalling. Usage of edge computing resources for these applications induces additional energy consumption besides the existing energy consumption of cloud computing.

A huge growth of these edge enabled services might create additional workloads for centralized data centres which, even in an increasingly decentralised edge-cloud constellation, will still be of great importance for all supra-regional concerns and for comprehensive big data analysis. The same is true for communication networks, which might have to carry even higher amounts of data through the rise of additional applications/services (Luo et al., 2017).

Computation offloading to the edge

> **The offloading of computation workloads from centralized cloud resources such as hyper scale data centres to decentralised edge resources.**

There are different motivations for offloading computational workloads from centralized cloud to ICT resources at the edge. One example of this could be analytics at the edge for data intense sensor live processing. This could be the analysis of a live video stream or other data sources. As such "cloudlets" are assumed to use similar or even equal hardware resources, and also virtualisation and management software like in traditional cloud computing, this allows edge cloudlets to run the same or similar applications on a virtualized layer, just like in bigger data centres. These characteristics will enable a flexible relocation of cloud tasks to different locations or a ubiquitous decentralised provision of selected services. As Gartner predicts for the year 2025 (van der Meulen, 2019), this could lead in the long term to a shift of data processing from big cloud data centres to decentralised cloudlets and the same could be true for the energy required. The impact of such a shift on the energy-efficiency is difficult to assess and depends heavily on what the future edge infrastructure will look like. However, it can be assumed that at least in slightly larger edge computing units (like MEC), IT components similar to those in central cloud environments will be used for economic reasons (e.g. customized servers with off-the-shelf chips).

> **The offloading of complex computational tasks from smart mobile devices (SMD) within the IoT spectrum.**

Research has shown that SMD can benefit from offloading computational complex tasks to nearby edge computing infrastructures, also called cyber foraging. Its main purpose is to minimize the energy consumption of SMDs and to improve the performance and thus user experience in complex computation tasks (M. Satyanarayanan, 2017). On the one hand, this offloading enables a longer battery life and energy harvesting technologies for the SMD, on the other hand it can improve the overall performance of some specific applications (J. Zhang et al., 2018). As the aim of these offloading schemes and process optimisation is to improve the usability of the SMD, there are big opportunities for a reduction of the energy consumption of the devices but it is very likely that such computation offloading will create a much higher additional energy consumption through additional network transmission and through the additionally needed edge computing resources. The gross additional energy consumption (or saving) depends on many factors and thus varies strongly. Some important factors are: type of workload, the communication technology used, the efficiency and capabilities of the SMD and the technology of the edge computing servers

Traffic offloading to the edge

The decentralised provision of data objects in distributed edge resources can help to significantly reduce data transmission in the superimposed networks. A wellknown example of this is the content delivery network (CDN), which acts as cache for huge files and is widely used for video streaming.

The reduction of network traffic has an energy saving impact on the energy consumption of backbone/core networks, but causes additional energy consumption for the decentralised edge ICT components. Simulations have shown that CDN typical edge caching can save about 20% of the network power (Araujo et al., 2013). Even higher savings are estimated for mobile network services and applications from (Yan et al., 2019) in combination of edge caching and offloading to smaller cells (macro to femto cell). Here the savings strongly depend from the type of application. For the most promising application type (virtual reality – VR) savings of 75% are possible, for web browsing and video play, savings of 45% in energy consumption are estimated.

As traffic offloading is highly dependent on the quality of predictions for the demand of specific data related to a specific region, there is a huge potential for improving these technologies with machine learning (Z. Chang et al., 2018).

Estimation of the impacts of edge computing on the energy-efficiency

The impact of the edge computing paradigm on the energy consumption of ICT has been the subject of various research efforts, but mostly with a focus on the energy saving effects for battery powered smart mobile devices (e.g. Ahmed & Rehmani, 2016; J. Zhang et al., 2018; P. Mach & Z. Becvar, 2017). There are only a few case studies that give an insight into the overall impact of edge computing on the energy consumption of networks or cloud environments (Li et al., 2017; Luo et al., 2017). The overall energy-efficiency effects of edge computing on the European network have not yet been investigated.

The IoT is often regarded as the strongest driver for edge computing, which is why it seems logical to assume that a future development of edge computing will be based on the development of IoT. The Ericsson mobility visualizer gives forecasts about the development of the number of subscriptions, as well as the traffic and data consumption of mobile devices (Ericsson, 2019).

(Li et al., 2017) has evaluated a model that describes the energy consumption of IoT devices using the example of data stream analysis by cameras embedded on vehicles. Scaled down to device level, edge computing servers consume up to 32.3 Watts per stream, about three times the consumption of the actual device.

Scaling up this device-related edge computing consumption by calculating the relation of the data traffic per device to the estimated mobile traffic for Europe in the year 2024 (21.7 EB/month) results in a total power demand of ~530 megawatts for edge computing that equals 4.6 TWh per year. However, this is only a very simplified calculation to give a rough idea of the magnitude of the energy consumed. It is based on rough estimations and simplifications:

- All mobile traffic is (pre-) processed by edge computing. It is quite likely that some services will still not be provided at the edge but by centralized cloud resources.
- The workload here refers to video analysis; according to the (Ericsson, 2019) video, it will account for about 75% of traffic in 2024, but the processing of IoT data will vary greatly depending on the application, and there may also be applications where the processing is completely different.
- This example refers to mobile edge computing (MEC), i.e. the processing of data in the radio access network. Compared to other edge computing environments, for MEC the architecture and functionality is already defined to some degree which makes it somewhat more predictable (ETSI, 2019). However, there will be other edge computing IT resources that enable services within e.g. vehicles, company buildings, production processes or residential buildings. An estimate of these consumers is still too vague today, as many predicted technologies are still at the development stage.

Management tools in cloud computing

Device level power management

Role and relevance for cloud computing

ICT devices typically have internal power management to reduce power consumption at times of low utilization automatically. There are many technologies that provide power management functions on device level. A widely used standard for power management is Advanced Configuration and Power Interface (ACPI) that delivers an interface for power management to operating systems and defines different power states for components. Through ACPI, the operating system becomes able to detect unused components and gets the ability to put them to sleep, depending on the predefined rules of the energy management. For equipment like CPUs, the Operating system can put them into different performance states (P-States) using dynamic voltage and frequency scaling (DFVS).

Relevance for energy-efficiency

It has been proven by various research, that power management of ICT devices can save considerable amounts of energy, depending on the aggressiveness of the energy management plan. To adjust the power and frequency to the respective needs can also improve the performance in a given thermal environment, especially in CPUs and GPUs. AWS recommends the usage of lower P- and C- states in multicore environments to create space within the thermal limits for other cores to achieve better turbo boost performance.

Data Centre Infrastructure Management

Role and relevance for cloud computing

Data centre Infrastructure Management (DCIM) solutions are typically software products designed to provide administrators with a holistic view of the performance of a data centre. The aim is to optimise the overall system as efficiently as possible in real time. DCIM should enable the convergence of IT and building functions within a company. DCIM can be used to optimise efficiency and to reduce the energy consumption with improved control of infrastructure equipment (e.g. cooling).

Relevance for energy consumption and efficiency

It can be assumed that in big data centre locations (e.g. hyperscale data centres) that are operated by one cloud provider processes are already controlled by DCIM for economic reasons. It might be different in colocation data centres, where the operation of cloud IT (server, storage etc.) and data centre infrastructure (cooling, power supply) are in the hands of different companies and therefore not coordinated with each other. Especially in the area of colocation it is not known how much DCIM is already used.

It has been shown that with machine learning (AI) additional predictive capabilities can further improve efficiency gains through DCIM (Evans & Gao, 2016).

Cloud management (scaling, orchestration, geographic allocation)

Role and relevance for cloud computing

Cloud infrastructure is complex as there are many different suppliers with a wide range of products - especially if cloud users deploy a hybrid-cloud or multi-cloud infrastructure, where many components (under certain circumstances from different suppliers) are combined. There are many tools that provide options for a comprehensive management of various cloud resources to economically fit the needs of a user (e.g. Scalr, RightScale, Openshift,).

For management within a public-cloud environment, management tools are usually provided (management console etc.). The user interface is typically a web browser front end or mobile app. There is often a dashboard that provides a quick overview of the applications. The console typically offers the possibility to start a multitude of cloud services, independent of the service model. For IaaS products, there are typically additional specific consoles to monitor the corresponding compute instances or storage more closely, to analyse their operating data and adjust parameters if necessary. There are also various tools that support the scaling of compute or storage resources, or tools that can be used to automate scaling.

Relevance for energy consumption and efficiency

Cloud infrastructure has the advantage that resources are only used and paid for by a user when they are needed (elasticity). This has great advantages over traditional data centre infrastructure, as the unneeded cloud infrastructures can be used by other applications at these times - good utilization of the components is thus possible. It is also often possible to automate cost-oriented shifting of workloads between different cloud providers with the help of such management tools.

For an energy-efficient use of cloud services, this management software is an important factor, because it enables automated scaling and the allocation of cloud resources to applications. However, in addition to the actual functionality of the software, configuration (rules) is also necessary for an efficient upscaling/downscaling of the applications, so part of the responsibility lies with the user of such tools.

The H2020 Project OPERA showed that energy-aware allocation algorithms within heterogeneous clouds can achieve energy savings of between 30% and 42.5% compared to other allocation policies (Scionti et al., 2018).

Software in cloud computing

Server virtualisation

Role and relevance for cloud computing

On a cloud server, workload is typically run in a virtualized environment. To enable this, a host system (hypervisor, virtual machine monitor) provides and manages the virtual environment. The basic level of server virtualisation provides hardware in a virtualized manner. On this virtual hardware, an application can be operated but needs to include the whole software stack including the operating system – a so-called virtual machine. There are different types of server virtualisation that can mainly be distinguished by the way how the guest system can access the physical resources or how they are emulated from the host system.

The term virtualisation or server virtualisation is sometimes wrongly used for “cloud computing”. Virtualisation only represents an important component in cloud computing for enabling some of the relevant characteristics of cloud environments. Besides, servers in cloud data centres (and also companies with on-premise IT) take advantage of server virtualisation.

Relevance for energy consumption and efficiency

Server virtualisation can lead to much higher utilization rates of the server, which can significantly increase the workload per server. Cloud providers claim that their server utilization rates reach up to 65% (Jeff Barr, 2015), compared to non-virtualized on-premise servers that are utilized at 15%. This can be a huge gain for energy-efficiency, especially when idling servers still consume huge amounts of energy.

Combined with a spot market for cloud computing virtual machine instances of public cloud providers, there can be monetary incentives for cloud customers to run non-time-critical processes during hours of low utilization - for example highly compute intensive calculations for science running during the night time on thousands of vCPUs.

OS Virtualisation / Container

Role and relevance for cloud computing

The so-called Operating System virtualisation (OS Virtualisation) or container virtualisation is (besides server virtualisation) another technology that provides a specific environment for the provision of ICT resources. It is arranged one level above server virtualisation within an operating system. Compared to a virtual machine, a container thus does not include the operating system itself. On the operating system, software is needed to host containers (e.g. Docker), allocate hardware resources and CPU time and to isolate different containers from each other. Container virtualisation plays a major role for the implementation of cloud native applications that are built on a micro service based architecture. Especially if the actual application is lightweight, the operating system of a virtual machine can make up 99% of the storage and a big part of CPU overhead consumption. Containers are also designed to separate certain resources of a server to isolate an application but still shares one operating system potentially with other applications that also run in containers.

The example of Netflix, where they increased its deployed containers within one year at the factor of 1000, which scalability opportunities container technologies offer (Andrew Spyker et al., 2017).

Relevance for energy consumption and efficiency

Container technology helps to make applications easily scalable without big overhead of additional storage and CPU for the operating system in VM. This makes it therefore already an efficient technology. But there are pre-built containers, which often include a whole compilation of micro services, of which in many cases only one is needed by an application – in what extend this affects the energy consumption needs to be investigated.

Docker as the most popular platform to run containers on, seems to have a big overhead in energy consumption. It was reported, that docker even in idle consumes big amounts of energy, even if there are no containers running in it. But also, if real workload is running in containers, docker induces still a considerable energy footprint (Santos et al., 2018).

Storage virtualisation

Role and relevance for cloud computing

Storage virtualisation enables the virtual abstraction of storage from physical hardware. This abstraction makes it possible to circumvent physical limits, such as the capacity of individual hard disks or maximum access rates. Software organizes the functional provision of storage for a large number of users who each have separated logical areas but might access one and the same physical device. Virtualized cloud storage can be organized in very different manners, three characteristically storage types are object storage, block storage and file storage.

Relevance for energy consumption and efficiency

Storage virtualisation helps to achieve much higher utilization rates for storage devices and reduce redundancy for reliability/backup through automatically deduplication of data. This can help to achieve reductions in energy consumption up to 80% compared to traditional storage (Hill, 2013).

Network virtualisation

Role and relevance for cloud computing

Just like server visualization, network virtualisation allows physical resources to be abstracted in order to improve operations. Network virtualisation creates opportunities to combine all available resources within a physical network to divide it into logical segments or to create a software-based network of virtual machines. It helps to optimise networks in terms of reliability, speed, flexibility, security and scalability. The term network virtualisation is closely related to the term software-defined network.

Relevance for energy consumption and efficiency

Network virtualisation is an important technology for improving operation within data centre networks overall but also within the aggregation and core networks of the internet. It can help to route traffic through the most efficient path(s) and to create options for powering off unnecessary equipment during times of minimum load.

(Kaup, 2018) showed that software-defined networking with a software-based open vSwitch has advantages for energy-efficiency especially for complex tasks near the core network, but in the aggregation networks hardware-accelerated switches perform much better in terms of energy-efficiency. Current developments of equipment for network functions are focusing on COTS x86 hardware, but offloading to FPGAs or ARM platforms is a promising approach for higher energy-efficiency (Kaup, 2018).

Efficient application software

Role and relevance for cloud computing

The application software represents the uppermost part of cloud deployment. Its purpose is the delivery of the actual cloud application (SaaS) on the basis of the (virtual) resources provided by the operating system and, if applicable, other platforms or application environments. Software for cloud applications is often designed differently from application software for individual devices. It may example be designed in a way that combines different software components (microservices) with standardized interfaces and scales them individually according to requirements. Application design for end devices, on the other hand, is often based on monolithic approaches. For cloud applications, developers often have at their disposal various application environments (including operating systems) as virtual machine images, comparable to a construction kit; the same also applies to prefabricated containers that enable certain microservices.

Relevance for energy consumption and efficiency

As it performs the task of realizing the actual function of a cloud application, the application software has a key role in terms of efficiency. Regardless of whether the cloud application directly provides a service for an end user or enables a secondary process, it is highly relevant to the provision of the actual service with a minimum of abstract and physical ICT resources and their respective power consumption.

There is a theory that with the increase in performance, software becomes more complex and therefore slower (also known as Wirth's Law) as a result of poor design decisions, eradicating the performance and efficiency gains of the hardware (N. Wirth, 1995). Against this background (that the IT hardware performance has developed enormously), the increasing need for additional computation infrastructure seems remarkable (e.g. one of today's fastest GPUs have - in terms of FLOP/s - computation capacities comparable to a 100m dollar supercomputer in 2000, while consuming only 1/10 000 of the power).

There is no single metric to describe the efficiency of software, as this is an extremely heterogeneous field where comparisons between different products are difficult or impossible.

Further issues and trends that affect energy-efficiency in cloud computing

The growth of compute intensive workloads in cloud environments

Cloud computing enables new computational-intensive applications, popular examples are:

- Distributed Simulation: AWS advertises the usage of 40k EC2 instances by Western Digital to perform compute intensive simulations on distributed cloud instances. For this simulation somewhat more than 1 million CPU Threads (vCPUs) from different AWS regions were used simultaneously to enable simulations in less time compared to traditional high-performance environments.
- Artificial Intelligence, especially deep learning technologies also often build on massive compute environments that typically combine multiple GPUs to enable up to billions of training iterations with large data sets. Those learning processes for an ML algorithm often require many GPUs in parallel operation and take many days or even weeks, consuming up to hundreds of MWh.

On the basis of its huge capacities in distributed computing facilities and devices, cloud computing is designated for compute intense workloads. So cloud computing can be seen as a competitor for High performance computing (HPC) which provides users with enormous computing power. This might be more expensive for users that do vast on a regular basis compared to on premise hardware, but for those who need these capacities from time to time, pay-per-use can be very attractive compared to a long-term investment in fast aging HPC infrastructure.

Blockchain technology and cloud computing

Role and relevance for cloud computing

Blockchain is a technology for accumulating data in defined structures (blocks) that are linked to each other using cryptography. Each block contains a cryptographic hash of previous blocks and a timestamp.

Blockchain is not necessarily a technology that is closely linked to cloud computing within the meaning of the NIST definition, but it can provide some computational trust which can be important for applications that run on heterogeneous and distributed hardware.

Blockchain based crypto currencies, namely Bitcoin and Ethereum are criticized because of their absurdly high energy consumption; this and potential correlations aspects of cloud computing are discussed in the next section.

Besides that, Blockchain technology provides some interesting opportunities for cloud computing. Blockchain could enable a distributed cloud computing environment based on a huge number of participating users, that provide their hardware (e.g. computers, smartphones, servers) for others do run their workload intense applications and to do huge computations.

Examples for this are the iExec project or the golem network (golem, 2016). These new approaches are intended to compete with traditional cloud operators in specific fields, where decentralised cloud hardware (fog computing) has advantages over centralized hardware in cloud data centres. (Gilles Fedak et al., 2018).

Relevance for energy consumption and efficiency

The future role of Blockchain in cloud computing cannot yet be foreseen, but there is great potential for the use of Blockchain. Since an application of Blockchain for the documentation of different stages of a value chain is also under discussion, the technology could be used to assign different physical components and their power consumption to the respective cloud computing applications. This would give users and developers a better insight into energy and resource consumption.

Blockchain based crypto mining

Role and relevance for cloud computing

Blockchain-based crypto currencies such as Bitcoin have attracted some attention in recent years due to their high energy consumption (O'Dwyer & Malone, 2014), (de Vries, 2018), (Digiconomist, 2019). Already in the first documented idea about Bitcoin in 2008, the author stated that […]In our case, it is CPU time and electricity that is expended[…] (Nakamoto [pseu-donym], 2008), to describe the incentive mechanism for participants in the network in a metaphorical way as gold mining.

Besides the concept of crypto mining on own devices (on-premise), the idea of public cloud-based crypto mining has been discussed (Krishnan et al., 2015). This brings the advantage of almost no investment in mining equipment (= low capex; almost no risk) and the potential to utilize big infrastructures only for a limited time during hours of attractive market conditions. But as most of the common cloud computing resources are designed for a wide spectrum of applications (e.g. x86 Server), they are not economically suitable for mining purposes, which is typically done on specialized architectures (ASICs). But a report in 2018 showed that cloud computing resources which were employed by big companies were illicitly used for mining activities by others (David Liebenberg et al., 2018).

Relevance for energy consumption and efficiency

Bitcoin is estimated to consume between 40 and 75 TWh, Ethereum currently about 7 TWh calculated on an annual basis (Digiconomist, 2019). The main problem with the energy consumption of crypto currencies is the distribution of the new created coins, weighted according to the contributed virtual work output (proof-of-work principle). As soon as there are more computing machines in the network (higher hash rate), the complexity of the encryption of transactions is artificially increased so that all machines can still prove their contribution at maximum computation load. This artificial increase in complexity is the main driver of the absurdly high energy consumption known from Bitcoin.

Instead of the proof-of-work (POW) principle for incentivising participation in the network, the proof-of-stake (POS) principle could be applied. This could reduce the energy consumption of such crypto currencies to a fraction of the POW principle (0.0006% - 0.006%) for the same useful work (The Bitcoin Green Team, 2017). This would lead to a massive reduction of the needed hardware components and would make the need for huge resources (which are also available in cloud environments for the purpose of crypto mining) obsolete.

Transparency issues about the ICT equipment of cloud providers

Role and relevance for cloud computing

Transparency in the physical infrastructure and the management approaches are important factors for calculation of cloud computing energy consumption. This applies both to research into the calculation of current cloud energy consumption and forecasts for the future, as well as to customers or users of cloud services who consciously want to deal with energy and resource consumption.

One problem is that details about hardware, management tools and energy consumption are often regarded as trade secrets by cloud providers, and little information is publicly available. In addition to purchased standard components, some cloud providers also develop their own hardware, which makes it even more difficult to draw a clear picture of the physical ICT below the available virtualized infrastructure.

Another problem with cloud computing is that different services share hardware resources. A physical server, for example, can easily represent multiple virtual instances that work in separate cores/threads but still share many of the server's resources, such as the power supply. This makes it difficult or impossible to assign a specific energy consumption of the cloud to a service.

Conventional methods of measuring consumption by electricity meters cannot solve these problems. However, alternative concepts could be developed to deduce the specific energy consumption of an application/service based on the demand of virtual (cloud) resources. Similar proposals have already been developed to link the billing of cloud services even more closely to the actual use of resources.

Relevance for energy consumption and efficiency

Better comparison of cloud sustainability through live monitoring and reporting of cloud infrastructure for the user of cloud services and reporting standards for market transparency. However, in order to characterize the technologies that are used to provide IaaS products, assumptions can be derived from some available sources. On the one hand, experts of IaaS supply companies repeatedly comment on the technology (Rich Miller, 2015). On the other hand, quality details on the products, such as the CPU series in Compute Instances (IaaS), are occasionally published. Also, other external IT experts publish some insights into the physical hardware from their own research based on different methodologies; for example, reading CPU information in a virtual machine through the linux command “cpuinfo” (Avdeev, 2018).

Low hanging fruit for energy-efficiency from a technological perspective

Based on a stakeholder consultation on the telephone and via online surveys, some technologies or technological areas can be considered as low-hanging fruit when it comes to further improvements of energy efficiency.

As for the physical elements, this applies in particular to improvements in CPU and GPU chips for computer servers in terms of their general performance per watt (like FLOPS8/watt), but also in terms of their specific abilities for complex tasks. Flexible circuits with FPGA chips or even application-specific chips (ASIC) are used already to help handle specific workloads (e.g. deep learning tasks) in a much more energy efficient way. A broad use of such technologies could also contribute to the energy efficiency of cloud computing. In the long term, quantum computers will also offer considerable potential for specific tasks.

Another promising development that concerns the physical elements is a reduction of the energy demand of cooling, which could be achieved in many places by using existing technologies or approaches (e.g. direct free cooling, Kyoto cooling, evaporative cooling etc.). Here it is often the warranty conditions of IT manufacturers, service contracts with customers in colocation data centres, or even regulatory requirements that make the dissemination and wider use of efficient technologies difficult. The focus here should be on smaller and older data centres as, in relative terms, the remaining energy saving potentials in modern and in most of the bigger data centres (>1 MW) are rather low.

In addition to potentials for physical elements, there are the easily accessible specific advantages of virtualised cloud environments (e.g. micro services based architecture, orchestration/management tools). These tools have not been widely implemented and the configuration of these tools often does not take energy efficiency into account. It can be assumed that a more stringent scaling policy for cloud services can lead to large savings. A promising approach here would be to promote the use of more efficient criteria in the default settings of cloud management tools.

Another promising field is the design of applications that run on the cloud infrastructure itself which could be more efficient. From a developer's perspective, ICT resources (and thus indirectly energy) are available in cloud environments in virtually endless amounts (compared to applications for mobile devices). Accordingly, the motivation to make the design of applications more efficient is relatively low. However, the development of apps for mobile devices in recent years has shown possibilities for energy efficient application designs – and the knowledge gained from this sector could be used to design energy efficient cloud services.

9. TASK 3 - POLICY ANALYSIS

Introduction and goals

Task 3 comprises:

- Review of current ways of compiling and analysing the impact of current approaches to stimulating or imposing eco-friendly procurement, use and provisioning of digital technologies (focus on cloud services and data centres as described in Task 1 & 2). Relevant standards for digital services in this area will be mapped out (Green Public Procurement will be analysed in detail in Task 5).
- Gap analysis.
- Assessment of the feasibility and effectiveness of policy measures (e.g. awareness raising, codes of conduct, voluntary schemes and self-regulation, labels, legislation etc.).

Objectives/structure

To reach these goals and to build the basis for the next work packages, the work will be divided into the following subtasks:

- Development of a methodical framework for Tasks 3, 5 and 6
- Compilation and analysis of current policy approaches
- Gap analysis
- Collection of best practice examples
- Assessment of the feasibility and effectiveness of current policy measures

Key findings

1 The energy-efficiency of the cloud is currently not directly addressed in EU legislation, future EU directives on energy-efficiency and specific regulations for data centre operators will need to address the energy consumption of the cloud.

2 As for the energy-efficiency of network and computing power, some work has been also done at the research level, but there is currently no universal solution when it comes to increasing the energy-efficiency of networking and computing power, and there is also no market at the moment for such products.

3 It will not be possible to control climate change without massive use of digital technologies; but their overall energy consumption must be drastically reduced in the coming years.

4 The public procurement of the future will increasingly rely on cloud services, e.g. for the procurement of services such as Smart Building, Smart Energy, etc. Few examples exist at the moment, but as soon as this will become a megatrend GPP will need to respond to that by updating the existing criteria (e.g. for energy, infrastructure, etc.) accordingly, e.g. to include the energy-efficient requirement for the cloud services.

5 There are no known implemented policy instruments for energy-efficient cloud computing and only a few policy instruments for energy-efficiency data centres.

6 For most of the analysed policy instruments no evaluations are available. But even if effects on energy-efficiency could be shown in evaluations, it is possible that energy-efficiency improvements are at least partly due to other factors like

independent technological development or economic trends and are not only caused by a policy instrument.

7 Even if the transferability of the results for the policy instruments used in ICT or data centres to policy instruments suitable for cloud computing is restricted, the analysed instruments were used as basis or inspiration for the development of some of the policy recommendations.

Development of a methodical framework for Tasks 3, 5 and 6

The aim of this Task was to define the framework characterizing the current situation of energy-efficient cloud computing. Framing the current situation is a necessary step to define the boundaries for the assessment of best practices and policy options for energy-efficient cloud computing and the gap analysis.

The analysis framework presented in this report considers:

- The existing EU legislative framework for Green Public Procurement (GPP)
- The existing EU legislative framework for energy-efficiency
- The existing EU legislative framework for cloud computing
- Other relevant initiatives
- Current existing initiatives on GPP
- The current status of energy-efficient cloud computing services, including an overview of existing energy-efficient data centres and current energy need, an overview of existing energy-efficient cloud services
- An overview of the future of cloud computing and GPP in a digitalized world

The analysis framework

EU legislative framework on GPP

Green Public Procurement (GPP) aims at supporting the public purchase of goods and services by taking into account environmental criteria in addition to technical and economic criteria. GPP, and general public procurement, are regulated at the international and at the EU level.

At the international level, the framework for public procurement has been set by the WTO agreement, the European Strategy on public procurement, and national legislative instruments.

At the EU level, public procurement and green public procurement is regulated by a number of pieces of legislation, directives and procurement rules. The relevant EU documents regulating GPP include the following key documents:

- Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement and repealing Directive 2004/18/EC (European Commisson, 2014a)
- Directive 2014/25/EU of the European Parliament and of the Council of 26 February 2014 on procurement by entities operating in the water, energy, transport, and postal services sectors and repealing Directive 2004/17/EC (European Commission, 2014b)

- COM(2008) 400 final: Public procurement for a better environment; COM(2008) 397 final: Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan; COM(2003) 302 final: Integrated product. (European Commmission 2008a; European Commission, 2008b; European Commission, 2003)

These three Directives had to be transposed into national law by the EU Member States by 18 April 2016, introducing new EU public procurement rules and stipulating principles for public procurement such as: wider use of electronic procurement (e-procurement), participation of small and medium-sized enterprises (SMEs) in public tenders, simplified procurement rules for public authorities, innovation partnerships to keep public services up to date, supporting social responsibilities and enhancing eco-innovation among others. Once the three Directives have been transposed, member states would be able to procure goods and services from any business based within the EU through a centralized platform. Procurement is conducted at the EU level only when contracting central government authorities conclude service contracts exceeding € 144 000, and other, sub-central, public agencies conclude service contracts exceeding € 221 000. Contracting authorities comprise state, regional or local authorities, bodies governed by public law or associations formed by one or more such authorities or one or more such bodies governed by public law. (European Commission, 2018e)

In October 2017 the European Commission released an updated public procurement strategy, laying down six policy priorities. Two of the priorities are to ensure broader uptake of innovative, green and social procurement, as well as pushing the EU towards greater digital transformation, since a strategic procurement environment can boost competitiveness and build markets for smart and sustainable technologies. Regarding digitalisation, the EU has decided to undertake a thorough rethinking of the public procurement process with new rules on e-procurement and the use of electronic tools for public procurement. (European Commission, 2017a)

In addition, the following EU initiatives recognize the importance of GPP for greening the economy:

- The Communication on Integrated Product Policy encourages the Member States "to draw up publicly available action plans for greening their public procurement" (European Commission, 2003)
- The recent EC Circular Economy Package, which emphasizes the importance of strategic public procurement. (European Commission, 2015a)

Currently there is no specific EU directive addressing the energy-efficiency of cloud services.

EU legislative framework on energy-efficiency

Three relevant pieces of legislation were identified with regard to energy-efficiency:

- The EU Ecodesign Directive 2009/125/EC (European Commission, 2009)
- The European Directive on Energy-efficiency 2012/27/EU (European Commission, 2012a), amended by EU Directive 2018/2002 (European Commission, 2018c)
- The EU 2020 Climate & Energy Package ”20-20-20” (European Commission, 2008c)

The Ecodesign Directive serves to create a framework for defining minimum Ecodesign requirements for energy-related products to help limit energy consumption and consequently also CO2 emissions. Complementary to the Ecodesign Directive is the Energy Labelling Regulation which supplements the Ecodesign requirements with mandatory labelling requirements (European Commission, 2019f). A Commission Regulation on “Ecodesign requirements on enterprise servers and data storage products” has also been prepared by the EC (European Commission, 2019f). The Commission has carried out a preparatory study to analyse the technical, environmental and economic aspects of servers and data storage products typically used for commercial purposes. The study has been carried out with stakeholders and interested parties from the EU and third countries, and the results have been made publicly available. The preparatory study shows that use-phase energy consumption by servers and data storage products can be significantly reduced. The effect of the Ecodesign requirements set out in Regulation (EU) 2019/424 is estimated to result by 2030 in annual energy savings of approximately 9 TWh (corresponding approximately to the yearly electricity consumption of Estonia in 2014) (European Commission, 2019f). The energy consumption of servers and data storage products could be reduced by applying existing non-proprietary technologies without an increase in the combined costs of purchasing and operating these products. Ecodesign requirements stated in the document will need to be applied for servers and online data storage products starting from 2020.

The European Directive 2012/27/EU on Energy-efficiency establishes a set of binding measures to help the EU reach its 20% energy-efficiency target by 2020, and requires from its member states concrete measures to save energy consumption. (European Commission 2012a). The amending Directive 2018/2002 on energy-efficiency has been prepared in December 2018. (European Commission, 2018c). Agreements on energy-efficiency:

- A headline EU energy-efficiency improvement target of at least 32.5 % to be achieved by 2030.
- Energy savings obligations of 0.8 % per annum between 2021 and 2030, to be calculated in terms of final energy consumption.

Member States shall comply to the Directive by 25 June 2020. (European Commission, 2018c)

The European Directive 2012/27/EU on Energy-efficiency establishes a set of binding measures to help the EU reach its 20% energy-efficiency target by 2020, and requires from its member states concrete measures to save energy consumption (European Commission, 2012a).

The EU 2020 Climate & Energy Package "20-20-20"” (European Commission, 2008c) requires European companies to achieve a reduction of CO2 emissions, an increase in the share of renewable energies and an increase in energy-efficiency by 20 % each by 2020. To this end, the EU has defined three main objectives:

- Reduce greenhouse gas emissions by 20 % (compared to 1990)
- Coverage of 20 % of the energy demand from renewable energies
- Increase in energy-efficiency by 20 % (European Commission, 2008)

Also, one of the biggest social challenges will be to replace fossil fuel energy use with more sustainable sources. The transition to a sustainable energy landscape is a huge interdisciplinary challenge that requires not only new technologies, but also a reorganization of the generation and provision of electricity to make the energy industry sustainable.

Given its huge energy consumption and future development (as investigated for this study), cloud computing will also play a role in the achievement of the EU energy goals. Since the energy-efficiency of the cloud is currently not directly addressed in EU legislation, future EU directives on energy-efficiency and specific regulations for data centre operators will need to address the energy consumption of the cloud. In the future, data centre operators will also have to measure their energy consumption and implement measures to reduce it. Some data centre operators are already working on minimizing energy consumption. Rising energy costs and the sustainability of energy production are also becoming increasingly important.

To accelerate progress on these goals, the European Commission has adopted a voluntary Code of Conduct on Data Centre Energy efficiency in 2008 which is updated every couple of years (European Commission, 2018b).

EU framework on cloud computing

The current EU policy on cloud computing in the EU is regulated mainly by the following documents:

- A European strategy for data (COM (2020) 66 final) (European Commission, 2020a)
- Digital Strategy "Shaping Europe's digital future", (COM (2020) 67 final) (European Commission, 2020c)
- European Green Deal (COM (2019)640 (European Commission, 2019e)
- EU Cloud Strategy 2012 (COM(2012) 529 final) (European Commission, 2012b)
- Digital Single Market Strategy for Europe (European Commission, 2015b)

With the Cloud Strategy, the EU aims at developing a first EU strategy to enable and facilitate faster adoption of cloud computing throughout all sectors of the economy in order to boost productivity, growth, and jobs. The importance of cloud energy consumption is stated in this document, which recognizes that an unprecedented increase in data flow and processing of information over the Internet has a significant environmental impact through energy and water consumption, and greenhouse gas emissions. Cloud computing can help mitigate these problems thanks to more efficient use of hardware, e.g. by building data centres which use low-energy servers and green energy. In order to address the challenges posed by an increased cloud use, harmonized metrics for energy consumption, water consumption and carbon emissions of cloud services had to be agreed with the industry by 2014. As part of the strategy, Cloud Standards in the Digital Single Market were developed to bring clarity on the variety of technical standards and especially regarding interoperability, data portability, and reversibility. (European Commission, 2012b)

In 2019, the Commission’s Information Technology and Cybersecurity Board approved the new Cloud Strategy of the Commission. This strategy describes how cloud computing is shaping the future of IT and how it is an enabler for the overarching European Commission’s Digital Strategy. At the heart of the cloud strategy is a cloud-first approach with a secure hybrid multi-cloud service offering. Among the targets of the strategy is also to achieve energy-efficiency, in line with the overall EU priority of lowering the carbon footprint and with the green public procurement policy. (European Commission, 2019f)

Based on the EU Cloud Strategy, the digital Single Market Strategy for Europe was published in 2015. This strategy was designed to speed up and increase the use of cloud computing across all economic sectors and especially by creating a level playing field for EU companies and businesses, in order to guarantee uniformity of data protection and consumer rules regardless of where their server is based. (European Commission, 2015b)

In the light of more recent development, different documents have been quickly adopted by the European Commission, which will support the transition towards a greener cloud.

The European Green Deal (European Commission, 2019e) has been recently adopted and recognizes the role of cloud computing in facilitating the digital transformation of Europe’s economy. Cloud computing and edge computing will be among those digital technologies that will contribute to achieving the sustainability goals of the European Green Deal in areas such as farming, mobility, buildings and manufacturing.

The European Green Deal will work on different initiatives such as the recently adopted European Data Strategy (European Commission, 2020a), and the Digital Strategy "Shaping Europe's digital future" (European Commission, 2020c). The first one aims to make the EU a leader in a data-driven society by creating a single-market for data. The second one aims at shaping the European digital future and endorses key actions, including investments for green cloud infrastructure.

Other relevant initiatives

- ENERGY STAR (agreement between USA and EU expired on February, 20th 2018)
- Guidelines – Energy-efficiency in Data Centres (by Bitkom)
- Energy-efficient Data Centre Operation (DE-UZ 161) - Blauer Engel
- EU Code of Conduct on Data Centre Energy efficiency and Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy efficiency
- Recommendations of the Study Groups of ITU's Telecommunication Standardization Sector (ITU-T)

These initiatives are described in detail in chapter "Description of the policy instruments selected as "best practice" examples.

European initiatives on GPP

Different relevant European initiatives exist for Green Public Procurement: Sustainable Public Procurement (SPP) and Public Procurement of Innovation (PPI) (European Commission, 2018d). These are typical voluntary instruments, established to help local governments to introduce sustainable procurement practices in their day-to-day activities. These initiatives often tackle energy-efficiency and ICT related topics. Their main activities concern the networking of stakeholders, dissemination of best practices, and preparation of documents and guidelines to facilitate procurement and in general, they ensure that know-how is shared among different Member States. The most important initiatives are:

- ICLEI global platform (ICLEI Local Governments for Sustainability): ICLEI has been working on procurement since 1996, assisting hundreds of cities, regions and public authorities to embed sustainable, circular and innovation criteria into public tenders directly and through collaboration projects. ICLEI provides professional information, advice, networking opportunities, training and tools to public authorities wanting to implement better, more cost-effective sustainable and innovation procurement practices. (ICLEI, n.d)
- SPP Regions – Regional network for sustainable procurement: Within SPP Regions, seven European regional municipality networks work together on Sustainable Public Procurement (SPP) and public procurement of innovation (PPI). The regional networks transfer skills and knowledge through their SPP and PPI activities with a focus on SPP tendering in the field of energy use in public buildings, vehicles/transport and in the food and catering services (SPP Regions, n.d).
- European sustainable procurement network (Procura+): Procura+ is a network of European public authorities and regions for connecting public procurers, as well as for exchanging best practices and acting on sustainable and innovation procurement. The network develops policies/criteria in specific areas related to

sustainable procurement in thematic Interest Groups and operates the Procura+ Helpdesk for individual advice and support (PROCURA+, n.d.).

- GPP 2020 – Procurement for a low-carbon community: This GPP 2020 initiative aims to support procurement across Europe to achieve the EU's goals of a 20% reduction in green-house gas emissions, a 20% increase in the share of renewable energy and a 20% increase in energy-efficiency by 2020. The initiative is co-funded through the Intelligent Energy Europe programme of the European Commission and more than 100 low-carbon tendering processes focusing on capacity building, training and best practice exchange have been funded which directly resulted in substantial CO2 savings (GPP, n.d)
- PPI platform – Public procurement for Innovation: The Procurement of Innovation Platform has its legal basis in the revision of the European Procurement Directives which took place in 2014. It is supported by the European Commission and works as a hub for information regarding innovation procurement. The aim is to steer scientific and technological breakthroughs in areas such as health and wellbeing, food security, sustainable agriculture or clean & efficient energy. The process will be co-funded through the Horizon 2020 fund and will support selected groups of procurers in undertaking joint PPI procurement (PPI, n.d.). (European Commission, 2018d)
- The PPI Platform is the first port of call for PPI. It contains the latest news and events, the European legal framework, policy support and updates on PPI-related projects. (European Commission, 2018d)
- The Procurement Forum is a space for procurers and other stakeholders to discuss, share and connect, allowing them to post comments and upload documents, images or videos. Users can create groups, which is ideal for developing and coordinating projects. (Procurement Forum, n.d)
- The Resource Centre provides a central database for PPI knowledge, gathering useful documents and examples in one place. Resources include national and European policy and strategy documents, tools, case studies, details of projects and initiatives, and reports.
- The Public Procurement of Innovation Award aims to recognize successful public procurement practices that have been used to purchase innovative, more effective and efficient products or services. (Public Procurement of Innocation Award, 2020)

In addition, a number of tools such as handbooks and guidelines have also been developed to support green procurement activities:

- UNEP SPP implementation guidelines – developed under the United Nations Environment Programme (UNEP). This document aims at providing guidance for all governments and organizations interested in the implementation of SPP. (United Nations Environmental Programme, 2012)
- Public Procurement as a Driver of Innovation in SMEs and Public Services: a guidebook for regional or national policy-makers on how to support specifically the public procurement of innovative solutions (PPI). (European Commission, 2014c)
- Procura+ Network: within the network and through its activities, a manual with practical advice on how to integrate sustainability into procurement was developed. (Procura+, 2016)
- Buying green! Handbook: comprehensive guidance on the implementation of GPP under the EU Procurement Directives, written by ICLEI on behalf of the European Commission. (European Commission, 2016c)

- Public Procurement for a Circular Economy: in order to support public purchasers to leverage support for a transition to a circular economy the European Commission published, in October 2017, this brochure containing a range of good practice case studies as well as guidance on integrating circular economy principles into procurement. (European Commission, 2017b)
- Energy Innovation Procurement. A Guide for City Authorities: this Guide provides a multi-level approach for ambitious city authorities that wish to achieve transformational energy outcomes across the city. It includes the methodology that was created and applied within the European project CEPPI (Coordinated energy-related PPIs actions for cities) known as the 'Flexible Framework for Energy Innovation Procurement', approaches to needs identification and planning, and strategies for procurement interventions to achieve innovation. (ICLEI, 2018)

Current status of cloud computing services and their energy-efficiency

Overview of data centres and their need for energy

Especially in recent years, cloud computing has become an alternative to traditional IT outsourcing and in-house operations as an efficient modern approach to the dynamic and needs-based provision of computing resources. Cloud computing also provides a flexible and high-performance environment to deliver on-demand, subscription-based online services over the Internet that can host applications on a pay-as-you-go basis. As a result, more and more cloud providers are relying on and using larger cloud data centres to meet the ever-increasing demands on digital capacity (computing power, data storage, and network).

In order to reduce service delays or failures and to be able to comply with or guarantee the Service Level Agreement (SLA), multiple redundant data centres must be operated around the clock. Enormous amounts of data must be processed as a result of digital activities such as streaming, file sharing, searches and social networking sites, e-commerce, and IoT sensor networks. This data must be stored across multiple cloud data centres and efficiently processed, in a way that allows the end users to use the service immediately and at any time. In this way, energy consumption is dramatically increased through extensive data creation, processing, and storage, which in the end negatively impacts the carbon footprint of Cloud Services.

In addition, the need for computing power and networking is not constant over time and can easily have positive or negative peaks during a day, which leads to an under- and overload of resources (variability) in the data centre infrastructure (cooling, computer, storage, networking, etc.). As a result, the energy consumption of cloud data centres cannot always be efficient (e.g. when left idle).

As a result and according to current projections, the use of cloud services is growing exponentially with the continued growth of Internet-based services, increasing data centre power consumption by 20-25% each year. Studies also found that 78.7 million tonnes of CO2 are produced by data centres, equivalent to 2% of global emissions (Li, X, Garraghan, P, Jiang, X et al., 2018). This means that the CO2 emissions of the data centres are globally already the same as those of the aviation industry. Furthermore, data centre energy consumption could rise to more than 800 terawatt-hours per year (TWh) by 2030, unless measures are taken (Dario Pompili, Abolfazl Hajisami, and Tuyen X. Tran., 2016; Sarah Fotuhi Piraghaj, Amir Vahid Dastjerdi, Rodrigo N. Calheiros, and Rajkumar Buyya, 2017).

One of the most difficult tasks for cloud providers will be to make cloud computing energy-efficient and sustainable while responding to dynamic changes in end-user requirements.

A constant compromise between performance and energy-efficiency to meet the required service levels will be necessary.

Energy-efficiency of data centres VS energy-efficiency of cloud services

Whereas a substantial number of studies on the energy-efficiency of data centres are already available, less attention appears to have been devoted to the energy-efficiency of the network and computing power.

As for data centres and their electricity demand, the interest in researching the impact of cloud computing on the environment is steadily increasing. Different studies started to investigate topics such as the energy consumption of data centres and the development of new architectures designed to reduce data centre power consumption already at the end of the last decade (Liu, L.; Wang, H.; Liu, X.; Jin, X.; He,W.B.; Wang, Q.; Chen, Y, 2009; Mingay, Simon, 2007). The interest in methods to reduce data centre energy consumption has further increased in recent years, as confirmed by the analysis of existing literature and studies. An analysis of the scientific studies since 2009 (based on the following search criteria: "Green Cloud Computing", "Sustainable Cloud Computing" and "Sustainable" in combination with "Cloud Computing") revealed a strong increase in the interest in Green Cloud Computing from 2013 onwards (Rania Fahim El-Gazzar, 2014). All in all, these studies have been very important for the development of energy-efficiency in data centres.

As for the energy-efficiency of network and computing power, some work has been also done at the research level.

Basically there is the possibility of optimizing resource consumption through dynamic consolidation using various techniques, which are briefly listed here:

- Live Migration: Virtual Machines (VMs) Migration to other physically suitable servers.
- Sleep Mode: during computing phases, servers and server components can be switched to sleep mode.
- Low Energy Cloud Platform: Migrate VMs to a low Energy Cloud Platform.
- DVFS (Dynamic voltage and frequency scaling): this is an energy-saving technique in computer architecture that is used to save energy when the server load is low. The frequency and voltage of the CPU are scaled to adapt dynamically to the server load.
- EEVS (energy-efficient scheduling algorithm of virtual machines): this algorithm deals with optimal frequencies for the processor to run the VM.
- LP-MKP (layered progressive resource allocation algorithm for multi-tenant cloud data centres based on the Multiple Knapsack Problem): a multi-stage layered progressive method for multi-tenant VM allocation, and efficient handling of unprocessed tenants at each stage.
- EABFD (Energy Aware Best Fit Decreasing): it is an algorithm for satisfying the Qos parameter (Pavithra.B.1, Ranjana.R.2., 2015).

The techniques are described in different studies and have been developed at least theoretically, but they pose the following problems. At first, these techniques must be tailored to the needs of specific use cases, and can only be employed under specific conditions, which might not suit other applications. As a result, developing such techniques is competitive only for big players, de facto excluding small and medium service providers and making it a niche sector since the products for energy-efficiency are difficult to be placed and sold on the market (e.g. currently there is practically no market).

In addition, these techniques are at odds with the required high quality services and have to compete against the cloud paradigm which wants to deliver continuous, uninterrupted access, rapid scaling, flexible and cost-effective service. Higher-level resource management is required since resource allocation is highly variable. Furthermore, the resources must be updated in real time if new conditions are set. There is currently no technology in cloud computing that can overcome these challenges.

Finally, it would not be possible to simultaneously adapt or optimise cloud services, since this would be possible solely via cross-client techniques. Also, techniques that perform optimisations with time-controlled mechanisms require a very detailed analysis of the business requirements and a rigorous categorization of all services (Pavithra.B.1, Ranjana.R.2, 2015).

In conclusion, it can be argued that there is no universal solution when it comes to increasing the energy-efficiency of networking and computing power, and there is also no market at the moment for such products. In addition, the complexity of cloud platforms/architectures makes performance modelling enormously complicated, which reduces the possibility to increase their energy-efficiency.

Future of cloud computing

As highlighted in the introduction chapter, digitalisation will radically change the way in which many sectors traditionally operate, such as the energy (smart grids, small grids), transport (connected mobility), industry (factory 4.0), services (e-commerce), buildings (smart building) and agriculture (smart farming, smart water) sectors. Digital technologies, which include Industry 4.0, autonomous driving, new telecommunications networks over 5G, audiovisual equipment, and IoT, will make the digital transformation possible.

Digital technologies are often looked at with confidence, as part of the solution to the challenge of reducing the energy consumption and CO2 emissions in a variety of sectors, since digital technologies will enable more efficient use of energy and resources (e.g. in smart houses, or through connected mobility). The conclusion of many studies is even that it will not be possible to control climate change without the massive use of digital technology.

Nevertheless, whereas many existing studies point out that the IT technologies of the future will contribute to achieving more energy-efficiency, less emphasis is in general put on the energy consumption of the cloud and how energy-efficiency will be achieved. Digital technologies will increasingly rely on cloud computing, hence the decentralized storage and processing of data will become increasingly important. This will require ever-larger data centres (hyper scale data centres) which ensure that data can be stored online and retrieved from anywhere. Other processes will rely on an increased network capacity (as the 5G) and computing capacity (as for big data analytics), resulting in ever increasing energy demand of the cloud.

In general, both sides of the digitalisation process (energy savings and energy-efficiency improvements which digital technologies will allow - versus the overall energy consumption needed to operate digital technologies) are equally important and shall be considered in R&D as well as at the policy development level.

Reducing data centre power consumption is a challenging and complex issue as computer applications and data grow so fast that more and more servers and hard drives are needed to handle them fast enough within the required time frame. A dynamic consolidation through various technologies in green cloud computing would be required, not only to achieve efficient processing and use of the IT infrastructure, but also to minimize energy consumption. Only in this way can it be ensured that the future growth of cloud computing will be sustainable. Otherwise, cloud computing will lead to a huge increase in energy consumption. To solve this problem, the resources of the data centre must be managed in an energy-efficient way. In particular, cloud resources need to be allocated in such a way that they not only meet QoS requirements set by users through Service Level Agreements (SLA), but also reduce energy consumption.

Future of GPP

Describing how GPP will look like in a digitalized future is not an easy task.

Currently, public procurement is increasingly moving into the cloud, with an increasing number of services that are being digitalized. This is resulting in an increasing amount of data moving into the cloud which needs to be stored, transmitted and processed, with a consequent increase of the demanded energy. Currently, the focus is on solving important data sovereignty, transparency, privacy, and security issues.

Two main trends will most likely shape the future of digital procurement and GPP:

- Increase in the demand for cloud services for big data management and especially in the research, genomics and healthcare sectors. Research centres and universities will need to pull resources together to afford bigger and more powerful datacentres, capable of performing the required operations. International cooperation will become more and more frequent in this regard.
- Digital services of the future will increasing rely on the cloud, due to a shift in how services will be provided and delivered. For instance, the public procurement of energy for buildings might soon rely on the Smart Buildings, and Smart Energy. The provided services will not just be the product itself (e.g. the provision of electricity), but the whole equipment (e.g. smart sensors) and cloud – services packet for collecting, processing, analysing and optimizing processes (e.g. the illumination in buildings). Some services are already offered, e.g. regarding Smart Irrigation, Smart Infrastructure, etc. In the future GPP should respond to that, for instance by updating the existing criteria so that they can take into account the new requirements (e.g. need for energy-efficient could service) as a result of the transformation of how services will be delivered in the future.

Working paper gap analysis and Working paper feasibility and effectiveness of policy measures

This chapter refers to the results of the steps: Compilation and analysis of current policy approaches, Gap analysis, Collection of best practice examples and Assessment of the feasibility and effectiveness of current policy measures and its deliverables: Working paper gap analysis and Working paper feasibility and effectiveness of policy measures.

Based on the decision to include the criteria “feasibility “and” effectiveness” in the gap analysis, which was considered a reasonable approach for the purposes of the study, the two deliverables were merged.

The goal of the deliverables was to provide a basis for the design of the policy recommendations for energy-efficient cloud computing (Task 6), using the insights gained from available policy instruments for data centres and – in the broadest sense – related ICT.

The description starts with an overview of the main results from the screening exercise on ICT, which shows that there are no known policy instruments for energy-efficient cloud computing and only a few policy instruments for energy-efficiency data centres. Most of the literature focuses on the economic or eco-innovation effects for companies to be achieved by using policy instruments.

The next section consists of an introduction to policy instruments in general and their typology, and gives an overview of the benefits as well as the restrictions and/or adverse effects of different kinds of policy instruments. It also points out that in the study an additional category of policy instruments is important: research & development efforts (see D 4.1. Recommendations for further RTD).

That a single policy instrument alone is sufficient to reach a political goal is an exception. Therefore, diverse kinds of policy mixes are introduced. Nevertheless, although the literature on policy instruments is increasing, there are still major gaps in understanding the relationship between technology diffusion, as in the case of energy-efficiency and policy instruments (Stucki & Woerter, 2016), and the chapter ends with the conclusion that no blueprint for a single policy measure or a policy mix can be derived when it comes to policy instruments for energy-efficient cloud computing.

To provide an insight into “best practice” examples of typical policy instruments, the main results from literature research and qualitative interviews, with representative selected instruments, are presented. They range from “soft” instruments (guideline) to voluntary selfbinding (code of conduct) and labels (Energy Star and Blue Angel), as well as to examples of standards, and finally include also three “hard”, legally binding EU Directives or Regulations.

The interviews were used as a basis for the gap analysis. Additionally, the results of evaluations were included, if available, for the respective policy instrument, and related to energy-efficiency. For the gap analysis, methodical obstacles had to be considered due to the diversity of the “best practice” examples and, therefore, different political intentions - e.g. that their aims did not always include quantitative goals. As for feasibility, distinctions were made between the technical, political and administrative feasibility of the best practice examples during the interviews, while in the gap analysis a summary on the feasibility of these different layers was included.

Have all efforts of the analysed policy instruments contributed to energy effectiveness in a satisfactory way? The estimation of their effectiveness suffered in some cases from the fact that clear goals and evaluations of the impact of these instruments on energy effectiveness are missing. It is also possible that sometimes energy-efficiency is not induced by these policy instruments alone or that it might happen completely independently anyway, due to ongoing technology developments and market trends. Such a counterfactual scenario, however, does not come within the scope of the study.

Even if the transferability of the results for the policy instruments used in ICT or data centres to policy instruments suitable for cloud computing was restricted by some factors, the instruments analysed in detail for this report were used either as a basis or at least as an inspiration for the further development of six of the 21 policy recommendations (see Task 6).

Typology and characteristics of policy instruments

Methodological approach

The first step of the work done for the report consisted of a compilation and analysis of current policy approaches that could be a basis or an inspiration for the development of policy instruments for energy-efficient cloud computing. Up to now, there have been no policy instruments for energy-efficient cloud computing, but a few policy instruments for data centres are available. Additionally, it was assumed that also lessons from related information and communication technologies (ICT) – in the broadest sense of the meaning - could be derived.

Therefore, mainly scientific literature on the efficiency of policy instruments for ICT or policy instruments in general was screened. The key words used for the screening exercise were: policy instruments and/or cloud, ICT, energy-efficiency, data centres, effectiveness, labels, eco-innovation. Exhaustive screening was not possible within the scope the project but the available results give a first impression: the screening exercise showed that according to our knowledge, no scientific literature on policy instruments for cloud computing exists. Most of the literature focuses on economic or eco-innovation effects of policy instruments on companies. The effects of policy measures on energy-efficiency as a political environmental goal were mainly found in reports from the European Union.

Typology of policy instruments

Policy instruments range from "hard" instruments to "soft" instruments. In the scientific literature, there are different classifications for these instruments. According to Nispen (2011), it is nowadays common to make a distinction between three families of policy instruments, also referred to 'sticks, carrots and sermons'. The first family consists of regulatory instruments, such as orders and prohibitions (licences, permits, regulations). The second family embraces financial means, providing incentives. They may be positive (grants, subsidies) as well as negative (taxes, user charges) from a consumer's perspective. The third family includes communicative tools (Nispen, 2011).

Classification

The classification of policy instruments is nevertheless a rather fuzzy one, e.g. some authors categorise taxes as economic instruments, and others see them as regulations. Also, European Commission 2017 states that in practice it is often hard to define the exact nature of a given soft regulatory approach where many hybrid solutions are also possible. Some new instruments or instrument mixes like nudge approaches can also be included in policy instruments.

Policy instruments at the EU level can, according to (European Commission, 2017c), be divided into four broad categories - although there may be overlaps or combinations of different instruments (such as obligations to accept a mutual recognition of alternative rules and standards):

- "Hard" legally binding rules
- "Soft" regulation
- Education and information
- Economic instruments

The following table uses the classification of policy instruments as suggested by (European Commission, 2017c) with the exception that the instrument "label" has its own row. The typology from (European Commission, 2017c) was complemented by additional information derived from the literature review, focusing on the key words mentioned above. The table specifies the type of policy instrument, gives a short description of the main features, and describes the main benefits and restrictions or the adverse effects of the policy instrument.

Type of policy instrument	Description	Benefits	Restrictions/ adverse effects

“Hard” legally binding rules			
“Hard" legally binding rules	Legally binding rules are used to prescribe the specific behaviour required of organisations or individuals. It is appropriate to address activities with potentially serious risks for the economy, the environment or individuals and where legal certainty and enforcement backed by legal sanctions are necessary. It may also be the only available option if there is no scope for "softer" self-regulatory actions by business organisations or when such approaches have failed. Alternatively, legally binding acts may be adopted to establish essential requirements or frameworks which are supported by "soft" instruments such as technical standards. (European Commission, 2017c, p107)	When well designed, such "hard" rules provide clarity as to the behaviour which is expected, making it relatively straightforward to identify non-compliant behaviour (European Commission,2017c, p107)”. Veugelers (2012) states that regulations/taxes have a larger effect than subsidies for inter-firm diffusion of green technologies. Regulation can promote innovation: first, regulations signal to companies likely resource inefficiencies and potential technological improvements. Second, regulations focus on information gathering which can achieve major benefits by raising corporate awareness. Third, regulations reduce the uncertainty about whether investments addressing the environment will be valuable. Fourth, regulations create pressure that motivates innovation and progress. Fifth, regulations create a level transitional playing field. During the transition to innovation-based solutions, regulations ensure that a company cannot opportunistically gain an advantage by avoiding environmental investments. (Porter & Van der Linde, 1995).	Regulators need to have the capacity, resources and sector-specific knowledge to make legislation work effectively. In addition, the "one size fits all" approach of uniform standards may not be suitable to capture the variations in the compliance costs for different economic operators, which leads to inefficiencies and raises the overall costs of the policy. (European Commission 2017, p107). The stringency of a regulation is a crucial element (Porter & Van der Linde ,1995). Tends to be reactive, with a focus on the current state of the art (Winzer 2016).
"Soft" regulation			
Self-regulation	Self-regulation is where businesses or industry sectors formulate codes of conduct or operating constraints on their own initiative and they are responsible for enforcing them. However, pure self-regulation is uncommon and at the EU level it generally involves the Commission in instigating	Self-regulation by the relevant industry can, in suitable cases, deliver the policy objectives faster or in a more cost-effective manner compared to mandatory requirements. Self-regulation also allows greater flexibility in the adaptation to technological changes (e.g. in ICT-related areas of activity) and market sensitivities	Voluntary agreements work when the interests of society and industry groups coincide; otherwise, it is unlikely that industry will voluntarily take the necessary steps without any pressure from outside such as the Commission or other parts of civil society such as NGOs. The challenge with such approaches is to ensure that the desired policy outcome is

	or facilitating the drawing up of the voluntary agreement (European Commission, 2017c).	(European Commission, 2017c). The success of self- and co-regulation depends on several key factors: representativeness, transparency, legal compliance and effective implementation and monitoring. Examples can be found in experiences with voluntary agreements under the Ecodesign Directive. The Commission services have prepared a set of best practice principles which should be reflected in all self and co-regulation initiatives (see appendix "European Commission 2017", p. 120) (European Commission, 2017c). Can be used in cases that are hard to define via regulatory instruments (Winzer, 2016)	actually delivered as the conventional enforcement mechanisms that work with regulations do not apply here (European Commission, 2017c). One example of self-regulation is the voluntary agreement with the European, Japanese and Korean car manufacturers on the reduction of CO_2 emissions from cars (European Commission, 2017c). Missing sanctions for non-compliance or freeloaders (Winzer,2016).
Co-regulation	Co-regulation is a mechanism whereby the Union Legislator entrusts the attainment of specific policy objectives set out in legislation or other policy documents to parties which are recognised in the field (such as economic operators, social partners, nongovernmental organisations, standardisation bodies or associations). Recognition of such public-private arrangements may be achieved through cooperation agreements or in Union legislation. Under this "light" regulatory approach, the relevant policy initiatives establish the key deadlines and mechanisms for implementation, the methods of monitoring the application of the legislation and any sanctions if applicable.	Co-regulation can combine the advantages of the binding nature of legislation with a flexible self-regulatory approach to implementation that draws on the experience of the parties concerned and can foster innovation. Co-regulation can remove barriers to the single market, simplify rules and can be implemented flexibly and quickly (European Commission, 2017c)	The success of self- and co-regulation depends in essence on several key factors which include: representativeness, transparency, legal compliance and effective implementation and monitoring. Examples of this can be found in experiences with voluntary agreements under the Ecodesign Directive. The Commission services have prepared a set of best practice principles which should be reflected in all self- and co-regulation initiatives (see European Commission, 2017c, p. 120)
Technical standards	Standards are private and voluntary documents developed by recognised	Such standards can avoid regulation (like "harmonised standards") or permit	Once a standard is satisfied there are no incentives to develop or adopt cleaner

	standardisation bodies that set out specifications and other technical information with regard to various kinds of products, materials, services and processes. They provide a common understanding among businesses, other stakeholders and public authorities on the commonly recognised state of the art and they are frequently reviewed and revised. They are developed internationally by the international standardisation bodies and in Europe by the European standardisation organisations (ESO). (European Commission, 2017c). Regulation (EU) No 1025/2012155 sets the legal framework for the Union to use voluntary European standardisation as a recognised policy tool in support of Union legislation and policies for products and for services. It sets procedures for the Commission to request the ESOs to develop voluntary European standards or European standardisation deliverables which e.g. can be used to specify how to comply with generally worded legal requirements (European Commission, 2017c)	legislation which concentrates only on essential requirements, with the technical details being left to voluntary standards (European Commission, 2017c).	technologies (…) firms may fear that environmental innovations will lead policy makers to raise previous standards (Fabrizi et al., 2018).
Recommendation	A legal instrument that encourages those to whom it is addressed to act in a particular way without being binding on them. A recommendation enables the Commission (or the Council) to establish non-binding rules for the Member States or, in certain cases, Union citizens (European Commission, 2017c)	Can be used when there is not sufficient evidence that would justify a need of a binding legislative instrument, or in policy areas where the EU has supporting competence, complementing the action of Member States, and cannot by definition be prescriptive (European Commission, 2017c)	Given the non-binding character of a recommendation, which per se cannot guarantee that action will be taken by all Member States, detailed monitoring and evaluation arrangements should be foreseen and presented in the IA. (European Commission, 2017c)
Open Method of Co-ordination	Created as part of employment policy & the Luxembourg process; defined as an instrument of the Lisbon strategy (2000).		

	Provides a framework for cooperation between the Member States, whose national policies can thus be directed towards certain common objectives. Member States are evaluated by one another (peer pressure), with the Commission's role being limited to surveillance. (European Commission, 2017c)		
Education and Information			
Education and Information	EU objectives may be reached by ensuring that citizens, consumers and producers are better informed. This type of policy instrument includes information and publicity campaigns, training, guidelines, disclosure requirements, and/or the introduction of standardised testing or rating systems (European Commission, 2017c)	The instrument can be cost-effective and it is easily adaptable to changing situations. It is generally most useful in those areas where: – the lack or costs of collecting information is shown to be a key driver of the problem; – the limited effectiveness of an existing piece of legislation is due to lacking information/clarity on how to comply with it or enforce it (European Commission, 2017c).	Impact unsure (Winzer, 2016)
Economic instruments			
Market-based instruments (MBIs): taxes, charges, fees, fines, penalties, liability & compensation schemes, subsidies and incentives, deposit-refund systems, tradable permit schemes (European Commission, 2017)	Market-based instruments can be applied to different components – e.g. on the inputs, and hence change the production costs, or on the outputs and hence change the price. In some situations, a change in cost will result in a change of the price (if the cost changes can be passed on to the consumer) and in other cases there will be less pass-through. The change in behaviour may not be immediate after a price change as it depends on the elasticity of demand, which in the short term is in fact usually inelastic as there might not be adequate alternatives or substitutes or the ability to change consumption patterns (European	MBIs – due to their economically efficient way of addressing environmental issues – are most commonly used in environmental policy where they fit very well as a tool to cater for market failures/externalities (European Commission, 2017c). MBIs e.g. taxes, subsidies are - for intra-firm diffusion of green technologies – more effective than command-and-control instruments (e.g. regulations). Environmental taxes are most effective among the MBIs in promoting the adoption of green technologies (Stucki & Woerter, 2016).	For their incentive effect, MBIs rely on individuals and/or firms having the ability to respond to a price signal (EC 2017). Time consistency in policy making is more important for energy tax regimes than for regulations (Stucki & Woerter, 2016).

	Commission, 2017c, p. 117).		
Labelling schemes 1) standardised labels including those required by law vs. voluntary labels 2) differentiated vs. specific vs. multidimensional, and 3) labels for (a) products, (b) producers, and (c) branches.(Kern et al., 2015)	Can consist of: 1) Quality classes like the EU Ecolabel with a comparative scale from A (most energy-efficient) to G (least efficient), including additional data or similar to Green Power Indicator 4: one general quality criteria has to be fulfilled by all of the sustainable software products. Higher ranking if more criteria than the basic ones met. Three different quality classes for Eco providers (Greensoft, 2019). 2) Yes/no label focusing on products with strong sustainability e.g. Blauer Engel, or low threshold minimum criteria for e.g. energy-efficiency like Energy Star. According to (Prieto-Sandoval, Alfaro, Mejia-Villa, and Ormazabal, 2016), ecolabels can be divided into three different categories, each clearly defined by an ISO standard. Type I ecolabels are, according to ISO 14024, voluntary, third party verified, multi-criteria ecolabels that are based on life cycle considerations (ISO, 2018). Type II labels, so-called environmental claims, are ecolabels that are, according to ISO 14021, self-declarations made by manufacturers, importers or distributors regarding the environmental attributes of products (ISO, 2016). Environmental claims are usually not third-party verified. Type III, known as environmental declarations, use, according to ISO 14025, third-party-verified life cycle assessments based on pre-set indices to provide quantified environmental product information (ISO,	Must be well-known, e.g. Ecolabel is a standard in all EU28 members and the best known label of all.	Minimum standards for labels remove only the worst ineffective products, they have a low impact on innovation and on helping the environment. Not all firms participate or are interested in reaching the ecological optimum. Standards for obtaining a label must be updated regularly, the impact of labels is not very high, competition between labels (Winzer,2016). The eco-labelling innovation cycle starts when consumers express their environmental expectations (Prieto-Sandoval et al., 2016) – if no consumer need exists, the motivation is missing. Different types of labels compete sometimes (Li & van't Veld, 2015). Producers should be informed on forthcoming revisions of criteria and further developments. Otherwise, there is a risk of lost opportunities in strategic sustainable development (Bratt et al., 2011).

	2006). In addition to these three types of ecolabels, there exists a fourth type of ecolabel which is often referred to as a 'type I-like' ecolabel or, as it is more commonly known, an 'energy label'. Although type I-like ecolabels undergo the same third-party verification process as type I ecolabels, they differ in the sense that they focus on single issues such as energy consumption (Baumeister & Onkila, 2018)		

Table 1 - Overview of policy instruments (based on European Commission, 2017c complemented with literature cited in the table)

Research and development as an additional policy instrument

While the above table is seen as useful for supporting the design of policy instruments, one group of instruments seems to be understated: research and development instruments.

Rogge & Reichardt developed a matrix typology that combines three instrument types (economic instruments, regulation and information) with three instrument purposes (technology push, demand pull and systemic concerns).

	PRIMARY PURPOSE		
PRIMARY TYPE	Technology push	Demand pull	Systemic
Economic instruments	RD&D* grants and loans, tax incentives, state equity assistance	Subsidies, feed-in tariffs, trading systems, taxes, levies, deposit-refund-systems, public procurement, export credit guarantees	Tax and subsidy reforms, infrastructure provision, cooperative RD&D grants
Regulation	Patent law, intellectual property rights	Technology/performance standards, prohibition of products/practices, application constraints	Market design, grid access guarantee, priority feed-in, environmental liability law
Information	Professional training and qualification, entrepreneurship training, scientific workshops	Training on new technologies, rating and labelling programs, public information campaigns	Education system, thematic meetings, public debates, cooperative RD&D* programs, clusters

Table 2 - Type-purpose instrument typology with instrument examples (Rogge & Reichardt based on literature, 2016)

This table is presented here because it is an example of the rather few typologies of policy instruments that also include a strong focus on cooperative research, development and demonstration, and on professional training and qualification.

Our study "Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market" – SMART 2018/0028 provides a comprehensive set of recommendations for further RTD which were validated at a stakeholder workshop. These recommendations are not only a stand-alone policy instrument package for research and development as an important support activity for energy-efficient cloud computing. They can also build a basis for some of the policy recommendations developed in Task 6, e.g. by developing a metric for recommendation No 3 "Cloud food print or virtual smart meter".

Combinations of instruments – policy mixes

Introduction

Policy mixes are characterised by the policy domains they cover (as mixes may not be confined to one domain), the underlying policy agendas and rationales, the targets (users, stakeholders, processes) and the instruments employed. The “policy mix” concept acknowledges that policy actions inevitably interact in a stream of existing events and activities, including other policy interventions. Policy interventions (or instruments) may interact with the portfolio of already existing interventions for a given target group, technology, sector or societal issue (Cunningham et al., 2013).

Regarding the instruments in this mix it may be useful to distinguish between core (or cornerstone) instruments and complementary (or supplementary) instruments of an instrument mix and to also take into consideration interactions between the instruments, because the influence of one policy instrument is modified by the co-existence of other instruments (Nauwelaers et al., 2009 in Rogge & Reichardt 2016).

Nearly every policy instrument is accompanied by another policy instrument: information. Information alone is unlikely to be wholly effective on its own but is nonetheless important as a complement to other instruments (European Commission 2017c). The rather weak outcome of information activities alone might be illustrated by Anderson and Newell (2004 in: Stucki & Woerter, 2016), using US data on energy audits. They found that firms only adopted 53% of recommended projects, although their payback time was on average just 1.29 years. Consequently, specific policy measures are necessary to trigger adoption in addition to information activities.

Monitoring is also likely to be needed to ensure the success and credibility of e.g. voluntary initiatives undertaken by industry. Economic instruments in the form of tax reductions coupled to binding rules can incentivise more effectively the desired behaviour such as an investment in low-carbon technologies (European Commission, 2017c, p118).

Policy mixes and innovation

Literature was screened to gain insights into how policy instruments should be designed to foster innovation for energy-efficiency. Especially the interaction between strict regulations, flexible regulatory policies and voluntary agreements and the impact on business and innovation is a topic discussed in scientific papers. Ambec et al., (2017) state that the traditional view among economists and managers on environmental protection is that it comes at an additional cost imposed on firms, which may erode their global competitiveness. Environmental regulations such as technological standards, environmental taxes, or tradable emissions permits force firms to allocate some inputs (labour, capital) to pollution reduction, which is unproductive from a business perspective. Technological standards restrict the choice of technologies or inputs in the production process. Taxes and tradable permits charge firms for causing emissions of air pollutants, a by-product of the production process that was free before. These fees necessarily divert capital away from productive investments. This traditional paradigm was challenged by a number of analysts, notably Professor Michael Porter (Porter,1991) and his co-author Claas van der Linde (Porter and van der Linde,1995). Based on case studies, the authors suggest that pollution is often a waste of resources and that a reduction in pollution may lead to an improvement in the productive use of resources. More stringent but properly designed environmental regulations (in particular market-based instrument such as taxes or cap-and-trade emissions allowances) can “trigger innovation [broadly defined] that may partially or more than fully offset the costs of complying with them” in some instances (Porter and van der Linde 1995 in Ambec et al., 2017).

On the empirical side, the Porter hypothesis, in its weak version, states that “properly designed environmental regulation may spur innovation” (Ambec et al., 2017) and is fairly well established. On the other hand, the empirical evidence of the stronger version (stricter regulation enhances business performance) is mixed, with more recent studies providing more supportive results. According to the narrower version, “flexible regulatory policies give firms greater incentives to innovate and thus are better than prescriptive forms of regulation” (Ambec et al., 2013, p. 6). This suggests that market instruments (e.g. pollution taxes, deposit-fund schemes, tradable permits) are preferable to non-market instruments (standards).

Finally, the strong version of the hypothesis affirms that “in many cases this innovation more than offsets any additional regulatory costs - in other words, environmental regulation can lead to an increase in firm competitiveness” (Ambec et al., 2013, p.6). Empirical studies, both at the firm and at the country level, have mainly found support for the weak and narrow versions of the Porter hypothesis while the evidence for the strong version is more controversial (see Ambec et al., 2013, Rubashkina et al., 2015 and Morales Lage et al., 2016, in: Fabrizi et al 2018).

Costantini et al., (2017) performed an empirical analysis of the influence of the characteristics of the policy mix on innovation performance in energy-efficiency technologies for the residential sector in 23 OECD countries for the period 1990–2010. The evidence presented showed that innovation performance in energy-efficiency technologies is driven by both demand-pull and technology-push policy instruments.(…) The results suggest that better coordination of policy mix designs between countries can represent a source of mutual advantages in terms of policy effectiveness and increased innovation performance (Constantini et al., 2017).

Wang et al., 2019 analysed OECD industrial sectors to validate the Porter hypothesis: that environmental policy has a positive impact on green productivity growth within a certain level of stringency. The impact becomes adverse when environmental regulation policy is stringent above a certain level, as the compliance cost effect is higher than the innovation offset effect (Wang et al., 2019).

In a study on the diffusion of green energy technologies in Switzerland, Stucki & Woerter (2016) found that voluntary agreements (non-political motives) are the most effective motive for inducing intra-firm adoption of more green energy technologies, followed by energy taxes and regulation. However, assuming the companies' rational behaviour, such voluntary measures are adopted for two reasons. First, firms want to avoid future governmental interventions which might distort competition. Consequently, they prefer to send a signal that industry can take proper steps to decrease the negative environmental impact. Hence, even non-political motives may indirectly be driven by the political framework in Switzerland. Second, they can select measures, e.g. labels that are simple and inexpensive and beneficial for committed firms since they increase the readiness to pay for such products and services given the receptiveness to environmental issues among the population. Moreover, the relatively large effect of voluntary measures may also be driven by a certain predisposition of the respondents to understand one's own activities as voluntary rather than imposed by the government (Stucki & Woerter, 2016).

Another outcome of the study (Stucki & Woerter, 2016) was that voluntary agreements require the availability of green energy technologies and that the availability of such technologies is more likely if adequate policies are in place. Moreover, it was found that time-consistency concerning governmental tax regimes is important since it very likely increases the confidence of firms that markets for green products or services will evolve due to a rising awareness of customers or due to internalised production externalities. Markets are usually characterised by many different operating policies and their complementarity might bring additional impulses for the adoption of such policies. In sum, the study points out that a consistent policy approach to energy taxes as well as non-political arrangements is very important for boosting the adoption of green technologies, which in turn would reduce the environmental burden of industrial production (Stucki & Woerter, 2016).

Bergek et al., (2014) reviewed cases from the energy and automotive sector and concluded that different types of instruments promote different types of innovations: general economic instruments tend to encourage diffusion and incremental innovation; general regulatory instruments enforce significant improvements based on modular innovation; and technology-specific instruments appear to be required for the development and deployment of radically new technologies, although the fostering of upgrades and cost reductions are necessary for all policies. Their final conclusion: in the real world there is no one best way, no one best instrument.

Fabrizi et al., (2018) analysed the single and joint impact of regulation policies and research network policies on environmental innovation. He says that flexible and market-friendly policies can spur innovative processes more effectively, whereas command and control policies do not drive innovation; rather, they tend to have a disincentive effect. Market-based regulation policies as well as participation in green European research networks (in particular with universities and public research centres) positively affect environmental innovation. Moreover, both policy tools have a complementary effect. This suggests that the effectiveness of environmental regulation policies can be increased by combining them with appropriate innovation policies (Fabrizi et al., 2018).

Although the literature is increasing, there are still major gaps in the understanding of the relationship between green technology diffusion and the choice of policy instruments. Different (policy) measures cause different reactions from firms, which as a result might adopt several and different types of green energy technologies in order to adapt to a new policy environment. Empirical studies so far have considered this fact insufficiently (Stucki & Woerter, 2016).

Summary

It can be derived from literature that:

- Too restrictive regulations might hinder eco-innovation – too stringent policies might have an adverse impact on company performance (e.g. due to high compliance costs).
- More flexible legislation combined with a consistent policy approach that comes with a certain stringency (e.g. in terms of energy taxes) has a positive impact on green innovation.
- Voluntary agreements require the availability of green energy technologies and the availability of such technologies is more likely if adequate policies are in place.
- Also, participation in green European research networks has a positive effect on environmental innovation and should be combined with flexible and market-friendly policies.
- Avoid potential negative interactions between policy instruments.

Analysis of best practice examples

Methodological approach

To gain deeper insights into existing instruments and to see what lessons could be derived from them for the development of policy recommendations, some “best practice” examples of typical policy instruments for energy-efficiency in data centres or ICT were selected for further analysis. The level of these instruments reaches from the national (e.g. the German Blue Angel for Data Centres), to the European level (e.g. the Energy Directive) to the global level (ITU-T recommendations). To analyse at least one global policy instrument in more detail, the ITU-T recommendations were selected instead of the European standard 50600 series “Information technology-data centre facilities and infrastructures” CENELEC-CLC/TR, 2019) . Even if not in the focus of this study, this series of standards is relevant for energy efficiency in data centre facilities and infrastructures. E.g. 50600-99-1 includes a compilation of recommended practices for improving the energy management (i.e. reduction of energy consumption and/or increases in energy efficiency) of data centres. It is historically aligned with the EU Code of Conduct on Data Centre Energy efficiency scheme (CENELEC-CLC/TR, 2019).

In the final phase of the study and after Task 3 was completed, another relevant ITU-T standard was released: GHG emissions trajectories for the ICT sector, compatible with the UNFCCC Paris Agreement (L1470). This recommendation provides detailed trajectories of GHG emissions for the global ICT sector and sub-sectors which are quantified for the year 2015 and estimated for 2020, 2025 and 2030. In addition, it defines a long-term ambition for 2050.

The following description of the so-called “best practice” examples is based on literature research and interviews with persons involved in the design and/or implementation of these examples. The literature research included the policy documents themselves (e.g. directives, standards, guidelines), but also evaluations and assessments if available. The literature research was complemented by semi-structured interviews following an interview guideline with one person involved in the design or implementation of the respective selected instrument. The interviews themselves were recorded (with one exception, where the interviewee did not agree to the recording) and transcribed. Following the requests of most of the interviewees, these transcriptions were used for internal work purposes only and not published, and the interviewees themselves remained anonymous.

The first step was to structure the results of the literature review and the interviews as follows:

- Name of instrument
- Reference to cloud computing
- Short summary
- Developed by national government; multi-national government, national industry association; international industry association, others (specify)
- Level: international, national (if yes, country)
- Type of instrument: legal and regulatory, standards and norms, strategy & planning, economy/market-oriented, self-regulation, capacity building/training/awareness raising and information
- Compliance (mandatory, voluntary)
- Verification (self-assessment, third-party verification)
- Link/literature
- Results/evaluations (if available)
- Clear objectives defined (if yes, which)
- Cost-benefits of measure described
- Effectiveness concerning energy-efficiency
- Technical feasibility

- Political feasibility
- Administrative feasibility
- Acceptance and support of stakeholders
- (Public) acceptance
- PR benefits
- Possible negative side-effects
- Possible positive side-effects (win-win) e.g. for innovation
- Impact
- Experiences (outside of evaluations)
- Literature

This served as a basis for the descriptions of the policy instruments listed below:

- Ecodesign Directive 2009/125/EC and Commission Regulation EU 2019/424 laying down Ecodesign requirements for servers and data storage products pursuant to Directive 2009/125/EC (European Commission, 2009, 2019f). Due to the fact that the Ecodesign requirements for servers and data storage were very new (March 2019) and no experiences with implementation available, the Directive and the Regulation were analysed and described together.
- The European Directive on Energy-efficiency 2012/27/EU (European Commission, 2012a), amended by EU Directive 2018/2002.
- ENERGY STAR
- Ecolabel Energy-efficient Data Centre Operation (DE-UZ 161) - Blauer Engel
- EU Code of Conduct on Data Centre Energy efficiency and Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy efficiency
- Guidelines – Energy-efficiency in Data Centres
- Recommendations of the Study Groups of ITU's Telecommunication Standardisation Sector (ITU-T). From these recommendations three were selected as examples
- L.1321: Reference operational model and interface for improving the energy-efficiency of ICT network hosts
- L.1325: Green ICT solutions for telecom network facilities
- L.1501: Best practices on how countries can utilise ICTs to adapt to the effects of climate change.

Types of selected policy instruments

The selected examples represent five different types of policy instruments: three examples of regulatory and statutory instruments (e.g. regulations, directives and decisions of the EU), one example of standards and norms, two examples of labels, one example of a voluntary self-binding agreement and one example of information/guidance.

Type of policy instrument	Name
Regulation/legislation	Ecodesign Directive 2009/125/EC and Regulation EU 2019/424 laying down Ecodesign requirements for servers and data storage products pursuant to Directive 2009/125/EC
Regulation/legislation	EU Directive 2012/27/EU on Energy-efficiency of 25 October 2012 and EU Directive 2018/2002 of 11 December 2018 amending Directive 2012/27/EU and the amending Directive (EU) 2018/2002
Standard/norm	ITU-T recommandations (L.1321; L1324; L.1501)
Label	Blue Angel for data centres
Label	EU Energy Star
Voluntary self-binding agreement	EU Code of Conduct on Data Centre Energy efficiency
Information/guidance	Guideline for data centres (Bitkom)

Table 3 - Type of policy instruments selected as best practices

The instruments chosen as examples represent the type of instruments that might be used as a starting point for the development of policy instruments in cloud computing

One of the instruments is not active in Europe anymore: The EU Energy Star programme followed an agreement between the European Community (EU) and the Government of the US to coordinate energy labelling of office equipment. The EU-US agreement expired on 20 February 2018 (Energy Star, 2019b).

The guideline for data centres, which has not been updated since its inception, is seen as rather outdated by its owner Bitkom.

Nevertheless, these two instruments were included in the list of relevant policy documents a) because no other similar instruments exist, b) for their archetypal character of a policy instrument and c) because of the fact that some lessons could be derived that might be useful for the development of policy recommendations (Task 6).

Description of the policy instruments selected as "best practice" examples

As an overview, a short description (1-2 pages) of the policy instrument is presented, focusing on the most important information that is needed. Due the differences between those policy instruments, information may sometimes be missing because it does not apply to the policy in question; in that case "not applicable" is used in the respective box. The structure of the tables was inspired by another SMART- project (Prakash et al., 2014) but adapted to the research questions of the current project.

Name of Instruments	**Commission Regulation (EU) 2019/424 of 15 March 2019 laying down Ecodesign requirements for servers and data storage products pursuant to Directive 2009/125/EC and Eco-design Directive (Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009)**
Developed by	Multi-national government
Short summary	The Ecodesign Directive (European Commission, 2009) provides consistent EU-wide rules for improving the environmental performance of products, such as household appliances, information and communication technologies or engineering. The Directive sets out minimum mandatory requirements for the energy-efficiency of these products. This helps prevent creation of barriers to trade, improve product quality and environmental protection. The Ecodesign Directive is implemented through product-specific regulations, directly applicable in all EU countries. Ecodesign and energy labelling regulations are complemented by harmonised European standards. These technical specifications indicate that a product complies with the mandatory requirements. Only then can the manufacturer affix the CE marking and sell it in the EU. National market surveillance authorities verify whether products sold in the EU follow the requirements laid out in Ecodesign and energy labelling regulations (European Commission, 2019f). The Commission Regulation (2019) for servers and data storage products states that Ecodesign requirements have to be set for energy-related products that present significant volumes of sales and trade, have a significant environmental impact and present significant potential for improvement in terms of their environmental impact without entailing excessive costs. Environmental aspects of servers and data storage products that have been identified as significant for the purposes of Regulation (EU) 2019/424 are energy consumption in the use phase and resource efficiency (European Commission, 2019f).
Level	EU
Type of instrument	legal [2]
Compliance	☒ Mandatory ☐ Voluntary
Verification	☐ Self-Assessment ☒ Third Party Verification
Available evaluation	Ecodesign Impact Accounting (European Commission, 2018a): includes also effects of the Ecodesign Directive as well as Energy Labelling; evaluation of energy labelling and specific aspects of the Ecodesign Directive (ECOFYS, 2014): evaluation of the Ecodesign Directive (CSES, 2012).
Clear objectives defined (if Yes, which)	The effect of the Ecodesign requirements for servers and data storage products is estimated to result, by 2030, in annual energy savings of approximately 9 TWh - approximately the yearly electricity consumption of Estonia in 2014 (European Commission, 2019f).
Cost-benefits	In general, the benefits outweigh the costs (Ecofys, 2014); the costs for industry for implementation are expected to be passed on to consumers (CSES, 2012); the costs for the EC and Member States are a very small fraction of the expected energy savings (CSES, 2012); the benefit-cost ratio is in most cases greater than 4, with only circulators and power supply units having a less favourable ratio (CSES, 2012); the cost-benefit ratio is estimated at 3.8 compared with 3 for average environmental policies (Ecofys, 2014).
Effectiveness concerning energy-efficiency	Indicators of significant improvements e.g. for standby power consumption. (CSES, 2012); it is possible that energy-efficiency improvement is in part due to other factors such as ongoing market trends in EE improvement independently of the policy. No ex-post counterfactual data is available to assess this. It is likely that a significant part of the EE improvement is due to the Directives (Ecofys, 2014).

Technical feasibility (for companies)	Rather high (Directive focuses on the prevention of worst performing products), still untapped potential for regulating further product groups.
Political feasibility	High on European Commission level, differences on Member State level; a few Member States reported no market surveillance activity up to 2013 (Ecofys, 2014).
Administrative feasibility (for companies)	Varying, sometimes extensive testing required by some authorities in Member States (CSES, 2012); sometimes unclear formulations in legal texts.
Acceptance and support of stakeholders	The main purpose of removing the worst performing products from the market is appropriate and this is a view shared by the great majority of stakeholders (CSES, 2012). Problems arise when it is not possible to refer to a certain standard (CSES, 2012), standard development processes are quite slow (CSES, 2012); market surveillance systems differ in Member States - non-compliant goods on the market (CSES, 2012). Uncertainty concerning the legal status of Voluntary Agreements (CSES, 2012).
Public acceptance	Some criticism in the media of labelling and/or energy-efficiency measures for certain products (Ecofys, 2014).
PR benefits	Yes, if companies are able to produce high energy-efficient products; the labels are well known in the general public, the term "Eco-design Directive" however is not (interview).
Impact	Available data does not reflect the impact of the Ecodesign Directive alone (CSES, 2012), although it plays a key role (CSES, 2012), supports the harmonised operation of the market and avoids fragmentation, increases energy-efficiency and reduces greenhouse gas emissions, increases security of energy supply and reduces dependence, increases the level of environmental protection, increases competitiveness of industry (CSES, 2012); objectives have been achieved, untapped potential for energy savings (ECOFYS, 2014); 10-25% of the products on the market are not compliant with Ecodesign and energy labelling; 10% of envisaged energy savings are lost due to non-compliance; some countries outside of the European Union apply European Commission Ecodesign regulations for some products.

Table 4 - Commission Regulation (EU) 2019/424 of 15 March 2019 laying down Ecodesign requirements for servers and data storage products pursuant to Directive 2009/125/EC and Eco-design Directive (Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009)

Name of Instruments	**European Directive on Energy-efficiency (Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy-efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC and Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy-efficiency)**
Developed by	Multi-national government
Short summary	The directive (European Commission, 2012a) includes provisions on the setting of energy-efficiency targets, general energy-efficiency policies and measures for specific energy consumption sectors as well as requirements for energy audits and management systems. Member States have to define national energy-efficiency targets based on different indicators such as energy consumption or energy savings. The EED includes the following measures: Energy or CO2 taxes should be used to reduce consumption;

	Suitable financing schemes and fiscal incentives for energy-efficient technologies should be applied; Existing regulations or voluntary agreements for a reduced energy consumption of technologies should be applied; Available standards and norms which focus on an improved energy-efficiency of products and services have to be integrated; Voluntary energy labelling schemes have to be taken into consideration; Training and education programmes for the application of energy efficient technologies or techniques; Energy audits and management plans are required for large companies, with cost-benefit analyses for the deployment of combined heat and power generation (CHP) and public procurement; Member States have to carry out a comprehensive assessment of the potential for the application of high-efficiency cogeneration and efficient district heating and cooling.
Level	EU
Type of Instrument	Regulatory
Compliance	☒Mandatory ☐Voluntary
Verification	☐Self-Assessment ☒Third Party Verification
Available evaluation	Qualitative measurement, studies concerning energy-efficiency.
Clear objectives defined (if Yes, which)	To achieve the Union's energy-efficiency targets of 20 % by 2020 and of at least 32.5 % by 2030 and to pave the way towards further energy-efficiency improvements beyond those dates (European Commission, 2018c). This means that overall EU energy consumption should be no more than 1483 million tonnes of oil equivalent (Mtoe) of primary energy or 1086 Mtoe of final energy (European Commission, 2019c).
Cost-benefits	No data on cost-benefit available (interview); initial costs of energy-efficiency often high but amortisation assumed to be possible in most cases (interview); an economic analysis (inventory of effects) carried out by the Member States is required by Annex VIIa (5) of Directive 2018 (European Commission, 2018c), but not yet available.
Effectiveness concerning energy-efficiency	The Directive allows for a possible upward revision of the target for 2023, in case of substantial cost reductions due to economic or technological developments.
Technical feasibility (for companies)	Rather high, the Directive has mainly been implemented by the Member States in companies. The requirements laid down in this Directive are minimum requirements and shall not prevent any Member State from maintaining or introducing more stringent measures. Such measures shall be compatible with Union law. Where national legislation provides for more stringent measures, the Member State shall notify such legislation to the Commission (European Commission, 2012a).
Political feasibility	Very high effort to find out who introduces which energy-efficiency measures where – a high amount of effort in knowledge transfer (interview). Political feasibility is therefore rather low to medium in the Member States, where considerable effort is needed to collect data on energy consumption as well as energy-efficiency and cost-efficiency (interview).
Administrative feasibility (for companies)	Medium (depends on the kind of company), energy audits and energy reporting required for large companies.
Acceptance and support of stakeholders	Good plans in Member States but less satisfactory implementation for political reasons (interview).

Public acceptance	Not applicable
PR benefits	Not applicable
Impact	In 2005-2016, consumption at EU level fell by −11 % in primary and −7 % in final energy. In terms of primary energy, final energy demand was the most decisive explanatory factor behind the decrease in primary energy consumption, while the hike of just over +2% over the period 2014-2016 was exclusively attributed to the increase in final energy demand during this latest 2-year period (European Commission, 2019d). If the increasing trend in energy consumption since 2014 continues in the coming years, the achievement of the 2020 target both for primary and final energy consumption could be at risk (European Commission, 2019b). Task force meeting to see if energy-efficient measures are possible in the short term (interview).

Table 5 – EU Energy-efficiency Directive, Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy-efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC and Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy-efficiency

Name of Instrument	**ITU-T L.1321 - Reference operational model and interface for improving energy-efficiency of ICT network hosts; Working Group of the Telecommunication Standardisation Sector (ITU-T)**
Developed by	International industry association
Short summary	Recommendation ITU-T L.1321 (ITU-T, 2015) was prepared by the ITU-T study group 5, describing a reference operational model and interface for improving the energy-efficiency of ICT network hosts. The International Telecommunication Union (ITU) is the United Nations' specialised agency in the field of telecommunications, information and communication technologies (ICTs).The recommendation specifies a reference model for improving the energy-efficiency of wired network hosts so that network hosts can reduce energy consumption by entering an energy saving sleep state. It describes the specification for improving energy-efficiency by defining a reference operational model of a network proxy to handle mandatory protocols for network hosts in the sleep state (ITU-T, 2015).
Level	International (UN)
Type of instrument	Technical standards - normative recommendations (ITU-T 2019)
Compliance	☐ Mandatory ☒Voluntary
Verification	Not applicable
Available evaluation	ITU-T has no information on how often or how much the standards are used. Download data is available but no information on implementation (interview).
Clear objectives defined (if Yes, which)	Not applicable, provides a reference model but no quantitative goals.
Cost-benefits	Not applicable
Effectiveness concerning energy-efficiency	Not applicable
Technical feasibility (for companies)	High (interview)
Political feasibility	High due to bottom-up process of ITU-T (interview).

Administrative feasibility (for companies)	No information available
Acceptance and support of stakeholders	High (bottom-up process of ITU-T)
Public acceptance	Not applicable
PR benefits	Not applicable
Impact	The level of compliance is nonetheless high due to international applicability and the high quality guaranteed by ITU-T's secretariat and by members from the world's foremost information and communication technology (ICT) companies and global (ITU-T, 2019).

Table 6 – ITU-T L.1321 - Reference operational model and interface for improving energy-efficiency of ICT network hosts; Working Group of the Telecommunication Standardisation Sector (ITU-T)

Name of Instrument	**ITU-T L.1325 - Green ICT solutions for telecom network facilities; Working Group of the Telecommunication Standardization Sector (ITU-T**)
Developed by	International industry association
Short summary	Recommendation ITU-T L.1325 (ITU-T, 2016) has been developed to introduce highly efficient infrastructure solutions, including highly efficient power solutions, renewable energy solutions, air conditioning energy-saving solutions and free and economical cooling solutions. Not every solution mentioned in this recommendation is fit for everywhere. When operators choose a solution, it should be selected according to local circumstances. With the development of information and communication technologies, and especially high power-density equipment, the energy consumption of the communication industry is increasing. Therefore, we must pay attention to energy conservation, and the protection of our environment (ITU-T, 2016).
Level	International (UN)
Type of instrument	Technical standards - normative recommendations (ITU-T 2019)
Compliance	☐Mandatory ☒ Voluntary
Verification	☐Self-assessment ☐Third Party Verification
Available evaluation	No formal evaluation available; ITU-T has no information on how often or how much the standards are used (interview).
Clear objectives defined (if Yes, which)	No defined objectives for energy-efficiency
Cost-benefits of measure described	Not applicable
Effectiveness concerning energy-efficiency	Not applicable
Technical feasibility (for companies)	No information available
Political feasibility	High due to bottom-up process of ITU-T (interview)

Administrative feasibility (for companies)	No information available
Acceptance and support of stakeholders	High due to bottom-up process of ITU-T (interview)
Public acceptance	Not applicable
PR benefits	Not applicable
Impact	No data available. Generally, the level of compliance is nonetheless high due to international applicability and the high quality guaranteed by ITU-T's secretariat, and by members from the world's foremost information and communication technology (ICT) companies (ITU-T,2019).

Table 7 – ITU-T L.1325 - Green ICT solutions for telecom network facilities; Working Group of the Telecommunication Standardization Sector (ITU-T)

Name of Instrument	**ITU-T L. 1501 - Working Group of the Telecommunication Standardisation Sector (ITU-T)**
Developed by	International industry association
Short summary	Recommendation ITU-T L.1501 (ITU-T, 2014) provides guidance on how information and communication technologies (ICTs) can help countries to adapt to the effect of climate change. It also provides a framework and a checklist for countries to integrate ICTs in their national climate change adaptation strategies. The recommendation is part of the ITU-T L.1500 series Recommendations on adaptation to the effects of climate change. It is designed to assist countries in integrating ICTs into their national climate change adaptation strategies. It is designed as a guide for regulators and policymakers with the aim to minimise the impact of climate change and to provide a 'multi-level framework for ICT integration in climate change adaption' to assist countries in integrating ICTs into their national climate change adaptation strategies (ITU-T, 2014).
Level	International (UN)
Type of instrument	Standards (normative recommendations) but rather in the way of capacity building and mainstreaming, not as technical standards.
Compliance	☐ Mandatory ☒Voluntary
Verification	Not applicable
Available evaluation	ITU-T has no information on how often or how much the standards are used.
Clear objectives defined (if Yes, which)	The qualitative goal is the integration of ICT into national adaptation strategies.
Cost-benefits	Not applicable
Effectiveness concerning energy-efficiency	Energy-efficiency is only a minor topic.
Technical feasibility (for companies)	Not applicable
Political feasibility	Rather high (interview)
Administrative feasibility (for companies)	Not applicable

Acceptance and support of stakeholders	Not applicable
Public acceptance	no information
PR benefits	no information
Impact	no information

Table 8 – ITU-T L. 1501 - Working Group of the Telecommunication Standardisation Sector (ITU-T)

Name of Instrument	**Blue Angel Energy-efficient Data Centre Operation**
Developed by	National Government
Short summary	The German Ministry of Environment and the German Federal Environment Agency implemented an ecolabel for energy-efficient data centres. To receive the label, the data centre owner/operator has to comply with defined requirements. Candidates have to provide a basic analysis of their data centre according to specified guidelines. This includes among others the size of the data centre, energy consumption, basic data on installed IT equipment, data management and data protection. The Blue Angel requires the implementation of an energy management system including monitoring, documentation of new items, and an updated IT inventory. Furthermore, applicants have to measure energy-efficiency over a period of 12 months. Applicants also have to fulfil requirements regarding procurement and management of IT and infrastructure. Life cycle cost calculations have to be considered for all purchased equipment (Blauer Engel, 2019).
Level	Germany
Type of instrument	Self-regulation (label)
Compliance	☐Mandatory ☒Voluntary
Verification	☐ Self-Assessment ☒ Third Party Verification
Available evaluation	No evaluation available
Clear objectives defined (if Yes, which)	The aim is to exploit existing efficiency potentials in the data centre in order to make optimum use of existing hardware resources. In addition, ambitious environmental criteria should be adhered to when making new investments. A further goal is to create more transparency for operators regarding the hardware resources they use, so that they can react efficiently to changes in framework conditions at an early stage (Blauer Engel, 2019).
Cost-benefits	Investments in measurement equipment should be compensated for after 1.5-2 years (interview).
Effectiveness concerning energy-efficiency	In addition to the PUE, other criteria are used to better determine energy-efficiency in data centres (interview). Would be more effective if there were more participants.
Technical feasibility (for companies)	Feasibility rather low: measurement & documentation equipment need to be installed; the instrument focuses on the top third of the data centres (interview).
Political feasibility	Due to the fact that the Blue Angel already existed in Germany, political feasibility was rather high (interview).

Administrative feasibility (for companies)	Feasibility rather low: measurement equipment needs to be installed, effort rather high (interview).
Acceptance and support of stakeholders	Stakeholders are included in the consultation mechanism for the Blue Angel, initial scepticism as one was under the impression that data centres were very energy-efficient (according to the PUE measurements only), but after test runs for a research project it was shown that the measurements did not reflect the same perceived levels of efficiency. Criteria are seen as appropriate but the label itself requires effort as it requires measurement and documentation. Reluctance to see that in former years the data centre was not as efficient as one had wanted to believe (interview).
Public acceptance	Currently 4 data centres, but there are more that were certified only once without recertification; approx. 15 in the last years (interview).
PR benefits	Rather an instrument for data centres within public administration. Otherwise, the Blue Angel is a good instrument for presenting new topics to the public. If a company does not present its data centre on the market it makes no sense to use the Blue Angel as a PR instrument; therefore, a Blue Angel for colocation data centres (typical service providers on a competitive market) is currently being developed. In the general public, the problem of the high energy demand of everyday applications is not known (interview).
Impact	1) Work on the Blue Angel for colocation data centres; 2) Blue Angel criteria in the GPP guidelines of federal administrations, the States ("Länder") will adopt them soon; 3) 2015 Research project KPI4DCE", Key Performance Indicators for Data Centre Efficiency and 2017 project "Green Cloud Computing" initiated as well as another project concerning a Blue Angel label for resource and energy-efficient software; 4) Impact on DIN EN 50600 (interview).

Table 9 - Blue Angel Energy-efficient Data Centre Operation

Name of Instrument	**Energy Star**
Developed by	Multi-national and national government (EU-US agreement expired Feb. 2018, in US still active).
Short summary	In 1992, the US Environmental Protection Agency (EPA) introduced Energy Star as a voluntary labelling programme designed to identify and promote energy-efficient products to reduce the energy consumption of products when in use (thus greenhouse gas emissions as well). In 2001, the EU Commission and the US Environmental Protection Agency (EPA) signed an agreement to coordinate energy labelling of office equipment by applying the "Energy Star" in Europe, for a limited time, until the EU completed the development of its own legislative framework on energy related products (Energy Star, 2019b). This agreement was implemented in 2003, including, progressively, computers, monitors, imaging equipment (i.e. printers), servers and uninterruptible power supplies. The EU-US agreement was renewed twice for 5 years and finally expired on 20 February 2018 (Energy Star,2019b).
Level	EU-US
Type of Instrument	Self-regulation (labelling)
Compliance	☐ Mandatory ☒ Voluntary
Verification	☒ Self-Assessment ☐ Third Party Verification When initially signed, only self-certification was foreseen. From 2009 onwards, EPA made ex-ante third-party testing mandatory but the EU never agreed, which led to the end of mutual recognition.
Available evaluation	No formal evaluation available

Clear objectives defined (if Yes, which)	It was expected that the increased consumer focus on energy-efficiency caused by Energy Star in the EU countries was going to save 10 TWh annually in 2015, which is equivalent to about 0.4 % of the electricity consumption in the 15 EU countries (Energy Star, 2019a).
Cost-benefits	It is difficult to estimate the real impact of Energy Star in Europe (and questionable), because of the progressive overlap with mandatory vertical and horizontal EU regulations or other voluntary measures (interview).
Effectiveness concerning energy-efficiency	The Energy Star label for the products included in the agreement focused on the energy consumption of the product when “in use”, except for computers (energy use when computer is “idle”, not during computations). Advertisement was the task of the industry (not the EU), the scheme was little known to EU consumers (compared to 93% who knew about the European mandatory energy labelling scheme). Moreover, no requirements were set for “non-energy” aspects, such as durability, reparability, recycling, etc. (as in the EU Ecodesign/energy labelling framework). For example, for imaging equipment, over the entire life cycle, the consumption of energy “in use” is 1-2% of the total consumption, with a big share accounted for by consumables (ink/toner/paper). Consequently, the EU Ecodesign/labelling scheme is more holistic and thus better covers all relevant energy-related aspects (interview).
Technical feasibility (for companies)	High
Political feasibility	Initially high in the EU because in the EU no labelling scheme for office equipment existed in the 1990s and at the beginning of 2000; the Energy Star was initially adopted in the context of implementing the Kyoto Protocol. Later the EU started developing a full and successful legislative framework that, together with the need to avoid double labelling and the low recognition of the Energy Star pictogram on the part of the European consumers, undermined the relevance of the Agreement. For similar reasons, Australia and New Zealand stopped the programme as well (ECCA 2017). President Trump announced to scrap the Energy Star programme and cut financing (Wired, 2017), further undermining the relevance of a continued support of the programme in the EU.
Administrative feasibility (for companies)	Relatively low burden in the EU, but from 2010 onwards high for EU SMEs exporting to the US - mutual recognition stopped, so application to the EU programme became useless (interview).
Acceptance and support of Stakeholders	Depending on the product type: high (printers, computers) or none (servers, UPS) (interview).
Public acceptance	Energy Star was very little known to European consumers - whereas the European energy label is recognised by 93 % of the European citizens and 79% use it for their purchase choice.
PR benefits	As a yes/no and voluntary labelling scheme, it appeared less transparent and not as easy to interpret compared to the 7-class A-G European energy labelling scheme: i.e. depending on how much time has passed since the last review of requirements, the Energy Star labelled products may be among the best 25 % or the best 90 %; while for products not labelled, there is no way to know if they would deserve the label or would not pass (interview).
Impact	Depending on the product type: high (printers, computers) or almost none (servers) (interview).

Table 10 - Energy Star

Name of Instrument	**EU Code of Conduct on Data Centre Energy efficiency and 2019 Best practice Guidelines for the EU Code of Conduct on Data Centre Energy efficiency**
Developed by	Multi-national government

Short summary	The EU Code of Conduct on Data Centre Energy efficiency has been established in response to the increase in energy consumption in data centres and the need to reduce related environmental, economic and energy supply security impacts. The aim is to inform and stimulate data centre operators and owners to reduce energy consumption in a cost-effective manner without hampering the mission critical functions of data centres (European Commission, 2019g). The best practice list provides a common terminology and frame of reference for describing an energy-efficiency practice, to assist participants and endorsers in avoiding doubt or confusion over terminology. Customers or suppliers of IT services may also find it useful to request or provide a list of Code of Conduct practices implemented in a data centre to assist in procurement of services that meet their environmental or sustainability standards (European Commission, 2018b).
Level	EU
Type of instrument	Self-regulation (code of conduct)
Compliance	☐ Mandatory ☒Voluntary
Verification	☒Self-Assessment ☐ Third Party Verification
Available evaluation	No formal evaluation available. Some insights into implementation and effects included in the study: Trends in data centre energy consumption under the European Code of Conduct for Data Centre Energy-efficiency (Bertoldi et al., 2017).
Clear objectives defined (if Yes, which)	No quantitative energy-efficiency goals to be reached or defined under the broad application of the policy instrument. The aim is to inform and stimulate data centre operators and owners to reduce energy consumption by improving the understanding of energy demand within a data centre, raising awareness, and recommending energy-efficient best practices and targets (EU Code of Conduct on Data Centre Energy efficiency, European Commission, 2019g). A subgroup of best practices gives an indication of the minimum expected level of energy saving activities that is required to be a participant (Bertoldi et al., 2017).
Cost-benefits	Costs low compared with savings (interview)
Effectiveness concerning energy-efficiency	No formal evaluation available but an analysis (Bertoldi et al., 2017) shows that the average PUE of the data centres participating in the EU Code of Conduct on Data Centre Energy efficiency is declining (1.64 in 2016). The average annual electricity consumption has declined since 2014. There are a number of date centres, which already achieve a PUE equal to or below 1.2.
Technical feasibility (for companies)	Relatively high, IT equipment is replaced very regularly (interview).
Political feasibility	High, voluntary agreement
Administrative feasibility (for companies)	Relatively high
Acceptance and support of stakeholders	Rather high
Public acceptance	Not applicable
PR benefits	Annual "EU Code of Conduct Award for Energy efficiency in Data Centres"
Impact	It is not a label but it is very much seen by the EU as a certification scheme (interview); the success criteria are the number of participants and the data on energy consumption collected from the participants (interview). In 2019, 342 companies (Bertoldi, 2019) participated; participation of all data centres would be ideal.

Table 11 - EU Code of Conduct on Data Centre Energy efficiency and 2019 Best practice Guidelines for the EU Code of Conduct on Data Centre Energy efficiency

Name of Instrument	**Guidelines - Energy-efficiency in Data Centres**
Developed by	National industry association
Short summary	The Guidelines on Energy-efficiency in Data Centres provide support for the planning, modernisation and operation of energy-efficient data centres. They were developed in 2015 as a bottom-up process by a working group of the German digital association Bitkom and targeted also at small and medium data centres, supporting a low-threshold approach. They include topics like energy management (process, key performance indicators, MSR, data centre infrastructure management, energy contracting), optimisation of IT hardware and software (general measures, virtualisation, server, storage, network) and optimisation of the infrastructure of data centres (Bitkom, 2015).
Level	Germany
Type of instrument	Information/capacity building
Compliance	☐Mandatory ☒Voluntary
Verification	☒Self-Assessment ☐Third Party Verification
Available evaluation	No evaluation available
Clear objectives defined (if Yes, which)	To give guidance for implementation of standards and norms for smaller data centre owners (interview).
Cost-benefits	No information available (interview).
Effectiveness concerning energy-efficiency	No information available (interview).
Technical feasibility (for companies)	Rather high feasibility due to low-level approach, also usable for small data centres (interview).
Political feasibility	Bottom-up project of the members of the working group "data centres" of Bitkom, therefore high acceptance (interview).
Administrative feasibility (for companies)	Feasibility rather easy - due to low-level approach (interview).
Acceptance and support of stakeholders	Downloads: 800 in the first year, 500 downloads 2018/2019, but downloads says nothing about implementation (interview).
Public acceptance	Not relevant, instrument for members of Bitkom and other companies (interview).
PR benefits	Not relevant, instrument for members of Bitkom and other companies (interview).
Impact	The Guidelines were used as a basis or orientation for calls for tender (interview). It is hard to evaluate the success of a guideline (mostly verbal or written feedback from a few small- and medium-sized data centre providers is available), they are not the most successful guidelines of Bitkom (in contrast to others). Downloads: 800 in the first year, 500 downloads 2018/2019 (interview).

Table 12 - Guidelines - Energy-efficiency in Data Centres

Some of the instruments listed above define minimum requirements: the two Ecodesign Directives, the Commission Regulation for servers and data storage products and the Energy Star. The Energy-efficiency Directive defines minimum requirements that should not prevent any Member State from maintaining or introducing more stringent measures.

Other instruments, e.g. the Blue Angel or the U Code of Conduct on Data Centre Energy efficiency include minimum requirements (in the case of the Blue Angel) or other criteria but, in contrast to the Ecodesign Directive, the Commission Regulation and the Energy Star, they focus additionally on continuous support, along with the further development and optimisation of energy-efficient processes in the data centres participating in these voluntary schemes, and are therefore more dynamic.

The Bitkom guideline and the selected standards are tools for supporting and informing an interested audience.

Two of the policy instruments have a strong relationship with research and development: the EU Code of Conduct on Data Centre Energy efficiency and the Blue Angel. This is also reflected in the rather dynamic nature of these two instruments (in contrast to e.g. the Directives).

Taxes related to energy-efficient cloud computing

The selected so-called best practice examples did not include taxes. To gain additional insights into how a tax or taxes can be used to foster energy-efficient cloud computing, an interview with an expert on ecological taxes was conducted. A suggestion that a dedicated tax should be created for energy-efficient cloud computing providers or customers was refused by the expert on the following grounds:

- If cloud providers produce their own energy (e.g. by solar energy, wind park etc.) and/or the energy does not enter the public grid, this energy cannot be charged with a tax. Energy related taxes refer only to energy traded in and consumed via public grids.
- Taxes need a defined assessment base and a clear legal framework. Additionally, it must be easy to calculate the assessment base and to collect the taxes. It is complicated to tax energy use e.g. by imposing a tax on services that might be (due to the nature of a cloud) dislodged and geographically blurred.
- Imposing a tax on individual uses of cloud services (e.g. when a certain amount of data is used up) is likely to be complicated. High transaction costs have to be expected for a measurement system as well as for controlling and trading remaining amounts. Additionally, a tax says nothing about the energy-efficiency of the service that is provided.

A special tax targeting energy use in cloud computing is therefore not considered to be especially promising.

But what is highly recommended is a well-designed general CO_2 or energy tax that ensures a high level of flexibility and uses market mechanisms to incentivise companies to save energy where it can be saved most efficiently.

Gap Analysis

Methodological approach

The gap analysis is based on the literature review and on the interviews conducted and gives, for each policy instrument selected as a best practice example, an overview of the estimated energy demand (if stated for the instrument within its area of application), the expected energy-efficiency (= goal), the overall feasibility of the policy instrument and the gap that needs to be closed to reach the goal as well as a comment on effectiveness.

The gap analysis encountered the following methodical obstacles:

- Diversity of policy instruments: the policy instruments that were analysed range from regulatory to informal instruments and on the geographical scale from the national (two instruments from Germany) to the multi-national (EU, EU-USA, UN) level.
- Missing information on estimated future energy demand: information concerning the future energy demand of the range of products targeted by the respective instrument is available in the Commission Regulation for servers and data storage, the Energy-efficiency Directive, the Blue Angel and the guideline for data centres. For the future energy demand of products covered by the Ecodesign Directive, secondary literature is available (e.g. European Commission, 2018a: Ecodesign Impact Accounting). For the EU Code of Conduct on Data Centre Energy efficiency an analysis of the data on the participants combined with references to the future energy demand of data centres is available (Bertoldi et al., 2017). The energy star and the informal instruments of ITU-T do not refer to quantitative future energy demands.
- Heterogeneous target groups: The target groups of the policy instruments are also diverse ranging from the Member States of the European Union to companies (in their roles as producers, service providers or procurers) and consumers (= the general public).
- Different goals: the policy instruments have different energy-efficiency goals that do not always include quantitative goals:

Only two instruments, the Energy-efficiency Directive and the Commission Regulation for servers and data storage products, state quantitative goals for energy savings in the text of the Directive or Regulation . The Energy-efficiency Directive should sets the headline target for energy-efficiency at 20 %, the revised Directive raises this target to at least 32.5 % (European Commission, 2018c).

The Commission Regulation for servers and data storage centres is estimated to lead to annual energy savings of approximately 9 TWh by 2030 - approximately the same amount as Estonia’s annual electricity consumption in 2014 (European Commission, 2019a).The Ecodesign Directive (2009/125/EC) itself does not mention a quantitative goal for the overall energy-efficiency to be achieved by the implementation in the Directive itself, but secondary literature on this topic exists and is included in the gap analysis.

Some policy instruments such as the informal Bitkom guideline for data centres or the ITU-T recommendations do not refer to a public policy goal for energy-efficiency because they are either conceived as tools for energy and cost savings for companies (the Bitkom guideline) or they focus on aspects of energy-efficiency that are to be embedded in a bigger context (the selected ITU-T recommendations).

The Blue Angel for data centres refers to the public goals of energy-efficiency, but only vaguely and without a quantified goal and sees its target group in the top third of the data centres. Nevertheless, targets and criteria for single data centres are defined, but they focus on the optimisation of energy-efficiency and other processes.

The EU Code of Conduct on Data Centre Energy efficiency for data centres points out that it is not possible to set a minimum efficiency requirement for data centres, given their diversity, different responsibilities (some companies are only responsible for infrastructure, while others are responsible for IT equipment selection and operation). Therefore, it was decided that the key criterion for the EU Code of Conduct on Data Centre Energy efficiency was to ask the participating companies to monitor their energy consumption and to adopt a set of established best practice examples (Bertoldi et al., 2017). As the Blue Angel for data centres, the EU Code of Conduct on Data Centre Energy efficiency refers to the public goals of energy-efficiency, but only vaguely and without a quantified goal.

Similarly, the Energy Star lists minimum criteria for a range of products but the overall contribution to public energy-efficiency goals is not mentioned.

- Missing evaluations or other means of measuring the impact and effectiveness of policy measures: a formal evaluation concerning the impacts on energy-efficiency is available only for two (Ecodesign Directive 2009, Energy-efficiency Directive) out of eight policy instruments. In most cases, no formal evaluation has been performed or is public available. Due to the fact that the Commission Regulation for servers and data storage products is relatively new (March 2019), no results for its effectiveness are available. The evaluation of the Ecodesign Directive (European Commission, 2009) partly overlaps with the evaluation of the Ecolabel; nevertheless, two studies exist (ECOFYS, 2014; European Parliament, 2018). For the Energy-efficiency Directive an assessment of the progress made by the Member States towards the national energy-efficiency targets for 2020 and towards the implementation of the Directive exists. For the Energy Star, the ITU-T recommendations and the Bitkom Guideline for data centres no data on implementation or effectiveness is available. Regarding the EU Code of Conduct on Data Centre Energy efficiency a study that includes some aspects of the results achieved with the policy instrument (Bertoldi et al., 2017), e.g. the number of participants, the average PUE, is available. Participation in the Blue Angel label for data centres is currently very low; an impact on those companies that do not participate but orient themselves to the label's criteria is assumed but has not been evaluated.

Feasibility and effectiveness

Different layers of feasibility

Distinctions between technical, political and administrative feasibility were made in the description of the respective policy instruments. In the gap analysis a summary of available information on feasibility at different levels is included. Overall, feasibility was seen as rather high (i.e. rather easy) for instruments that are based on stakeholder involvement and/or bottom-up processes (ITU-T, Bitkom guideline) or for voluntary instruments (EU Code of Conduct on Data Centre Energy efficiency).

There were mixed views on the feasibility of the Ecodesign Directive due to missing political support, low resources in some Member States for implementation and surveillance, and exhaustive testing required in companies, as well as unclear formulations in legal texts. Similarly, the feasibility of the Energy-efficiency Directive was estimated as low to medium in the Member States because a lot of effort is needed to collect data on energy consumption as well as energy-efficiency and cost-efficiency.

Feasibility of the Energy Star was seen as high in the beginning, but considered to be low in the last phase due to differences in legal requirements between the European Union and the USA, which led to problems for European export companies. Feasibility of the Blue Angel for data centres is seen as low due to the need to install measurement systems for energy-efficiency in companies.

Effectiveness

The missing evaluations or other means of measuring the impact and effectiveness of policy measures were a barrier to assessing the effectiveness of the policy measures in regards to energy-efficiency.

Only for two policy instruments, the Ecodesign Directive 2009 and the Energy-efficiency Directive, a formal evaluation of the impacts on energy-efficiency was available. Concerning the effectiveness of the two Directives, both are hampered by insufficient implementation in the Member States. Market surveillance systems for the implementation of the Ecodesign Directive differ in the Member States and, as it happens, non-compliant goods are on the market (CSES, 2012). Due to different levels of implementation and a lack of compliance, it is estimated that 10-25 % of products on the market do not comply with the Ecodesign and Energy Labelling Directive. This leads to a loss of around 10 % of the envisaged energy savings and to unfair competition (European Parliament, 2018).

The effectiveness of the Energy-efficiency Directive is also encumbered by insufficient efforts of some Member States in implementing appropriate measures and in the collection of data on energy consumption as well as energy-efficiency and cost efficiency. If the increasing trend in energy consumption that has been observed since 2014 continues in the coming years, the achievement of the 2020 target both for primary and final energy consumption could be at risk (European Commission, 2018c).

Despite the fact that there is still some room for improvement, it can be assumed that both Directives have contributed significantly to improvements in energy- efficiency.

Due to the fact that the Commission regulation for Servers and Data Storage Products is very new (March 2019), no results for its effectiveness are available.

For the other instruments no formal evaluation is publicly available, but it can be assumed that they have an effect on energy-efficiency, although there are maybe still not enough participants. In the case of EU Code of Conduct on Data Centre Energy efficiency no formal evaluation is available but an analysis (Bertoldi et al., 2017) shows that the average PUE of the facilities participating in the EU Code of Conduct on Data Centre Energy efficiency is declining (1.64 in 2016). The average annual electricity consumption has declined since 2014. There is a number of facilities that already achieve a PUE equal to or below 1.2. Only some (342) of the data centres in Europe have been approved as participants (Bertoldi, 2019). And regarding best practice implementation, most data centres covered by the dataset used for the study (Bertoldi et al., 2017) have implemented between 26 and 50 practices, significantly less that the mandatory number of 81, as required by the latest guidelines.

Concerning the number of participants, the effectiveness of the label Blue Angel for data centres is currently very low. Only 4 companies participate and even if it is taken into account that there might also be an impact from companies that do not actively participate in the label scheme but use the criteria for orientation, the number is still too low to create an effect.

For the Energy Star, the ITU-T recommendations and the guideline for Bitkom data centres, there is no data on implementation or effectiveness available.

Transferability of examples

The transferability of the policy instruments that have been analysed as well as the approaches that have been described in the presentation of the general policy instruments needs to take into consideration the following:

- **Missing counterfactual approach:** The study suffers from a lack of available data from evaluations for most of the policy instruments used as so-called best practice examples. But even if effects on energy-efficiency could be shown in evaluations, it is possible that energy-efficiency improvements are at least partly due to other factors like independent technological development or economic trends and are not only caused by a policy instrument.

As stated in the evaluation of the Ecodesign Directive 2010 (CSES, 2012), the available data do not solely reflect the impact of the Ecodesign Directive. Other instruments – primarily the Energy Labelling Directive but also other policy tools at the European and Member State level – also play a role in the development of more energy-efficient appliances. The way these different policies interact may vary among product categories. (…) to establish causality is not only a challenge for this evaluation but a common challenge encountered in evaluations in general. (…) In addition, it is likely that the effects of the Directive or a particular implementing measure may have begun even before they formally entered into force. Interviews with stakeholders have confirmed that the prospective need to change - in response to Ecodesign requirements, at a stage when these requirements are still under consideration - already focuses the attention of producers on improving energy-efficiency. (…) This anticipatory action is, in fact, a rather common phenomenon associated with the introduction of legislation that aims to set mandatory requirements. (…) Some producers react quickly and devote significant resources to increases in energy-efficiency. Others react more slowly. Anticipatory effects are referred to as indirect effects; effects caused directly by the standards are referred to as direct effects (CSES, 2012).

- **Satiation levels of consumer needs:** examples of policy instruments, e.g. for white goods, are restricted in their transferability to ICT and especially cloud computing. A satiation of consumers' needs (Sorrell et al., 2009; Wörsdorfer, 2010 in: Galvin, 2015) does not seem to occur in the same way with ICT/electronics as it does with other products. There is a limit to how far a car owner needs or wants to drive in a day or year, or how warm a family would want their home to be, but there seems to be no limit on how many Gigabytes of memory, Gigahertz of processor speed, or Terabytes of storage, a user needs for a home or office computer. Furthermore, while cars, home insulation, washing machines and refrigerators were developed to meet specific human needs, which do not seem to have changed radically in the last half-century, ICT and electronics seem to constantly create new human needs, many of which were not even thought of in pre-ICT-age science fiction (Galvin, 2015). This leads to rebound effects:
- **Rebound effects:** The history of ICT/electronics shows that energy-efficiency increases inevitably lead to increases in energy consumption (Galvin, 2015). The evaluation of the Ecodesign Directive (CSES, 2012) gives an example: the actual savings and emission reductions resulting from the implementation of the Directive and the Implementing Measures can be influenced by the presence and the extent of the rebound effect. A direct rebound effect refers to the increased level or frequency of use of products by consumers as a result of the improved levels of energy-efficiency and the lower costs per use. (…) Thus, while the products on the market become more efficient as a result of technical improvements and the minimum requirements set by the Implementing Measures, the initially expected reductions in total energy and the use of other resources may not be achieved. A rebound effect may also arise from a "feel good perception of being green" that can encourage increased consumption for certain green products (CSES, 2012).
- **Potential bounce effects are likely to increase the environmental impacts of the ICT sector:** mostly linked to changes in consumer patters, these 'hidden' effects are complex to include in environmental assessments. For instance, data storage on cloud servers rather than internal local servers allow for a "mutualisation" of servers based on need. However, this usually comes with an extra number of

servers to ensure data safety (multiple copies), estimations of the maximum usage scenario, and an incentive for end-users to store more data /as more storage capacity is available). Another example is the decrease in the useful life of some ICT equipment (e.g. fast turnover of smartphones, used for a shorter period than the expected lifespan), which limits the effects of an increased efficiency of products (Deloitte, 2019).

- **The nature of cloud services:** in contrast to the policy instruments that have been analysed which focus on products (i.e. the “material” part of cloud computing, e.g. data centres), energy-efficient cloud computing comprises also an "immaterial" part, e.g. software or services for customers. Examples are the Ecodesign Directives (European Commission, 2009; European Commission, 2019): both of them are focused on products and are designed in such a way that they can currently not be applied to services. Nevertheless, the idea to further develop the Ecodesign Directive in that direction will be included in the set of recommendations of Task 6, to open a window of opportunity for a discussion of these instruments and whether they can be adapted (e.g. by suitable modules).

Conclusions

- The study reveals that due to the nature of cloud computing and the diversity of cloud service providers, no blueprint for a policy instrument, or a policy instrument mix, for energy-efficient cloud computing is available.
- Nevertheless, existing instruments can - to varying degrees – be used as a starting point or at least as an inspiration for further developments or new designs of such instruments. An example of such an instrument is the EU Code of Conduct on Data Centre Energy efficiency, which can be used as a solid basis for a step-by-step development of a Code of Conduct for cloud computing. The same is true for the Blue Angel, the Bitkom guideline, or the Ecodesign Directive.
- Some interview partners pointed out that a more holistic approach to energy-efficiency should be preferred by e.g. including life-cycle considerations etc.
- Criteria for recommendations include the inclusion of stakeholders in the dialogue on the design of the policy instruments and the prolonged cooperation with them.
- Anticipatory action by stakeholders is a phenomenon that tends to happen in advance of legislative actions.
- Positive examples that include continuous development and connecting with research activities are the EU Code of Conduct on Data Centre Energy efficiency and the Blue Angel. The interaction between these policy instruments and R&D - especially as regards further developments of metric and measurement - is exemplary and should be included in the design of further policy instruments.
- On the other hand, an interaction between the EU Code of Conduct on Data Centre Energy efficiency and the Blue Angel seems to be missing. Networking and an exchange of experiences between these two policy instruments – and also other green IT initiatives - is needed.
- Too restrictive regulations might hinder eco-innovation – too stringent policies might have an adverse impact on company performance (e.g. due to high compliance costs).
- Voluntary agreements require the availability of green energy technologies and the availability of such technologies is more likely if adequate policies are in place.

- Also, a participation in green European research networks has a positively effect on environmental innovation and should be combined with flexible and market-friendly policies.
- Avoid potential negative interaction between policy instruments, strive for positive or complementary interaction outcomes (Rogge & Reichardt, 2016).
- As shown in the gap analysis of the selected best practice examples, missing goals and a lack of evaluation hinder an estimation of and reflection on the effectiveness of the measures, and are a barrier to the continuous improvement of policy instruments for a rapidly changing technology like cloud computing. That means that for the policy instrument finally selected, or for the mix of policy instruments, a kind of reporting system (even when using simple indicators) should be considered.
- An ex-ante-assessment is recommended to prove that considerable results for energy-efficiency can be achieved by the policy recommendations finally selected.
- What did not come within the scope of the study was an analysis of policy instruments that might incentivise energy use and undermine energy-efficiency. Policy makers should also carefully scan the existing instrument mix for instruments that are inconsistent with a given policy strategy, including different policy fields, which may have to be adjusted or phased out (Rogge & Reichardt 2016). In the case of energy-efficient cloud computing, consistency should assured with related strategies e.g. the Digital Strategy “Shaping Europe’s Digital Future” (European Commission, 2020c) that points out that the ICT sector also needs to undergo its own green transformation and that data centres and telecommunications will need to become more energy efficient, reuse waste energy, and use more renewable energy sources and formulates the goal that data centres can and should become climate neutral by 2030 (European Commission, 2020c).
- To avoid fragmentation, all policy recommendations should be embedded in an appropriate framework: As (Rogge & Reichardt, 2016) state, a policy mix for sustainability transitions ought to include a strategic component. There is recent empirical evidence of the importance of long-term climate targets for companies’ innovation strategies (Rogge & Reichardt, 2016). More flexible legislation, combined with a consistent policy approach and a certain stringency (e.g. in terms of energy taxes), has a positive impact on green innovation. The European Green Deal (European Commission, 2019e) could be such a framework in that it points out that Europe needs a digital sector that puts sustainability at its heart. The Commission will also consider measures to improve the energy-efficiency and circular economy performance of the sector itself, from broadband networks to data centres and ICT devices. The Commission will also assess the need for more transparency on the environmental impact of electronic communication services and more stringent measures when deploying new networks (European Commission, 2019e). Framework conditions for cloud computing are also a topic included in the European strategy for data (European Commission, 2020a). Data centres and telecommunications are also a topic in the Digital Strategy “Shaping Europe’s Digital Future” with the explicit goal for initiatives to achieve climate-neutral, highly energy-efficient and sustainable data centres by no later than 2030 and transparency measures for telecoms operators on their environmental footprint (European Commission, 2020c). As stated in the European strategy for data (European Commission, 2020a), the European Commission has plans for a coherent framework around the different applicable rules (including self-regulation) for cloud services by 2020, in the form of a ‘cloud rulebook’. At the first instance, the cloud rulebook will offer a compendium of existing cloud codes of conduct and certification on security, energy-efficiency, and quality of service, data protection and data

portability. In the area of energy-efficiency, earlier action will be considered (European Commission, 2020a).

- Especially legal instruments should try to avoid uncertainties as much as possible. Unclear formulations in legal texts contributed, for example, to a less than desirable implementation of the Ecodesign Directive. Current legal uncertainties are mentioned in the European strategy for data (European Commission, 2020a), for example compliance of cloud service providers with important EU rules and standards, e.g. on data protection.

One of the elements of a framework that could serve as an umbrella for all policy mixes for energy efficiency is a general CO2 or energy tax. Well-designed tax reforms that play a direct role as they send the right price signals and provide the right incentives for sustainable behaviour among producers, users and consumers are also part of the European Green Deal (European Commission, 2019e).

10. TASK 4 - ASSESSMENT OF RESEARCH AND TECHNOLOGICAL DEVELOPMENT (RTD)

Background and Methodology

The work of Task 4 builds in particular on the preparatory work in Task 1 and Task 2. Task 1 modelled the EU-wide energy consumption of data centres, which required approximately 76.8 TWh of energy in 2018 and for which further growth is forecast (see chapter 6). A reference architecture for Cloud Services was developed in Task 2. This model allows analysts to describe the range of technologies required to provide cloud services and to analyse them in terms of energy-efficiency.

Based on the research in Task 2, the reference architecture developed and an advanced literature analysis, Task 4 initially identified the main technology fields in which RTD can be used to increase the energy-efficiency of cloud computing.

The following six key technology areas were identified and described:

- IT equipment: from edge devices to hyper scale data centres (servers, storage, networks)
- 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

In the next step, the relevance of these technology fields for RTD was discussed in an intensive stakeholder process and possible recommendations for the RTD policy were developed. The ideas and suggestions developed are based on interviews with experts from various stakeholder groups such as data centre operators, ICT manufacturers, software developers, cloud providers and scientific institutions. Also, in a two-stage online survey, various stakeholders suggested recommendations, which were included as well. Similar recommendations were combined.

Figure 25 shows the result of the online consultation with selected cloud computing experts on the need for RTD in the key technology areas identified. The experts confirmed the relevance of all six areas for energy-efficient cloud computing.

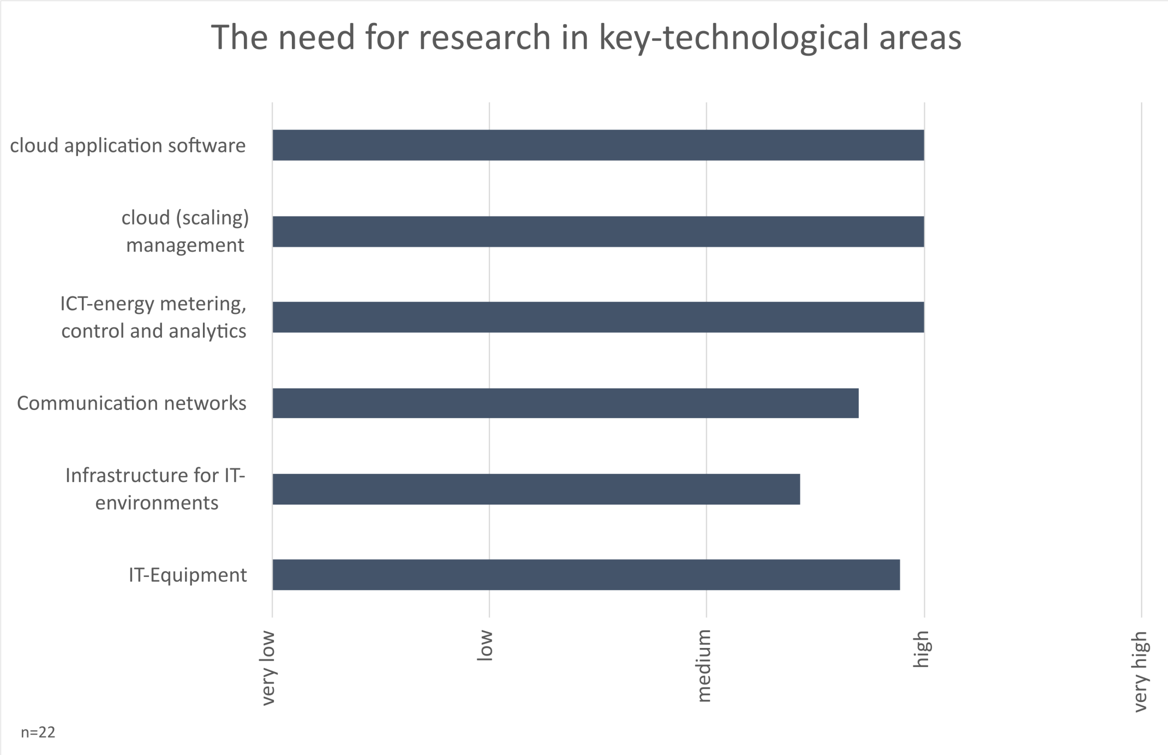

Figure 25 - The need for RTD in key technological areas – result of the online consultation

In the stakeholder process, a total of 38 concrete recommendations for RTD policy to increase energy-efficiency were developed (see Annex 5). Some of the recommendations resulting from the stakeholder process are direct connected to RTD policy, others support RTD Policy, as described below. The recommendations were grouped in four characteristic areas:

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

The recommendations were discussed, adapted and prioritised with stakeholders during a validation workshop on 10 September 2019 in Brussels.

The results of the validation workshop were summarised, evaluated and supplemented into a total of seven summary RTD policy recommendations, which are presented below.

Therefore, the focus is on the following political instruments that are directly connected to RTD policy:

- supporting excellent science, e.g. funding for collaborative research and research infrastructures, providing researchers with excellent training
- funding/supporting industrial research, e.g. investing in key industrial technologies, facilitating access to risk finance, supporting SME

- incentivizing cross-disciplinary, cross-sectoral, cross-policy and international collaboration, bringing together resources and knowledge across different fields, technologies and disciplines

In addition to directly connected RTD policy instruments, other policy instruments in the broader sense can be expected to support RTD policies for energy-efficient cloud computing. They include:

- public procurement,
- organizing and financing the discourse (long-term visions, technology assessment, awareness measures, planning cell),
- education and training (initiating and promoting the development of university degree programmes and vocational training programmes),
- regulatory policy (competition policy, regulatory policy, influencing private demand).

Key findings

1 Extensive need for political action to support RTD

The ever-increasing demand for central computing capacity in the EU due to digitization requires high efficiency gains to prevent energy consumption from growing too rapidly. Additional and extensive potentials for efficiency improvements exist. Whether and how quickly these potentials can be tapped depends on political support

2 Six key technological areas

Six key technological areas were identified in which experts see particularly great potential for increasing energy-efficiency

3 Seven summary recommendations for clear political action

Seven summary recommendations with political options were derived from 38 recommendations proposed by various experts and stakeholders.

4 Broad consensus among stakeholders

An extensive dialogue with providers of cloud computing services, data centre operators, consulting firms, IT and energy experts and academic institutions has shown that there is broad agreement on the energy-efficiency potential for cloud computing, the starting points for further improvements and the RTD policy options.

5 Besides energy-efficiency, climate emissions should be kept in mind

While saving energy is very important, the overall goal is to reduce the emission of greenhouse gases. Direct use of renewable energies has considerable potential to reduce the CO2-intensity of the electricity consumed. However, it must be said that CO2 offsetting does not make the energy supply completely sustainable.

Summary recommendations for RTD policy

Recommendation 1: Stipulate transparency requirements and foster uniform indicators for energy-efficiency

Cloud computing applications and services are delivered by combining a variety of different and sometimes very complex technologies. This has to do with the fact that the actual application software runs on a distributed and highly abstract infrastructure. In addition, there is the shared use of multi-tenant public resources, where one piece of physical hardware is used by a large number of users. Cloud services often also combine ICT resources from more than one infrastructure provider (hybrid cloud/multi-cloud). Therefore, it is practically impossible to allocate energy consumption on the physical side to a specific cloud application or a cloud service in the absence of complete transparency of the infrastructure and standardized, automatic recording.

Existing efficiency indicators for specific fields, such as servers (e.g. SPEC-Energy) or the performance ratio of the data centre infrastructure (e.g. PUE) provide only limited information about which cloud service is most efficient. To address this problem, a comprehensive, uniform KPI for the energy-efficiency of cloud applications should be defined and its dissemination and use on the basis of a standard should be supported. Although CO_2 emissions should ultimately be the primary factor in terms of climate protection, we also recommend explicit reference to energy-efficiency. Otherwise, there is the risk that existing efficiency potentials will remain untapped if data centre operators out-source their climate responsibility by purchasing cheaper CO_2 offsets instead.

In Horizon Europe, research projects could be funded, to develop software that continuously determines the virtual resource requirements (virtual machines, storage, network capacity) of cloud services and makes them available in a transparent manner. In addition, it should be evaluated to what extent virtual resource demand and the corresponding effects on energy demand and CO_2 emissions are correlated. As a result, every cloud service could come with an automatic recording of the carbon footprint.

When assessing many technology trends, it is difficult to estimate their impacts on the future energy consumption of cloud computing. Therefore, technologies developed in publicly funded research projects should always be assessed in terms of their need for cloud computing resources (especially computing power and data transmission) and their energy consumption.

Recommended supporting measures, although not RTD measures in the strict sense, include transparency regulations that cover the import of ICT equipment such as servers, the operation of central facilities (computer centres) and their rated power input for statistical purposes at national level.

The proposed actions can be seen as a basis for further measures for which uniform assessment of energy-efficiency is essential, especially for comparability in procurement, efficiency labelling or even direct product regulation such as Ecodesign.

Recommendation 2: Promote the use of native optimisation tools of cloud computing

One key feature of cloud computing is its scalability and automatic control and optimisation of resource use (Mell & Grance, 2011). Compared to the traditional provision of computing services in data centres, it can result in high savings potentials – however, applications must be adapted in their basic architecture and tools must be configured accordingly. The virtualized ICT resources in cloud computing make it possible to organize these resources very extensively and precisely. This enables a flexibly scalable use of resources for the applications and, at the same time, potentially higher utilization of the physical servers.

A broader use of cloud native software development, as well as stricter cloud scaling rules and the adoption of cloud orchestration tools can help to reduce the energy consumption of cloud services. Here it is necessary to strengthen the Open Source community and to apply the tools through demonstration projects. At the same time, new types of AI applications can be used to better predict the workload, which can reduce the amount of server power required.

In the future, a uniform KPI (see recommendation 1) and transparency requirements could enable the workload between different cloud data centres or even cloud providers to be shifted continuously to the most efficient one, depending on their individual site conditions (temperature, solar energy availability, etc.). Better software management that optimises Quality of Service in terms of energy consumption would also be helpful. For example, latency-critical application parts could be equipped with much greater reserves of ICT resources, while non-critical applications would be optimised for efficiency.

To achieve this, it is necessary to further develop existing tools for the management of cloud environments and to optimise them for efficiency. Providers of IaaS cloud solutions could inform their customers if they waste energy or fail to fully utilize the cloud infrastructure capacity they have contracted. Here, an action-oriented research project of providers and users of IaaS cloud services could demonstrate which tools are available and what the effects of different configurations are. In addition, the research project could examine to what extent an efficiency strategy with pay-per-use based tariffs could be compatible with the interests of cloud providers.

Software developers should be better trained in the area of orchestration tools and scaling management with regard to energy-efficiency. For this purpose, research can develop special guidelines that are made available to educational institutions.

Recommendation 3: Support technological innovation for specific issues

In addition to the energy-efficiency potentials of holistic cloud management, there is still considerable potential for improving the efficiency of the individual elements of the cloud value chain – starting with chip architectures, through data centre cooling and data transmission technologies, to edge devices. RTD policy can promote the energy-efficiency of cloud computing by funding research projects in the EU, particularly in the following areas:

- Beyond Moore's Law: The main driver for energy-efficiency in ICT has been the miniaturization of CMOS circuits, which is currently slowing down. Future performance gains might be based more on parallelization, which leads to increasing energy consumption.
- Potentials for more energy-efficiency by using hardware acceleration (ASICs, FPGAs, GPU computing)
- New energy-efficient System on a Chip (SoC) design
- 'Standby-ready' equipment and architectures
- Energy-efficient networks (mobile networks, wired networks)
- Reuse of heat generated by data centres (optimizing existing technologies, definition of standards, promoting the application of heat reuse technologies, as it is targeted in (European Commission, 2020b). It should be kept in mind that the main purpose here is to utilize waste heat, not to meet energy consumers' demands for energy.

While in the area of IT technologies the focus should be on promoting research and development of new solutions, many alternative solutions already exist in the area of data centre infrastructure. Here, the adoption of the technologies should be supported in particular, e.g. by promoting best practices and by including the relevant requirements in public procurement guidelines.

Recommendation 4: Improve software efficiency

Software has a considerable influence on the energy requirements of IT systems in general, and this applies specially to cloud computing systems. In order to increase the software efficiency of cloud services, RTD policy can address two main issues:

- **Energy-efficient programming (in general)**

  The program code design of an application has a high impact on its energy consumption. Studies have shown that very similar applications may sometimes require completely different consumption of IT capacity (CPU load/RAM/network) and thus different energy consumption. Wirth's law (N. Wirth, 1995) states that software is getting slower as hardware becomes faster. Software is a major factor for energy-efficiency when the final cloud computing product is viewed in relation to the energy consumed.

  Software development should therefore focus more on efficient code to provide the same functions on less hardware and thus with less energy. Important steps in this direction include generating better knowledge about energy-efficient software development and a study that produces developer guidelines for energy-efficient software development. Such guidelines should also be used in training for software developers.

- **Promoting the development and use of cloud native programming**

  Promoting open-source-based cloud native programming is likely to increase the use of energy-efficient cloud computing and significantly improve the utilization of IT systems. It is also important to further research the potential and requirements of cloud native programming with regard to the energy-efficiency of cloud systems.

A research project that is targeted specifically at software efficiency in cloud environments and sheds light onto the state of the art of efficient software development, could be supported by the research framework of Horizon Europe. This would fit into Pillar 2 – Global Challenges and European Industrial Competitiveness. The goal should be to find strategies for software design, to reduce usage of ICT components by identifying relevant factors and demonstrate efficient programming. For better dissemination, the project should aim at cooperation with the open source software community and the potential for absorption into widely used software components.

Recommendation 5: Exploit the potential of SMEs and make SMEs cloud-ready

Research and development concerning energy-efficient cloud computing is not only a topic for large companies. RTD policy should also focus on SMEs in particular. Two main topics are relevant for RTD policy:

- So far, SMEs use cloud services less than larger companies do. This means that large parts of the economy are not making use of the energy-efficiency potentials of cloud computing. Research projects can provide insights into the requirements of SMEs for cloud services and develop cloud services further to make them attractive to SMEs.

- Start-ups and SMEs in particular generate new impulses and innovations in both software and hardware development. An RTD policy geared towards energy-efficient cloud computing should particularly promote research and development in SMEs.

- A European cloud solution that relies on widely distributed and diverse providers, whose solutions are well connected due to appropriate standards, helps new providers to enter the market. While cloud services today are mostly provided by a few large players, a greater variety of providers has the potential to deliver innovation faster. The development of the European Data Infrastructure offers many opportunities for supporting innovative SMEs with research support, possibly provided by Horizon Europe.

Recommendation 6: Focus on researching emerging trends

There are always new and rapidly emerging trends and technologies in ICT. This gives rise to uncertainties as to how the energy requirements of ICT will develop in the future. Currently, it seems that the topic of edge computing in particular will have a significant impact on the future energy requirements of cloud computing. According to various market forecasts edge computing will see strong growth in the coming years. It is unclear how this will affect overall energy-efficiency. Yet it is evident that there are some trade-offs in energy-efficiency if one takes a holistic view. While the load on some components in the network is reduced, additional power consumption is generated by the decentralised computing units. However, these are subject to completely different framework conditions (direct cooling if necessary, longer maintenance cycles, other types of workload, etc.), which makes an assessment of the effects on energy-efficiency very complex.

One aim should be to integrate the topic of energy-efficiency into general research projects on edge computing. In addition, research projects on edge computing with a specific focus on energy-efficiency and climate action could be funded by Horizon Europe.

In addition to edge computing, other technology developments such as artificial intelligence, IOT, Blockchain or high-performance computing as a service can also lead to rapidly growing energy requirements. An RTD policy oriented towards energy-efficiency must observe and analyse these and other trends.

Recommendation 7: Integrate energy-efficiency of cloud services into other RTD programs

The megatrends digitization and sustainability must be addressed in an integrative manner to achieve a policy geared towards sustainability. This applies in particular to cloud computing. The EU’s RTD policy should therefore also take account of sustainability requirements in all cloud-relevant areas, especially requirements for energy-efficiency. This applies in general to the EU cloud strategy and in particular to special programmes on cloud security and the development of an EU cloud infrastructure, for example.

11. TASK 5 - GREEN PUBLIC PROCUREMENT FOR CLOUD COMPUTING SERVICES

Introduction

Goals

Task 5 is structured as follows:

- Review of current EU schemes and tools for GPP related to cloud computing services.
- Analysis of current National Action Plans (NAP), national approaches and best practices for GPP for cloud computing services.
- Formulation of conclusions and policy recommendations based on conducted research and analysis.

Objectives/Structure

The main objectives of Task 5 are:

- To define the scope of investigation for GPP and cloud computing services.
- To screen existing EU-driven initiatives, schemes, tools (policy options, current standards) and existing EU Green Public Procurement criteria contributing to the efficiency of cloud computing.
- To develop an analysis framework for green procurement of cloud computing services in close connection with Task 3 from the very early stages of the study; to identify the main elements of future cloud scenarios relevant for green public procurement; to prioritise the tools (such as policies, labels, etc.) identified and ranked in Task 3 (e.g. those from which the best environmental impacts can be derived) for the purposes of public cloud services procurement; to check completeness or to identify possible gaps.
- To identify the current status of inclusion of GPP criteria and tools (e.g. those identified below) for cloud computing services within the National Action Plans (NAPs) and other national initiatives for GPP.
- To identify selected best practices related to the public purchase of cloud computing services at the national level.
- To cluster Member States and their uptake of GPP criteria related to cloud computing, assessing in this way their qualitative impact, and identifying gaps and potential for improvement.

Based on the above-mentioned results: to formulate recommendations for the inclusion of cloud computing-related GPP criteria in the EU Member States National Action Plans and procurement strategies. The recommendations have been formulated in a way as to also take into account the most promising area of technological development and the potential for energy-efficiency resulting from Task 1 and Task 2. The recommendations have been discussed in a dedicated workshop.

The methodologies for the analysis as well as the preliminary results are introduced in the chapters below.

Key findings

1 A variety of best practices of energy-efficient data centres and server rooms can be identified throughout Europe.

2 The European Commission has been promoting energy-efficient cloud computing in public and private procurement with the development of a Code of Conduct and GPP Criteria documents. The uptake and implementation of these criteria at the Member State level (e.g. in National Action Plans GPP) are still lagging behind.

3 There is little awareness for energy-efficient cloud computing services in the GPP groups and platforms.

4 The topic of energy-efficient cloud computing is in general not tackled on national political agendas, nor in EU legislation.

5 Whereas many examples of implemented energy-efficient data centres can be found, little to no evidence is available for energy-efficient cloud services dealing with the network, data transmission and coding. The only examples have been found in research, but have never been commercialized.

Mapping of EU and member states best practices

Introduction

Part of the study aimed at collecting and analysing best practices for the energy-efficient procurement and GPP of cloud services, critically analyse them, and perform a gap analysis.

This deliverable aims therefore at:

- Introducing the methodology from the screening exercise
- Presenting a series of identified best practices
- Introducing and discussing highlights from the investigation
- Presenting the identified gaps in the procurement and GPP of energy-efficient cloud services

These will be discussed in the following chapters.

Methodology and highlights from the screening exercise

The aims of the screening exercise within this study were:

- to identify the current status of inclusion of GPP criteria and tools for cloud computing services within the National Action Plans (NAPs) and other national initiatives for GPP, and to identify selected best practices related to the public purchase of cloud computing services at the national level
- to identify existing EU-driven initiatives, schemes, tools (policy options, current standards) and existing EU Green Public Procurement criteria contributing to the efficiency of cloud computing

More specifically, the screening exercise performed in this study at the EU and Member State level aimed at answering the following questions:

- Which initiatives can already be identified that relate to the public procurement of energy-efficient cloud services?
- To which extent have GPP criteria already been developed at the EU and Member State level, e.g. National Action Plans? In which Member State?

- Is GPP for cloud computing regulated by national legislation on procurement to some extent?
- Have best practices already been adopted in different Member State, regardless of national legislation?
- What do best practices look like?
- What instruments/tools (e.g. standards, labels, etc.) can be identified? What are the most common instruments applied?
- What are the gaps? What is generally missing to fully unlock the potential for GPP and the cloud computing services?

For the analysis, a number of sources were first collected via desk research and then screened, in order to identify initiatives, criteria, and best practices. Firstly, the sources listed in the inception report were screened. Additional sources were found based on additional searches and the crosschecking of references, e.g. from relevant documents and websites. The links to NAPs, GPP criteria, and national procurement centres were obtained from the document National Action Plans (NAPs) – the status in the EU Member States" (European Commission, 2018). A crosscheck of the references and further desk research allowed us to find additional sources.

The information collected has been benchmarked against:

- relevance to cloud computing
- relevance to energy-efficiency

In total, 195 sources of information relevant to procurement, Green Public Procurement, and energy-efficient cloud computing were first identified at the EU and Member State level and then screened.

For the screening exercise, the following information was collected:

- title of the initiative and summary
- typology (see below)
- country/EU
- website
- relevance to cloud computing
- relevance to energy-efficiency
- further notes
- contact person (to identify relevant stakeholders for the questionnaire and the workshop)

The different initiatives and best practices were prioritised.

The screened sources included the following typologies:

- National Action Plans (NAPs) from the EU Member States
- National and EU-wide GPP Platforms & Web Portals
- National and EU-wide GPP Networks
- National and regional Public Procurement Agencies and Centres

- National competence centres for GPP
- National Agencies for digitalisation
- GPP criteria
- IT related best practices
- Articles, white papers
- Cloud computing-relevant research projects
- Labels, ICT standards, and tools for IT/ Energy
- GPP guidelines
- National Digital Roadmaps
- EU Legislations and Communications

About 143 sources have been collected at the national level and about 52 at the EU level.

All sources have already been screened. A full list of sources can be found in Annex 3. The most relevant initiatives are presented in the "Mapping of best practices". At the EU level, the screened sources include the following:

Figure 26 - Screening of EU & national initiatives

At the Member State level, broad geographical coverage was ensured. Sources include 24 European countries as shown in the figure.

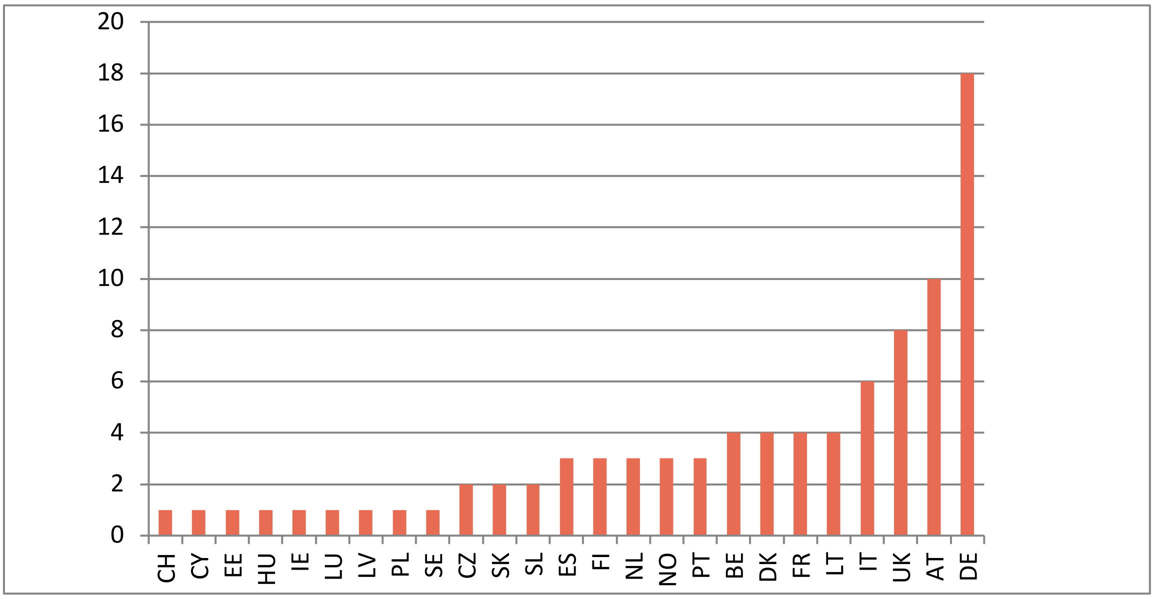

Figure 27 – Geographical coverage of screened initiatives

Out of the whole analysed sample, some examples were considered particularly relevant to the scope and will be presented below.

In addition, a questionnaire targeting the Members of the EU green Public Procurement Advisory Group and public procurers was prepared to gather additional information for the screening exercise, and in particular, to identify criteria in National Action Plans and best practices for energy-efficient cloud computing services at the Member State level. The responses to the questionnaire were remarkably low, and it has been included to the possible extent in the results of this analysis.

Out of the sample, the most relevant are presented in the following, selected are 45 best practices. These are then shown in detail in the following chapters.

The findings of the analysis of the whole sample are presented in the last chapter.

Mapping of best practices

The following tables provide an overview of the best practices presented in this document.

Type	n.	Title	*Key Words*
Energy – efficiency criteria	1	The EU Code of Conduct on Data Centre Energy efficiency	*energy-efficient cloud procurement*
GPP Criteria	2	EU green public procurement criteria for data centres, server rooms and cloud services	*energy-efficient cloud procurement*
National Strategies	3	National Plans for GPP	*national strategies, GPP*
	4	National Digital roadmaps	*national strategies, cloud*
EU-wide research project	5	CloudWATCH2 (Think Cloud Services for Government, Business and Research	*Procurement platform, cloud standards*
	6	PICSE (Procurement Innovation for Cloud Services in Europe)	*Procurement of Innovation, cloud services*
	7	ASCETIC (Adapting Service lifeCycle towards EfficienT Clouds)	*cloud software and energy-efficiency*
	8	SUNFISH (SecUre iNFormatIon Sharing in Federated Heterogeneous private cloud)	*cross-cloud infrastructure and energy-efficiency*
	9	CloudLightning project (Self-Organising, Self-Managing Heterogeneous Cloud)	*cloud infrastructure and energy-efficiency*
	10	RECAP project (Reliable Capacity Provisioning and Enhanced Remediation for Distributed Cloud Applications)	*cloud software, elastic cloud models, energy-efficiency*
	11	ARCADIA	*cloud applications, energy-efficiency*
	12	ICT Footprint EU project	*Platform for cloud computing and energy-efficiency, standards*
	13	Helix Nebula - The Cloud of European researchers	*open cloud service, science cloud*
	28	EURECA - A toolkit for sustainable procurement for data centres – EU-wide initiative	*Public Procurement of Innovation, Data Centres*

use case	14	Sustainable Data Centres in Linköping, Sweden	*renewable energy, public procurement, city data centres*
	15	Energy- efficient genomics in the Earlham Institute, UK	*carbon- neutral data centre, genomics, big data analysis, Iceland*
	16	Free- cooling system for data centres in Coimbra University, Portugal	*free cooling, universities, data centres*
	17	Information campaign for energy- efficient data centres run by Energie Schweiz - Switzerland	*awareness raising, IT private operator, data centres*
	18	Optimizing data centres for public organization- GreenServe, Netherlands	*server virtualisation, public organizations, server & data centres*
	19	GreenConcept Project - France	*capacity building, eco-design in digital services, awareness raising, SMEs*
	20	Energy- efficient Centre for Scientific Computing Goethe University Frankfurt - Germany	*super computers, universities, renewable energy, waste to energy, passive cooling, data centres*
	21	Excess heat from servers to warm households - Digiplex and Stockholm Exergi, Sweden	*reuse of heat, district heating, public private partnership, public procurement*
	22	Heat reuse for district heating – the Yandex data centre Finland	*reuse of heat, district heating, public private partnership, public procurement*
	23	Telia Helsinki Data Centre, Finland	*renewable energy, data centres, district heating*
	24	Energy-efficiency in data centres: the Alibaba cloud provider.	*hyperscale data centres and energy-efficiency*
	25	Procurement Platform for green data centres, EU-wide initiative	*procurement platform, data centres, awareness raising, knowledge sharing*
	26	Successful implementation of the EU Code of Conduct on Data Centre Energy efficiency at Microsoft Data Centre, Ireland	*data centres, EU Code of Conduct on Data Centre Energy efficiency*
	27	Green IT initiative of the Federal Government in Germany	*data centres, Blue Angel*
Ecolabel	29	The Blue Angel	*ecolabel, data centres*
	30	ENERGY STAR	*ecolabel, IT products*
EU legislation	31	The EU Ecodesign Directive (2009/125/EC)	*Ecodesign, legislation*
	32	The EU Directive on Energy-efficiency 2012/27/EU	*energy-efficiency, legislation*
EU Strategy	33	The EU 2020 Climate & Energy Package „20-20-20“	*energy-efficiency, legislation*
	34	The EU Cloud Strategy	*cloud computing, policy implementation*

Guidelines	35	Energy Innovation Procurement. A guide for city authorities (ICLEI, 2018)	*energy-efficiency, procurement*
	36	Buying green! A handbook on green public procurement (European Commission, 2016c)	*green procurement*
	37	Public Procurement as a Driver of Innovation in SMEs and Public Services (European Commission, 2014c)	*PPI*
	38	Guidelines - Leitfaden - Energieeffizienz in Rechenzentren (German Text)	*energy-efficiency, data centres*
EU Tools for sustainable procurement	39	Public Procurement of Innovation	*energy-efficient cloud procurement*
	40	Pre- commercial procurement	*energy-efficient cloud procurement*
Standards	41	ITU- T- L1300, 1301, 1302, 1303, 1320, 1321, 1325, 1501	*energy-efficiency, IT and cloud*
	42	ETSI GS OEU 008, ES 205 200, 103 199	
	43	EN 60600-4-3	

Table 13 - Mapping of best practices

Practices for energy – efficient cloud computing

The following criteria, tools, initiatives and best practices are relevant to the purposes of this study.

The EU Code of Conduct on Data Centre Energy efficiency

The EU Code of Conduct on Data Centre Energy efficiency (European Commission, 2018b) is a voluntary initiative created in 2008 which prescribes a series of practices for sustainable data centres. It includes criteria for the following categories:

- Entire Data Centre
- New Software
- New IT Equipment
- New build or retrofit
- Optional Practices

Among the practices which are listed in the document are:

- Consider the proportion of energy used by the data centre that comes from renewable/sustainable sources.
- Introduce Environmental and Energy Management Plans

The core of the programme is the commitment by the participant to carry out an initial energy audit to identify the major energy saving opportunities; to prepare an action plan; to implement the action plan; and to monitor energy consumption. At the heart of the Code of Conduct are the Best Practices Guidelines, which indicate the areas for energy-efficiency upgrades in data centres, covering day-to-day operations, equipment substitution, major re-furbishment and new data centre design. The Best Practices Guidelines reflect on the principle of areas of responsibility for different types of operators.

A number of data centres already implemented the code of conduct. The complete list of organizations (Code of Conduct Data Centres Partners) is available at: https://e3p.jrc.ec.europa.eu/node/575. (European Commission, Joint Research Center)

The EU green public procurement criteria for data centres, server rooms and cloud services

The European Commission has developed the working document “EU green public procurement criteria for data centres, server rooms and cloud services” (European Commission, 2020b), to provide background information for the development of the EU green public procurement criteria. The inclusion of these criteria in technical tenders is voluntary. The scope encompasses:

- The IT equipment and associated network connections that carry out the primary function of the Data Centres, including the servers, storage and network equipment.
- The Mechanical & Electrical equipment used to regulate and condition the power supply (transformers, UPS) and the mechanical systems to be used to regulate the environmental conditions (CRAC/CRAH) in the white space14.
- Data centre systems as a whole or a managed Data Centres service.

The document was adopted in March 2020.

The National Action Plans for GPP

In total, 25 National Action Plans (including also regional action plans, such as for the Flanders, Welsh, Scotland and Northern Ireland) were screened. Most of the NAPs include IT energy-efficiency criteria, but these are mostly related to end-users devices such as PCs, laptops, monitors, printers, etc. The topic of cloud computing seems to be rather new in this domain, and just marginally considered. In particular, the following countries have initiated to include the concept of cloud computing in their respective National Action Plans for public procurement. In particular:

The Norway National Action Plan stresses the fact that the country pioneers hydro electrical power to generate green energy, and the importance of green Data Centres. Also, the Norway Agency for Procurement (Anskaffelser.no) provides general criteria for the purchase of cloud computing, which nevertheless do not include energy-efficiency.

In Germany, the document setting the rules for the general administration of the procurement of energy-efficient IT products and services (Allgemeine Verwaltungsvorschrift zur Beschaffung energieeffizienter Produkte und Dienstleistungen) was published in 2013. This mandates the use of labels such as “der Blauer Engel” and the “Energy Star” for the public purchase of IT products and services. Despite the term “services” can be interpreted broadly and include also cloud computing services, the term “cloud computing” is not explicitly mentioned.

National Digital roadmaps

Different national digital roadmaps and strategies have been adopted by several EU Member State recently. Different roadmaps including those from Austria, Italy, United Kingdom, Flanders and Slovakia have been thoroughly screened in order to assess if their scope would also include the energy-efficiency of cloud and digital services.

- In the Flanders Cloud Strategy, some principles are pushed forward which include: promoting a public cloud strategy, providing a multi-cloud offer within the Flemish Government, guaranteeing continuity through a hybrid cloud architecture, and managing risk with measures at the level of the Flemish Government. The energy-efficiency is here not included.
- The Austrian Digital Roadmap sets 12 principles for the digitalisation of Austria, including democracy and inclusion, education for the new generations, safety, innovation etc.
- The Italian Digital Roadmap pus emphasis on the digitalisation of administrative processes and data from citizens.

The screening highlighted therefore that the roadmaps, which are in the most cases the very first ones that Member State are adopting, focus on a variety of topics which are relevant to data security, transmission, sovereignty, transparency, privacy etc.; but which are not including the environmental impact, the energy-efficiency or the sustainability of the cloud.

The new European Green Deal of the European Commission

In December 2019, the European Commission adopted the European Green Deal (European Commission, 2019e), that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy with no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use.

Digital technologies are a critical enabler for attaining the sustainability goals of the European Green Deal in many different sectors. The Commission will explore measures that are designed to ensure that digital technologies such as artificial intelligence, 5G, cloud and edge computing and the Internet of Things can accelerate and maximise the impact of policies aimed at dealing with climate change and protecting the environment. The Commission will also consider measures to improve the energy-efficiency and circular economy performance of the sector itself, from broadband networks to data centres and ICT devices. And the Commission will also assess the need for more transparency on the environmental impact of electronic communication services, and for more stringent measures when new networks are deployed.

The European Commission´s Digital Strategy

In 2020, the European Commission released the European Commission Digital Strategy (European Commission, 2020c),

In particular, among the goals of the EU's digital strategy are:

- invest in digital competences for all Europeans.
- accelerate the roll-out of ultra-fast broadband for homes, schools and hospitals throughout the EU.
- expand Europe’s super-computing capacity to develop innovative solutions for medicine, transport and the environment.
- use technology to help Europe become climate-neutral by 2050.
- reduce the digital sector’s carbon emissions.
- empower citizens with better control and protection of their data.

- create a European health data space to foster targeted research, diagnosis and treatment.
- fight disinformation online and foster diverse and reliable media content.

Hence, among the goals of the strategy is also to deliver a more sustainable and energy-efficient cloud.

Research projects

The European Commission's Software, Services and Cloud Programme gives companies and research institutions the opportunity to innovatively engage in cloud computing. In this way, European research initiatives can develop solutions for the Digital Single Market. Europe is a global leader in research and innovation in cloud software and services, with the European Commission increasingly investing in research. One of the goals of the Digital Single Market Strategy is also to create long-term growth potential. Europe needs a digital market that allows it to develop new business models, create start-ups, and supply industry with innovative products to compete globally.

A number of EU-funded projects investigating the energy-efficiency of cloud computing services which can be also relevant for public procurement are presented below.

CloudWATCH2 (Think Cloud Services for Government, Business and Research

Regarding the provision of cloud computing services, the EU project Cloud-WATCH2 , hosted in the web platform “Cloudwatchhub”, was funded under the EU Horizon 2020 research programme and focused on the market uptake and sustainable competitiveness for a wider uptake of innovative cloud services and products from European research and innovation initiatives, in view of an European Digital Single Market. One of its objectives is to map the EU cloud ecosystem of products, services and solutions emerging from EU R&I projects. The project is proactively supporting the adoption of standards and certifications, and has compiled a cloud standard guide which gives information on the main cloud standards for portability, interoperability and security. CloudWATCH has also identified the main areas where standards are missing, although the list does not include energy-efficiency standards; it focuses on other aspects. European research initiatives in particular should develop continuous improvements in the cloud sector in order to provide services and solutions with increasing added value for the Digital Single Market.

The overall scope is wide and includes many elements which are not necessarily related to the energy-efficiency of the cloud, but touch upon security, interoperability, trusted secure services, risk management of could services, etc. Again, the topic of energy-efficiency seems to be marginal.

Keywords: Procurement platform, cloud standards

Website: https://www.cloudwatchhub.eu/cloudwatch2-think-cloud-services-government-business-and-research-0

PICSE (Procurement Innovation for Cloud Services in Europe)

This is a project funded under the Horizon 2020 Programme and intended to develop simpler procurement models for cloud services, published a guideline for procuring authorities which details methods for effective requests for cloud service contracts. The project has the following objectives:

- To provide a landscape of cloud procurement in the European public research sector

- To propose actions within the three pillars of the Digital Single Market Strategy which focus on maximizing the growth potential of the digital economy
- To formulate relevant recommendations regarding the procurement of cloud services for public research organizations in Europe
- To provide a guide to cloud procurement, supported by best practices adopted worldwide

The energy-efficiency component is nevertheless not taken into account.

Keywords: Procurement of Innovation, cloud services

Website: http://www.sustainable-procurement.org/resource-centre/

ASCETIC (Adapting Service lifeCycle towards EfficienT Clouds)

The project, funded under the Horizon 2020 Programme, focused on providing novel methods and tools to support software developers aiming to optimise energy-efficiency and minimize the carbon footprint resulting from designing, developing, deploying, and running software in clouds. This project investigated how to include energy-efficiency criteria at the very early stage of designing software architecture. Although it has a direct impact on the system's energy consumption, software usually controls how computing equipment is utilized. Covering the full service life cycle, from application design, development, deployment and operation, as ASCETiC aims to do, is crucial to determining and optimizing the energy usage of the complete system, considering software and hardware as interrelated mechanisms. Although this project does not focus directly on GPP, it is one of the few studies in which the development of energy-efficient cloud services has been considered. The project, which ended in 2016, offers different tools. Further analysis has been conducted in order to find out if the projects have appeared on the market, but it seems that the deliverables were never commercialized.

Keywords: cloud software and energy-efficiency

Website: http://www.ascetic-project.eu

SUNFISH (SecUre iNFormatIon Sharing in Federated Heterogeneous private cloud)

The project addresses the lack of infrastructures and technologies allowing players from the public sector to federate their private clouds, and at the same time to respect legislative and security barriers to using commercial technological solutions. Nowadays, the main public bodies rely on their own private clouds, leading to a multitude of secluded, non-interoperable cloud centres. The lack of reliable cross-cloud infrastructure hinders the effective and practicable exploitation of clouds in the public sector. SUNFISH has built upon this need by providing a software platform that, via the principled usage of a Blockchain infrastructure, offers a decentralised, democratic and secure federation of private clouds. SUNFISH's deployment model leads to lower energy use and thus lower CO2 emissions, due to the higher efficiency of the services provided by the SUNFISH platform. Implementation cases include, among others, the Italian Ministry of Economy and Finance (MEF).

Keywords: cross-cloud infrastructure and energy-efficiency

Website: http://www.sunfishproject.eu/

CloudLightning project (Self-Organising, Self-Managing Heterogeneous Cloud)

The CloudLightning project is aimed at developing a new way of provisioning heterogeneous cloud resources to deliver cloud services. In particular, it is aimed at providing cloud service providers with an energy-efficient, scalable architecture for managing cloud infrastructures through the separation of concerns, making their architecture more accessible to customers, specifically via high performance computing (HPC). HPC is a particular segment of the IT market that provides significant technical challenges for cloud service providers but it also exemplifies many of the challenges facing cloud service providers as they conceptualise the next generation of cloud architectures.

Keywords: cloud infrastructure and energy-efficiency

Website: https://cloudlightning.eu/

INPUT's OpenVolcano platform (In-Network Programmability for nextgeneration personal cloud service support)

The project is a holistic solution enabling the dynamic instantiation in the fog/mobile edge computing facilities of highly demanding personal cloud services by third-parties for endusers with guaranteed QoS/QoE, anywhere, anytime, while ensuring: confidentiality of sensible information; cost efficiency; high manageability and low complexity interfaces; energy-efficiency; business viability; easy integration with service providers. The INPUT platform is an edge computing system, specifically designed to run within NFV-ready Telecom infrastructures to provide personal cloud services in a highly efficient and scalable fashion.

Keywords: personal cloud services

Website: http://openvolcano.org/

RECAP project (Reliable Capacity Provisioning and Enhanced Remediation for Distributed Cloud Applications)

The project aimed at developing the next generation of cloud/edge/fog computing capacity provisioning and remediation via targeted research advances in cloud infrastructure optimisation, simulation and automation. The outcomes of the project paved the way for a radically novel concept in the provision of cloud services, where services are elastically instantiated and provisioned close to the users that actually need them via self-configurable cloud computing systems. Hence, the project incorporates a much more elastic model, which delivers services and allocates resources in a dynamic manner, tied to time-varying user requirements. This will ensure that communication-critical applications will always achieve their goals without unnecessary delays, no matter where they are located. This, in turn, will minimize operational costs and improve the effectiveness and energy-efficiency of data centre resources.

Keywords: cloud software, elastic cloud models, energy-efficiency

Website: https://recap-project.eu/

ARCADIA

The ARCADIA project is aimed to design and validate a Novel Reconfigurable-By-Design Highly Distributed Applications Development Paradigm over Programmable Infrastructure. Thus, the optimisation of the application's execution according to multiple objectives (e.g. energy-efficiency, QoS, security), as set by the end users, will be supported.

Keywords: cloud applications, energy-efficiency

Website: https://www.cloudwatchhub.eu/serviceoffers/arcadia-novel-reconfigurable-design-highly-distributed-applications-development

ICT Footprint EU project

The project, funded under the Horizon 2020 Programme, is the European platform promoting the adoption of carbon footprint methodologies in the ICT sector. The goal is to support organizations in becoming more energy-efficient and reducing their carbon footprint, ultimately increasing their competitiveness. More specifically, the platform offers a set of standards, procedures, and metrics that aim at helping organizations in addressing their needs regarding carbon footprint consumption.

The results of the projects should affect the European cloud market. Currently, there is still no implementation in the public and private cloud services sector of the solutions presented. Most activities ended with the end of the project.

Keywords: Platform for cloud computing and energy-efficiency, standards

Website: https://www.ictfootprint.eu

Helix Nebula - The Cloud of European researchers

The Helix Nebula project aimed at paving the way for the development and exploitation of a Cloud Computing Infrastructure, initially based on the needs of European IT-intense scientific research organisations, while also allowing the inclusion of other stakeholders' needs (governments, businesses and citizens). The pan-European partnership across academia and industry worked to establish a sustainable European cloud computing infrastructure, supported by industrial partners, which will provide stable computing capacities and services that elastically meet demand. The work started by the Helix Nebula - the Science Cloud project is today continued by the Helix Nebula Initiative, a partnership between industry, space and science to establish a dynamic ecosystem, benefiting from open cloud services for the seamless integration of science into a business environment. Today, the partnership counts over 40 public and private partners.

Keywords: open cloud service, science cloud

Website: https://www.helix-nebula.eu/

Use cases

Sustainable Data Centres in Linköping, Sweden

This is a GPP initiative for green data centres run by Linköping City Council. In particular, the ICT environment's energy consumption, cost, and carbon footprint are monitored since 2008. Most importantly, the city data centre is run by carbon-neutral hydropower. Since its implementation, the city achieved a reduction of energy consumption in data centres of 8%, and decrease of over 30% of city's total ICT footprint in 2013, and no increase in city's total energy consumption despite the increased number of computers, smartphones, projectors, and networked equipment used (40% new equipment between 2008 and 2013 - representing 4,000 new units).

Keywords: renewable energy, public procurement, city data centres

Website: https://www.ictfootprint.eu/en/link%C3%B6ping-sweden

Energy- efficient genomics in the Earlham Institute, UK

The EARLHAM Institute is a research institute renowned for its contribution to the analysis and data-sharing of the highly complex wheat genome. The institute has selected a carbon-neutral data centre campus in Iceland to investigate the efficiencies of distributing large-scale genomics and computational biology data analysis. Through Verne Global, EI will have access to one of the world's most reliable power grids producing 100% geothermal and hydroelectric renewable energy. Thanks to this initiative, the institute will save up to 70% in energy costs (based on 14p to 4p KWH rate) and with no additional power for cooling.

Keywords: carbon-neutral data centre, genomics, big data analysis, Iceland

Website: https://www.ictfootprint.eu/en/earlham-institute-uk

Free-cooling system for data centres in Coimbra University, Portugal

The Laboratory of Advanced Computer of the Coimbra University installed a free-cooling system in its data centres. When the outdoor temperature is below the indoor temperature, cold ambient air is drawn inside the data centre to accomplish cooling while the conventional mechanical chilling system is off (or in standby). The free cooling system allowed for energy savings of about 90 MWh/year, corresponding to a PUE decreased by 0.2 points, while providing similar environmental conditions as in the old system (same temperatures). The installation costs of the system were about €6,040. Taking into account the financial incentive, the payback period was estimated to be around one year.

Keywords: free cooling, universities, data centres

Website: https://www.ictfootprint.eu/en/university-coimbra-portugal

Information campaign for energy-efficient data centres run by Energie Schweiz - Switzerland

The campaign "Less power, more efficiency in server rooms and Datacen-tres" run by EnergieSchweiz - Switzerland aims to draw IT operators' attention to the energy-saving potential in their Data centres. This is achieved through a direct marketing campaign, online assessments, a catalogue of measures, presentation of best practice examples as well as newsletters and networking events.

Keywords: awareness raising, IT private operator, data centres

Website: https://ictfootprint.eu/en/energieschweiz-switzerland

Optimizing data centres for public organization- Green-Serve, Netherlands

The project was commissioned to understand the state-of-the-art situation of the ICT used by public organisations, and to assess opportunities to enable more efficient energy and power management. The analysis highlighted that between 66% & 90% of energy applications and cloud services energy can be saved through the use of new ICT equipment, proper setup and optimal use of the capacity of the servers. The main benefits achieved include:

- Energy consumption savings around 20% and utilisation increases an average 10% through server virualization
- Energy-efficiency improvement of an average 25% with a corresponding reduction in execution times via query scripts
- 61 MWh energy savings & 30/32 Mton CO2 per year with the installation of more modern and energy-efficient equipment

Keywords: server virtualisation, public organizations, server & data centres

Website: https://www.ictfootprint.eu/en/greenserve-netherlands

GreenConcept Project - France

The GreenConcept project, which is lead by the Occitanie Chamber of Commerce, aims at assisting 30 Small and Medium enterprises to implement the principle of Ecodesign into the development of their digital services.

Many types of applications like websites, platform B to B, IOT appliance, web conference, have been analysed with a common life cycle analysis methodology. The Ecodesign of digital service is then promoted through conferences and training and communication media (video, website). The implementation of the identified would permit to halve the environmental impacts of the digital services analysed.

Keywords: capacity building, eco-design in digital services, awareness raising, SMEs

Website: https://www.ictfootprint.eu/en/greenconcept-project-france

Energy-efficient Centre for Scientific Computing Goethe University Frankfurt - Germany

The Centre for Scientific Computing (CSC) of the Goethe University Frankfurt created the LOEWE-CSC, a hybrid cluster used for research purposes. The energy consumption, inherent to the use of super computers, was tackled by implementing passing cooling elements and using power generated in local biogas station and local waste incineration power plant. The cooling system implemented contained four electrically powered components: primary pump (6 kW), secondary pump (28 kW) and two fans located in the towers (4.5 kW each). The cooling towers used the principle of evaporation cooling. In addition, each rack contained an autonomous Linux based microcontroller, which monitored air and water temperature and adjusted cooling performance accordingly for the cooling performance to match heat load. The energy-efficiency of the LOEWE CSC computer is reflected in its PUE value of 1.076. Compared to a traditional similarly sized data centre (with a PUE value of 2.00), the computer saves 3,37 GWh/year, i.e. approximately €462,000/year. In addition to reducing power consumption, the large utilization of passive cooling elements and the reduction of electrical components in the cooling circuit led to improved reliability and lower maintenance costs.

Keywords: super computers, universities, renewable energy, waste to energy, passive cooling, data centres

Website: https://www.ictfootprint.eu/en/goethe-university-frankfurt-germany

Excess heat from servers to warm households - Digiplex and Stockholm Exergi, Sweden

Nordic datacentre operator Digiplex and Stockholm Exergi, the Swedish capital's leading energy supplier, are going to be using excess heat from servers to warm the equivalent of 10,000 households. The two companies say their large-scale heat reuse agreement is the world's first where an operational data centre with indirect evaporative air-to-air heat exchangers is being retro-fitted to transfer excess heat to a city's district heating grid.

Keywords: reuse of heat, district heating, public private partnership, public procurement

Website: https://www.ictfootprint.eu/en/digiplex-and-stockholm-exergi-sweden

Heat reuse for district heating – the Yandex data centre, Finland

Yandex data centre Finland is located at Mäntsälä, Finland. The data centre benefits from the cold ambient conditions and makes use of the direct outside air for cooling. The data centre is designed for 40 MW of IT loads, with phase one – 10 MW – currently in operation. To reuse the energy consumed by the data centre, heat exchangers are installed to absorb the warm air stream. As a result, the cold water that runs through the pipes of the heat exchanger is heated up to more than 30 °C. The water is then upgraded by a heat pump station which is located next to the data centre. Finally, the hot water is transported to its final destination where the data centre heat can be reused.

Keywords: reuse of heat, district heating, public private partnership, public procurement

Website: https://www.greendatacenterplatform.com/project/royal-haskoning/

Telia Helsinki Data Centre, Finland

The Telia Helsinki data centre is located at Pitäjänmäki in Helsinki, Finland. The design capacity of the data centre is 24 MW. The design has received a CEEDA Gold design-stage certification and is on its way to a LEED

certification. The data centre will use exclusively “green” electricity generated from renewable energy sources and the waste heat is captured and reused which makes it “double green”. The temperature of the data centre cooling process is approximately 30 °C. From there, the temperature is increased to about 70 – 80 °C by a group of two stage heat pumps. The high caloric energy is then supplied to the district heating system. When the maximum number of 5,000 racks is fully operational, the data centre will be able to warm around 20,000 flats with 200,000 MWh of delivered thermal energy annually.

Keywords: renewable energy, data centres, district heating

Website: https://www.greendatacenterplatform.com/project/royal-haskoning/

Procurement Platform for green data centres, EU-wide initiative

Green Data Centre Platform is an initiative to accelerate the energy transition and improve energy-efficiency in the Datacentre sector by sharing knowledge, best practices and lessons learned. The main objectives include: Implementing a smarter use of energy, encouraging the reuse of data centre heat and accelerating the energy transition across borders.

Keywords: procurement platform, data centres, awareness raising, knowledge sharing

Website: www.greendatacenterplatform.com

Energy-efficiency in data centres: the Alibaba cloud provider

Alibaba is investing in energy-efficient data centres and services. Reportedly, the company aims to reduce consumption at its energy-hungry data centres by installing cooling and water-efficient systems supported by intelligent management technology and the use of renewable energy. For instance, the Qingdao Lake Data Centre adopts a state-of-the-art deep lake water cooling system that saves 300 million kWh of electricity and reduces CO_2 emissions by 300,000 tonnes per year compared to other conventional data centres. The technology lowers its annual average Power Usage Effectiveness to as low as 1.17, lower than many leading Chinese data centre companies. Located in Hebei province, in a naturally cool region with great access to wind power, the Zhangbei Data Centre is powered 100% by renewable energy including solar and wind and represents another good example of Alibaba's approach to energy-efficiency. This increases the data centre's energy-efficiency by more than 4% while reducing construction and maintenance costs. The technology reduces the temperature of its servers, which keeps its average Power Usage Effectiveness at only 1.25 and reduces the energy consumption typically used for cooling by 59%. An immersion liquid cooling technology enhances the energy-efficiency of Alibaba.

Despite the fact that the case study is related to public procurement, it is interesting since it tackles the issue of energy-efficiency in data centres. It also highlights one major point which is often mentioned in this very study, namely that "big cloud providers such as Google, Amazon, Alibaba, etc. are those which can afford to build their own data centres (e.g. hyperscale data centres) which they can offer to any other cloud service provider. They can thus have a direct influence and control over the energy consumption of data centres, as opposed to the majority of medium and small cloud service providers that need to purchase their cloud space.

Keywords: hyperscale data centres and energy-efficiency

Website:https://www.alibabacloud.com/de/press-room/alicloud-launches-new-energy-efficient-qiandao-lake-data-center

Successful implementation of the EU Code of Conduct on Data Centre Energy efficiency at Microsoft Data Centre, Ireland

To tackle the data centres' energy consumption, Microsoft has adopted a strategy to dramatically improve its data centres' energy-efficiency. The company signed the EU Code of Conduct on Data Centre Energy efficiency, which includes a commitment to comply with European standards and best practices. Microsoft opened a new data centre in Dublin, Ireland, that has a Power Use Effectiveness (PUE) of 1.25. The new Microsoft data centre in Ireland already consumes approximately 50 % less energy than a traditional data centre of similar size and level of activity. Besides the EU Code of Conduct on Data Centre Energy efficiency, this is possible due to a range of innovations, one being the use of outside air to cool the data centre at almost zero cost. This provides dramatic environmental savings as artificial cooling normally consumes approximately 38 % of the facility's electricity consumption and 18 million liters of water per month. In addition, the latest generation of servers and 24/7 monitoring will help to create further energy savings.

Keywords: data centres, EU Code of Conduct on Data Centre Energy efficiency

Website: https://www.ictfootprint.eu/en/microsoft-ireland

Green IT initiative of the Federal Government in Germany

The "Green IT Initiative" was launched in 2008 by the Council of IT Officers of the Federal Authorities of Germany. The aim was to reduce energy consumption by the federal administration in the IT sector by 40 % by the end of 2013 within 5 years. The implementation of sustainable IT procurement was carried out via the implementation of the Data Centre Evaluation Criteria ("Blue Angel") aiming at energy and resource efficiency. In 2016, with a real measured value of 353 gigawatt hours, the orientation value (390 gigawatt hours per year) was not only achieved, but significantly undercut.

Keywords: data centres, Blue Angel

Website: https://www.bmu.de/themen/wirtschaft-produkte-ressourcen-tourismus/produkte-und-konsum/produktbereiche/green-it/green-it-initiative-des-bundes/

EURECA - A toolkit for sustainable procurement for data centres – EU-wide initiative

The EURECA project focused on empowering public procurement teams to tackle the problem of data centre energy-efficiency and environmental soundness by developing common practices and procedures for Public Procurement of Innovation (PPI) and Pre-commercial Procurement (PCP) for Datacentres. The project focused on the public sector because of its enormous IT buying power (more than 55.6 billion in Europe in 2015). The tool includes a web-based platform that helps public procurers and data centre professionals to self-assess the energy-efficiency and profile of their data centres, and provides improvements and suggestions. This is based on the latest standards, best practices and frameworks as well as research findings and industry input. In particular, the tool maps the Data Centre Maturity Model (DCMM) to EU Code of Conduct on Data Centre Energy efficiency to provide tailored recommendations for data centres energy-efficiency. Also, the tool provides a market directory and procurement support with various templates and case studies.

Keywords: Public Procurement of Innovation, Data Centres

Website: https://dceureca.eu/

Tools (standards, eco-labels, criteria, legislation)

A number of tools have been identified related to energy-efficiency and cloud computing services and are summarized below.

These include the criteria for cloud computing which have been developed by the European Commission and two Ecolabels used for a long time for energy-efficient products (although Energy Start expired in 2018 and its use is no longer prescribed by the European Commission). Furthermore, the EU Energy-efficiency and Ecodesign Directive, a series of IT standards, and guidelines for sustainable / innovative / green public procurement.

- Criteria
    - EU Code of Conduct on Data Centre Energy efficiency (European Commission, 2018b; JRC, 2019)
    - The EU green public procurement criteria for data centres, server rooms and cloud services (European Commission, 2020b)
- Ecolabels
    - The Blue Angel (Der Blaue Engel)
    - The ENERGY STAR (expired on February 20th 2018)
- EU Directives
    - The EU Ecodesign Directive 2009/125/EC
    - The EU Directive on Energy-efficiency 2012/27/EU
    - The EU 2020 Climate & Energy Package „20-20-20“
    - The Commission Regulation (EU) 2019/424 of 15 March 2019 laying down eco-design requirements for servers and data storage products pursuant to Directive 2009/125/EC.
- Standards
    - ITU-T L.1301 – Minimum data set and communication inter-face requirements for data centre energy management (Approved in 2015-05-07): This Recommendation establishes minimum data set and communication interface requirements for data centre management in a responsible manner.

- ITU-T L.1300 – Best practices for green data centres (Ap-proved in 2014-06-29): This Recommendation describes best practices aimed at reducing the negative impact of data centres on the climate.
- ITU-T L.1302 – Assessment of energy-efficiency on infra-structure in the data centre and telecom centre (Approved in 2015-11-29): This Recommendation contains the assessment methodology of energy-efficiency on infrastructure in the data centre and telecom centre.
- ITU-T L.1303 – Functional requirements and framework of green data centre energy-saving management system (Approved in 2018-11-15): Recommendation ITU-T L.1303 describes functional requirements and framework of energy-saving management system for the green data centre. The functional requirements of energy-saving management include requirements for measuring energy consumption and environmental condition, collecting and storing data, reporting data, and conducting energy-saving. The energy-saving management system consists of following functional blocks: data collecting block; data storing block; data process and analysis block; external system interfacing block; user interface block; control block. Operational flow of the energy-saving management system is also provided.
- ITU-T - L.1320 - Energy-efficiency metrics and measurement for power and cooling equipment for telecommunications and data centres (Approved in 2014-03-22): This Recommendation contains the general definition of energy-efficiency metrics and measurement for power and cooling equipment for telecommunications and data centres.
- ITU-T - L.1321: Reference operational model and interface for improving the energy-efficiency of ICT network hosts.
- ITU-T - L.1325: Green ICT solutions for telecom network facilities.
- ITU-T R - L.1501: Best practices on how countries can utilize ICTs to adapt to the effects of climate change.
- ETSI GS OEU 008: Operational energy-efficiency for Users (OEU); Global KPI for Information and Communication Technology Nodes.
- ETSI ES 205 200: Access, Terminals, Transmission and Multiplexing (ATTM); Energy management; Global KPIs; Operational infrastructures.
- ETSI 103 199: Environmental Engineering (EE); Life Cycle Assessment (LCA) of ICT equipment, networks, and services; General methodology and common requirements.
- EN 50600-4-3 "Information technology — Data centre facilities and infrastructures.
- L.1305: Data centre infrastructure management system based on big data and artificial intelligence technology.
- EN 50600 series standards for Data centre Energy Management, design and operation.

- Guidelines
  - Energy Innovation Procurement. A guide for city authorities (ICLEI, 2018)
  - Buying green! A handbook on green public procurement (European Commission, 2016c)
  - Public Procurement as a Driver of Innovation in SMEs and Public Services (European Commission, 2014c)

  - Guidelines „Leitfaden - Energieeffizienz in Rechenzentren“ (Bitkom, 2015)

The level of application within the preparation of procurement tenders will be investigated through the analysis of the responses to the questionnaire that was sent to the relevant stakeholders (see the section below), as well as in Task 3.

Other EU mechanisms to incentivize sustainable public procurement

The main issue with GPP is that the concept works based on criteria. Criteria are specifications for the purchase of certain service or products which the subcontractor must satisfy. Therefore, the contractor assumes that a market response, namely with products and services satisfying the criteria, exist. This is not always the case in cloud computing: the analysis showed that whereas criteria for technical cloud components exist (e.g. the energy-efficiency of the data-centres building), for many cloud services this might not be yet the case.

Other forms of public procurement for sustainable, innovative products also exist, which do not necessarily rely on the use of criteria as GPP. These can be considered as an alternative to GPP to stimulate sustainable solutions where these do not yet exist. In the following paragraph, Public Procurement for Innovation and Pre-Commercial Procurement are presented.

Public Procurement of Innovation

Public Procurement of Innovative solutions (PPI) happens when the public sector uses its purchasing power to act as an early adopter of innovative solutions that are not yet available on a large scale commercial basis.

Public Procurement of Innovative solutions (PPI) facilitates wide diffusion of innovative solutions on the market. PPI provides a large enough demand to incentivise industry to invest in wide commercialisation to bring innovative solutions to the market with the quality and price needed for mass market deployment. This enables the public sector to modernize public services with better value for money solutions and provides growth opportunities for companies.

The EC has been supporting PPI in different ways:

- Since 2009, the Commission has co-financed via “FP7” the establishment of networks of public procurers to prepare the ground for launching PPIs. Since 2013, the Commission is also co-financing, via CIP and Horizon 2020, public procurers from different European countries to undertake together PPIs on topics of common interest. The European Structural and Investment Funds (ESIF) are financially supporting individual procurers to prepare and undertake PPIs and are able to support them also to participate in Horizon 2020 funded PPIs.
- The Horizon 2020 Access to Risk Finance work programme provides, in cooperation with EIB and EIF, loans for individual or groups of public procurers to start PPIs and helps companies that are involved in PPIs to gain easier access to loans, guarantees, counter-guarantees, hybrid, mezzanine and equity finance to grow their business in view of wider commercialisation of solutions (Innovfin for innovators).
- The ”European Assistance For Innovation Procurement Initiative” provides free of charge technical and legal assistance to individual procurers to implement PPIs.
- Guiding documents have been prepared by the European Commission on Sustainable Procurement for Innovation:
  - Public Procurement as a Driver of Innovation in SMEs and Public Services (European Commission, 2014c)

- Commission notice. Guidance on Innovation Procurement (European Commission, 2018d)

Pre- commercial procurement

Pre-Commercial Procurement (PCP) is an approach to public procurement of research and development (R&D) services that are outlined in the PCP communication and associated staff working document. It is an important tool to stimulate innovation as it enables the public sector to steer the development of new solutions directly towards its needs.

In PCP, public procurers buy R&D from several competing suppliers in parallel to compare alternative solution approaches and identify the best value for money solutions that the market can deliver to address their needs. R&D is split into phases (solution design, prototyping, original development and validation/testing of a limited set of first products) with the number of competing R&D providers being reduced after each R&D phase. In PCP, public procurers share the benefits and risks related to the IPRs resulting from the research and development (R&D) with suppliers at market price. Suppliers retain IPR ownership rights, while procurers keep some usage and licensing rights.

The EC has been supporting PPI in different ways:

- Since 2009, the Commission has co-financed the establishment of networks of public procurers to prepare the ground for launching PCPs via FP7. Since 2012, the Commission is also co-financing public procurers from different European countries to undertake together PCPs on topics of common interest via FP7 and Horizon 2020
- The European Structural and Investment Funds (ESIF) are financially supporting individual procurers to prepare and undertake PCPs.
- The European Commission has recently launched an open market consultation for its upcoming European Blockchain Pre-Commercial Procurement (PCP). The PCP is looking for novel Blockchain solutions for the European Blockchain Service Infrastructure.

Highlights from the study

The analysis of current practices and best practices most relevant findings that can be highlighted from the study can be summarized as follow.

- A variety of policy options, instruments, and best practices for energy-efficient cloud computing can be identified throughout Europe.
- At the EU level, the European Commission prepared an EU Code of Conduct on Data Centre Energy efficiency, which sets criteria for energy-efficient data centres among others. The Code was adopted by about 130 EU organizations. On this basis, the document “EU green public procurement criteria for data centres, server rooms and cloud services“ (European Commission, 2020b), has also being adopted by the European Commission so far.
- Legislative instruments are available at the EU level to leverage on the need for energy-efficient cloud computing, such as the Energy-Efficiency Directive; but the topic of energy-efficient cloud computing is not directly addressed in the legislation yet. (European Commission, 2012a)
- At the national level, no Member State has yet included criteria on the energy-efficiency of cloud services and data centres in the screened National Action Plans, with Norway being the only country mentioning the importance of green data centres. No criteria have been developed at the EU and the national level

concerning the public procurement of energy-efficient cloud computing models such as the Saas and the Paas deployment models, or for software and networks.

- Some EU Member States are developing their digital roadmaps (e.g. Austria, United Kingdom, Italy). But again, the environmental aspects are not taken into account in the development of the roadmaps which focus rather on aspects like "paving the way towards a digital future" and focus on accessibility and coverage of internet, data security, transmission, and building of the infrastructure.
- Some research projects dealing with the energy-efficiency of cloud computing, and GPP, were also identified, and mostly funded under the EU Horizon 2020 Programme. Interestingly, some research projects deal with the energy-efficiency of cloud services (hence going beyond data centres). But the findings and results of most of these projects were not commercialized after the end of the project.
- Energy-efficient cloud computing services are in general not a mainstream topic in EU platforms for public procurement. Other forms of public procurement such as the Public Procurement for Innovation and the Pre-Commercial Procurement might also fit the purpose of delivering energy-efficient cloud services in public procurement.
- Guidelines and other funding EU-tools on GPP and other approaches to sustainable procurement such as PPI and PCP are available.

The best practices for energy-efficient data centres and server rooms include a variety of approaches, in the public as well as in private procurement. The most common approaches include:

- More efficient cooling systems
- Heat reuse, e.g. for district heating
- Virtualisation of software, optimal use of the capacity of the servers
- Energy-efficient genomics
- Eco-design for the efficiency of the infrastructures
- Employment of renewable energy to supply data centres
- Construction of data centres in geographically cold areas

No best practices have been found on the energy-efficiency of cloud services in a broader sense, for instance focusing on the different cloud services deployment models.

Gap analysis

The following gaps can be identified. Based on the GAPS and the mapping exercise of best practices, recommendations can be formulated.

- Inclusion of European Commission GPP Criteria (European Commission, 2020b) for energy-efficient cloud computing in NAPs and national Criteria for Cloud Computing

The screening exercise from the EU Member State National Action Plans for Green Public Procurement highlighted that the topic "energy-efficiency of cloud services and data centres" has not yet been included in any of the screened National Action Plans and set of criteria. Most of the considered NAPs have included the procurement of energy-efficient IT equipment, and apply criteria as the Blue Angel as standards for its procurement.

The EU elaborated EU green public procurement criteria for data centres, server rooms and cloud services, which have also not yet being implemented in the National Action Plans for

GPP, mainly likely due to the fact that the document is coming now to its finalized version. Also, the inclusion of these criteria in procurement tender documents is on a voluntary base.

Hence, there is a clear gap in Member States with the inclusion of EU green public procurement criteria for data centres, server rooms and cloud services for energy-efficient cloud computing, and especially regarding data centres and server rooms, in National Action Plans.

- Lack of criteria for energy-efficient cloud computing other than for data centres and server rooms (e.g. for network and applications, such as coding)

The analysis highlighted that there is quite substantial work already done for data centres and server rooms, and that most of the applied work on energy-efficient cloud computing services has focused on data centres and server rooms. This is true for the work conducted by the EU, so that the applicability of the criteria developed within the EU green public procurement criteria for data centres, server rooms and cloud services can be done for the physical system and/or components, and for data centre services which are supplied by the physical system and/or components.

The EU Code of Conduct on Data Centre Energy efficiency is another prominent example. The analysis also highlighted that the principle of energy-efficiency has also been applied in the praxis in different green data centres across Europe.

Nevertheless, the analysis highlighted that up-to-date, no criteria have been developed for energy-efficient cloud computing other than for data centres and server rooms.

- Lack of inclusion of energy-efficiency aspects in national Digital Roadmaps.

Some EU Member States are developing their digital roadmaps (e.g. Austria, United Kingdom, Slovakia, Italy). But again, the environmental aspects are not taken into account in the development of the roadmaps which focus rather on aspects like “paving the way towards a digital future” and focus on accessibility and coverage of internet, data security, transmission, and building of the infrastructure, especially in the light of the digital transformation which will happen in the next few years. National digital plans shall therefore include energy-efficiency aspects for cloud services in the future, in order to bring also this important aspect in the political agenda.

- Public procurement of energy-efficient cloud computing services is not a mainstream topic in EU platforms for public procurement.

Many of the analysed GPP platforms do not tackle the topic of the energy-efficiency of cloud computing yet. More awareness raising and education on the topic should be promoted on these platforms. It would be important to include the topic also in procurement platforms promoting innovation, and especially in the IT sector.

- Lack of awareness for energy-efficient cloud services in GPP community

There seems to be a knowledge gap in GPP groups (GPP competence centres and GPP Advisory Groups) when it comes to energy-efficient cloud computing. Also, people in these groups are mostly not those in charge of procuring cloud based services.

The topic of energy-efficiency in cloud computing should be made more prominent in the GPP discourse and awareness of the topic should be raised, e.g. by organising seminars or workshops.

This will in turn speed up the dissemination and uptake of good practices and also speed up innovation.

- Energy-efficient solutions for cloud computing software, application and deployment models as SaaS and Paas have been developed only in research.

The screening exercise evidenced that at the moment, some solutions for energy-efficient cloud computing software and deployment services (IAAS, SAAS, PAAS) have been developed in research, especially in international cooperation's through EU Horizon 2020 projects. Nevertheless, the results of these projects haven´t been yet exploited or brought to the market.

- Lack of inclusion of the topic "energy- efficient cloud computing" in the legislative framework

The review of the legislative framework highlighted that the legislative framework is currently not tackling the issue of energy-efficiency of cloud services. Legal provisions, regulating aspects such as the maximum allowed CPE of data centres, shall be introduced. Also taxes and levies (in forms of both bonus and malus incentives) might be introduced to promote the implementation of more energy-efficient data centres.

- Potential of SMEs to deliver energy-efficient cloud services

The analysis performed in this study revealed that there is a trend to move from private to public cloud, and that (at least as a rule of thumb), bigger data centres and server rooms can achieve higher energy-efficiency and energy savings. Still the required resources to implement and run bigger data centres and server rooms, i.e. hyper scale data centres, are substantial. Hence, just big IT companies can usually afford this business. Notably, these companies often reported that gains in energy-efficiency are an objective, since they allow substantial economic savings. SMEs don´t seem to have a prominent role in delivering energy-efficient cloud services. The inclusion of SMEs should be therefore fostered.

- The role of energy-efficiency might be prevaricated by other policy priorities

Clearly, the role of cloud computing across sectors is increasing and will continue to gain importance. An increasing amount of services are relying on the cloud to store, share, transmit and analyse data. This raises questions about data security, ownership and rights, security, transparency, etc. As evidenced also by the analysis of the best practices, current cloud policies are missing the link to energy-efficiency, which is considered "less urgent". The inclusion of this link should be ensured in further EU policy development.

GPP and its potential to contribute to energy-efficient cloud computing

Public procurement contributes to a high share of the GDP, and the demand for digital services in the public procurement is rapidly growing. Especially for data centres and server rooms there is already extensive information on how to improve their energy-efficiency; but the number of data centres which have adopted energy-efficient measures (e.g. EU Code of Conduct on Data Centre Energy efficiency) (European Commission, 2018b; JRC, 2019) is still relatively low. Also, no EU country has included criteria for energy-efficient cloud computing in their NAPs. This all indicates that there is still potential that can be exploited for promoting an energy-efficiency cloud infrastructure in the public procurement.

The growing demand for digital services in the public sector should be used as a momentum to promote the use of GPP criteria, and especially the recently adopted EU green public procurement criteria for data centres, server rooms and cloud services (European Commission, 2020b). Involving the European public procurement could have a huge impact in delivering an EU-wide energy-efficient cloud, and the demand for energy-efficient cloud services will serve as a stimulus for the market to deliver more sustainable solutions.

In order to increase the uptake of the EU green public procurement criteria for data centres, server rooms and cloud services, their transposition into the NAPs in the several countries shall be promoted. This will constitute an important guidance document for the preparation of procurement tenders for energy-efficient cloud services. National and regional GPP competence centres and national focal points for sustainable procurement should be involved in the transposition process. It is suggested that the criteria “Server Energy-efficiency”, “Power Utilization Effectiveness”, “Renewable Energy Factor”, “Use of Refrigerants and their Global Warming Potential and “Cooling System best practices” should be priority criteria for transposition into the NAPs.

This will initiate the mechanism of integration of energy-efficiency principles in the development of cloud computing service, but it is unlikely that the EU green public procurement criteria for data centres, server rooms and cloud services and their transposition into the NAPs alone will be sufficient to substantially increase the energy efficiency of cloud computing in public procurement. At first, GPP criteria are a voluntary instrument. Due to the high costs that the procurement of cloud infrastructure has, and considering that at the moment there is no legislative requirement for the energy efficiency performance of cloud services, (hence making it harder to justify higher costs to satisfy sustainability criteria), the focus of the criteria will likely remain on technical quality and financial aspects. Also, the implementation of many projects and tendering process happens in the practice at the regional and local level rather than at the national level. Therefore, the practical uptake of the GPP criteria should be further stimulated at the regional and local level, and in particular through the existing EU financing mechanisms, such as the European Structural Investment Fund or the European Regional Development Fund. These already focus, among others, on delivering digital agendas and cloud computing services. Especially the inclusion of the EU green public procurement criteria for data centres, server rooms and cloud services in the tendering process for financing projects and activities related to cloud computing shall be promoted. Some of the criteria might be even made mandatory for tendering- and awarding process. Particularly interesting could be the “renewable energy factor” criteria for the development of a carbon-free cloud, or establishing minimum thresholds for the PUE.

12. TASK 6 - POLICY ANALYSIS

Goals

The understanding of the main objectives of Task 6 is as follows:

- To provide an overview of different approaches to fostering private, corporate and Green Public Procurement (GPP) of cloud services and connected technologies;
- To identify best practices enabling sustainable and energy-efficient cloud services;
- To provide recommendations to assist policymakers and practitioners at the European and national level in defining or improving policy instruments with a view to creating a low carbon footprint cloud service market;
- To facilitate stakeholder consultation and feedback to ensure the acceptance and practicability of the proposed policy instruments, and to adapt the policy mix so as to foster its implementation and raise its effectiveness;
- To include the feedback results in the final version of the policy recommendations.

Task 6 is based on the work done in the previous Tasks 3 and 6: In Task 3 expert interviews and a review from a policy perspective including successful approaches from similar topics (e.g. green ICT), limitations, and gaps for energy-efficient cloud computing were carried out. Task 5 provides an analysis of EU schemes and National Action Plans for Green Public Procurement (GPP) for cloud computing services and formulates recommendations for the inclusion of cloud computing-related GPP criteria.

Based on the work done in these tasks, all conclusions came together in Task 6, where recommendations for policy measures were formulated and discussed during a validation workshop with more than 40 participants from the IT business sector and policymaking institutions, that took place on December 4th, 2019 in Brussels. During the workshop, recommendations were ranked by the participants, hence the outcome of the workshop is a series of validated and prioritised policy recommendations to address energy-efficient cloud computing in the EU.

Based on the outcomes of the stakeholder feedback and input, the final version of recommendations can be found below.

The recommendations include the following types of policy instruments:

- information and raising awareness measures
- transparency enhancing measures
- guidelines for energy-efficient cloud computing
- certification schemes
- labels
- incentives
- standards
- adaptations of the legislative framework
- options to stimulate energy-efficient cloud computing in GPP
- policy awareness raising

The 6 top-ranked instruments (as rated during the workshop) are listed below:

- Including the term carbon footprint/neutrality in the cloud computing and energy-efficiency discourse
- Incentives to support energy-efficiency in data centres
- Cooperation on the development of standards
- Cloud footprint or virtual smart meter
- Guideline for energy-efficient cloud computing
- Put energy-efficiency for cloud computing on national digital agendas

In general, one instrument alone will not be sufficient to sufficiently enhance energy-efficiency in cloud computing. Additionally, some recommendations and policy instruments from the RTD work package (Task 4) will be needed either for complementary actions or as a basis for the single recommendations of Task 6; e.g. better metrics might provide important knowledge for the development of a cloud footprint or a virtual smart meter (see recommendation No 3).

The recommendations can be used either individually or combined - e.g. recommendations No 1 and No 2 (information campaign(s) on the impact of cloud computing on energy demand for different target groups) can be used as an instrument to accompany other recommendations.

Outside the scope of the study is an impact assessment of single policy instruments or policy mixes.

What was not included in the study either was an analysis of policy instruments that might incentivise energy use and undermine energy-efficiency in cloud computing.

All policy instruments listed above need a sound policy framework such as the European Green Deal (European Commission, 2019e), the European strategy for data (European Commission, 2020a) and the Digital Strategy “Shaping Europe’s Digital Future” (European Commission, 2020c). The recommended policy instruments and their further development need to be embedded in these strategies.

In the following paragraphs

- the full list of recommendations, including the rationale behind their formulation, is presented;
- the prioritisation of the recommendations performed by the stakeholders is introduced, and
- an indication of feasibility of the implementation of the recommendations is provided.

Recommendations

Information / awareness raising measures

Recommendation		Main target groups
1	Information campaign(s) on the impact of cloud computing on energy demand	Broad public
Goal		
Create/improve/accelerate general awareness on the extent of energy demand of cloud computing (digital environmental impact) in the public as well as in organisations, institutions and the research community. Present possible measures: • Discuss rebound effects that overcompensate dematerialisation directly induced by technical progress • Stimulate public dialogue on "responsible digital behaviour" and contributions of cloud computing to the SDGs • Different rollouts (with a focus on different topics) • In combination with and or accompanying other instruments • Impact of video streaming		
Short description		
Despite its growth, the energy demand of cloud computing (and its resulting CO_2 emissions) is not discussed in the public as much as e.g. mobility, food production or housing and their impact on sustainable development, SDGs, the Paris agreement and the implementation of the European Green Deal (European Commission, 2019e). The general public is not aware of the energy demand of applications and the material footprint of digital technology. The cloud makes the physical reality of uses all the more imperceptible (invisibility of the infrastructure) and leads to an underestimation of the direct environmental impacts (SHIFT). This has impacts on behaviour, as responsibility (ownership) needs information and transparency for informed decision-making on the consumer side, and/or to support the implementation of policy instruments. Additionally, it needs to be communicated why e.g. labels, apps etc. need to be developed and applied. But: no "individualisation of responsibility". For this general awareness campaign, estimates of energy demand can be presented, showing the energy related effect of selected applications (as e.g.in the SHIFT project) by way of example. The fact that estimations showing the energy related effect are used should be pointed out in the campaign. Once more detailed results are available, the estimations should be substituted by more accurate data derived from scientific projects to assure better transparency). A well designed information campaign concerning energy-efficient cloud computing with different roll-outs should be closely coordinated with, or even incorporated into, information activities of the European Green Deal (European Commission, 2019e), the European data strategy (European Commission, 2020a) and the Digital Strategy "Shaping Europe's Digital Future" (European Commission, 2020c).		

Table 14 - Recommendation 1 - Information campaign(s) on the impact of cloud computing on energy demand

Recommendation		Main target groups
2	Information campaign on energy-efficient cloud computing for providers & companies & universities and politicians	Companies, science, politicians
Goal		
An information campaign targeted at institutions and companies that: • should be more informed on the topic • develop tools • participate in training to support the uptake of energy-efficient processes • set up an appropriated framework that enables and support energy-efficient cloud computing		
Short description		
Innovation itself does not necessarily lead to sustainability or energy-efficiency. This is also true for cloud computing, where it should be avoided that energy-efficiency gains in cloud computing are neutralised or even impeded by a growing demand for energy. Companies should become more aware of their externalised digital ecological impact; science should be more aware that there is a demand for research (also applied research in cooperation with companies) and training. Politicians should be alerted that there is a need to act and to create a framework to enhance energy-efficiency and reduce rebound effects. Already existing initiatives should be better disseminated (e.g. EU Code of Conduct on Data Centre Energy efficiency, Kubernetes). Cooperation for dissemination activities with already existing associations, e.g. the cloud native computing foundation. An information campaign concerning energy-efficient cloud computing for different target groups with their respective rollouts should be closely coordinated with, or even incorporated into, information activities of the European Green Deal (European Commission, 2019e) and the European data strategy (European Commission, 2020a).		

Table 15 – Recommendation 2 Information campaign on energy-efficient cloud computing for providers & companies & universities and politicians

Transparency

Recommendation		Main target groups
3	Cloud footprint or virtual smart meter	Broad public
Goal		
• Development and implementation of instruments for users to illustrate the energy demand of diverse applications • Measure the energy impact of using cloud services • Relate to daily life experiences		
Short description		
A cloud footprint can be illustrated and symbolised via apps or add-ons on websites. To foster transparency and to enhance the understanding of the energy demand of cloud services, the impact of e.g. streaming, should be illustrated by comparing with activities well known from daily life (e.g. heating, driving a car, eating meat,….). Impacts can also compare diverse virtual activities (e.g. writing an e-mail and streaming – see SHIFT project). Hindering factors can be privacy issues, technical difficulties, questions about accuracy, decrease of the novelty effect over time (fall-back effect) and the fact that in order to produce an effect engagement is necessary. (Pereira et al., 2012; Wilhite & Ling, 1995). But: can be combined with a bonus for user behaviour change. How transparency is ensured should be the responsibility of the companies and a topic featuring in a stakeholder dialogue. As such a transparency initiative needs creativity as well as the development of possible tools, a two step-approach is suggested: In the first stage, a cloud footprint can be developed for 3-4 examples of cloud service usage (video on demand or storage). The cloud footprint at this stage shows rather relations than exact numbers. At the next stage, a more sophisticated transparency tool could be developed.		

Table 16 - Recommendation 3 Cloud footprint or virtual smart meter

Recommendation		Main target groups
4	Digital Environmental Repository (DER)	Companies, GPP, public

Goal

- The aim of the development of a Digital Environment Repository (DER) is to describe, in the form of characteristic quantities and ratios, the environmental footprint of the digital ecosystem in terms of equipment and uses (recommendation of Lean ICT Report, SHIFT).

Short description

The objective is to present orders of magnitude considered fundamental to making the environmental impact of digital technologies concrete. The environmental footprint of the digital ecosystem is characterised by a quantification of:

- Energy or electricity consumption (depending on the relevance of one or the other to the case in question);
- Greenhouse Gas (GHG) emissions;
- Consumption of critical metallic raw materials;
- The volume of metallic ore moved for the extraction of raw materials.

The elements chosen to represent the digital ecosystem are of two types:

- Equipment (or groups of equipment);
- Digital actions (typical uses of equipment).

The items of digital equipment selected in the DER are the following:

- Smartphone; laptop computer; connected TV;
- data centre;
- Internet access routers ("boxes”).

The quantification of digital actions simply aims to give examples of the energy and material content of certain so-called "virtual actions" (Lean ICT report, SHIFT), the starting point for a major project that would lead to a standardised and universal database on the net environmental impact of digital technology.

The DER can be updated to include cloud computing technology and applications. A model that describes the real energy consumption per cloud resource (virtual machine / vCPU) as a function of the already transparent usage of CPU, network RAM etc. would help to assess energy consumption on cloud service level.

Table 17 - Recommendation 4 Digital Environmental Repository (DER)

Guideline

Recommendation		Main target groups
5	Guideline for energy-efficient cloud computing	Providers, SMEs with own data centres
Goal		
• Elaboration and dissemination of a guideline for energy-efficient cloud computing as an easy to adapt and flexible tool (based on the latest developments in energy-efficiency for cloud computing) Measure the energy impact of using cloud services.		
Short description		
The guideline is targeted at cloud providers and regularly updated in the light of the latest scientific evidence, in cooperation with the relevant companies (e.g. cloud providers and SMEs with own data centres), in order to be as state of the art as possible. It points out the main entry points for enhanced energy-efficiency, gives support for planning, operation and modernising and supports cloud providers with recommendations for typical cloud related processes. It should support small and medium-sized companies with a low-threshold approach, in contrast to the recommendation below (Code of Conduct for cloud computing that focuses on bigger providers). As a first step, output from recent scientific reports (e.g. Masanet et al., 2020) and elements of the existing EU Code of Conduct on Data Centre Energy efficiency, should be selected and adapted during a stakeholder dialogue to create a practical set of guidelines. After a test run in a few SMEs, the guidelines can be further refined and publicised. To ensure that the guidelines are state of the art, they have to be updated on a regular basis.		

Table 18 - Recommendation 5 Guideline for energy-efficient cloud computing

"Soft"- certification scheme

Recommendation	**Main target groups**
6 Code of Conduct for cloud computing	Providers of CC
Goal	
• Development of a flexible tool as a reference framework for energy-efficient cloud computing.	
Short description	
Based on the already existing EU Code of Conduct on Data Centre Energy efficiency, a EU Code of Conduct for energy-efficient cloud computing should be developed according to a step-by-step process in close cooperation with stakeholders and science. The current EU Code of Conduct on Data Centre Energy efficiency is an independent scheme in the EU to certify that a data centre has adopted best practices in energy-efficiency. It is a voluntary initiative managed by the European Commission's Joint Research Centre, with the aim to reduce energy consumption through ambitious energy-efficiency measures. The aim is to inform and stimulate operators and owners to reduce energy consumption in a cost-effective manner by improving the understanding of energy demand within the data centre (or within the cloud if further developed), raising awareness, and recommending energy-efficient best practices and targets. All participants have the obligation to continuously monitor energy consumption and adopt energy management in order to look for continuous improvement in energy-efficiency. One of the key objectives of the Code of Conduct is that each participant benchmarks their efficiency over time, using the Code of Conduct metric (or available alternatives) to have evidence of continuous improvements in efficiency. First step: adaptation of the existing EU Code of Conduct on Data Centre Energy efficiency in cooperation with stakeholders and initiatives in the field of energy-efficient cloud computing, to guarantee a state-of-the-art approach and to make the EU Code of Conduct on Data Centre Energy efficiency, more flexible and adaptable while also increasing its acceptance. The EU Code of Conduct on Data Centre Energy efficiency prizes will continue to be awarded also in the future. In the future, the EU Code of Conduct on Data Centre Energy efficiency for data centres should be developed further so that a Code of Conduct for energy-efficient cloud computing is available, in cooperation with stakeholders and the scientific community.	

Table 19 - Recommendation 6 Code of Conduct for cloud computing

Labels

Recommendation		**Main target groups**
7	Label for cloud computing – low threshold provider endorsement label	Providers of CC and GPP
Goal		
• Elaboration and implementation of a low-threshold label to promote energy-efficiency in cloud computing for a target group of cloud service providers that is as broad as possible.		
Short description		
A low threshold label for energy-efficient cloud computing includes the recommendations for energy-efficiency targets of the EU Code of Conduct on Data Centre Energy efficiency and the high threshold label (see next recommendation). The criteria for this label are continually updated by the inclusion of stakeholders from companies, GPP experts, science and CSOs. Even with a low threshold label, one needs to ensure that it is not too easy to meet the requirements, as this could have the inverse effect of hindering a market transformation. The label needs third party verification (lasting 2 years). The label is promoted EU-wide and becomes a requirement for GPP.		

Table 20 - Recommendation 7 Label for cloud computing – low threshold provider endorsement label

Recommendation		Main target groups
8	Label for cloud computing – high threshold provider endorsement label	Providers of CC and GPP
Goal		
• Elaboration and implementation of a high-threshold label to promote and support energy-efficiency as best practice and framework for GPP.		
Short description		
Influenced by the German 'Blaue Engel' (Blue Angel) label for data centres, the high threshold label sets strict requirements and makes it possible to identify any optimisation potential. In addition to the PUE, other criteria are developed to define energy-efficiency in cloud related processes. When new components are acquired, they are subject to significantly tougher requirements in comparison to the existing technology. The aim of the Blue Angel is to ensure the efficient operation of existing technology. Investments in new technology should only be made when necessary for specialist or technical reasons. Another basis for such a label can be the existing EU Code of Conduct on Data Centre Energy efficiency. The criteria for this label are continually updated by the inclusion of stakeholders from companies, GPP experts, science and CSOs. • The label can be designed as endorsement label, which demonstrates that certain criteria are met. • The label needs third party verification (lasting 2 years). • The label is promoted EU-wide and becomes a requirement for GPP.		

Table 21 - Recommendation 8 Label for cloud computing – high threshold provider endorsement label

Recommendation		**Main target groups**
9	Label “ECO-Cloud”: a service label	Broad public, GPP
Goal		
• Similar to “green electricity certification“: users pay a little more (on a voluntary basis) for a certified Eco-Cloud service.		
Short description		
It does not mean that the user gets a 100% energy-efficient cloud computing service if that is not possible at the moment, but the label supports the demand for and the creation of green/energy-efficient cloud computing. The problem is to ensure that the available amount of green/energy-efficient cloud computing is not sold twice. Criteria for the establishment of an Eco-cloud are transparency and control mechanisms (otherwise danger of green-washing). Benefits can be that the needed transparency gives orientation for end users. As a first step, the use of 100% renewable energy can be shown on a service label: “Green electricity for cloud computing”. As a next step, a service label for energy-efficient cloud computing can be developed.		

Table 22 - Recommendation 9 Label “ECO-Cloud”: a service label

Standards

Recommendation		Main target groups
10	Cooperation on the development of standards	Administration, politics, providers
Goal		
• Standards help to ensure uniform technical criteria and processes for energy-efficiency in companies. • Standards for cloud computing are developed using existing institutions, processes and networks for standardisation.		
Short description		
In December 2012, the European Commission (EC) and the European Telecommunications Standards Institute (ETSI) launched the Cloud Standardisation Coordination (CSC) initiative. The aim of the Standards Coordination initiative led by ETSI was to create a detailed map of the standards required to support a series of policy objectives defined by the European Commission, in particular in critical areas such as security, interoperability, data portability and reversibility. This cooperation should be continued and expanded for cloud computing. A 2020 ITU-T recommendation concerning GHG emissions trajectories for the ICT sector compatible with the UNFCCC Paris Agreement provides detailed trajectories of GHG emissions for the global ICT sector and sub-sectors, which are quantified for the year 2015 and estimated for 2020, 2025 and 2030. In addition, it defines a long-term ambition for 2050. On the European level the main documents are the ‘EN 50600 series standards for Data centre Energy Management, design and operation’ (CENELEC-CLC/TR, 2019). It includes e.g. a classification system, based on the key criteria "availability", "security" and "energy-efficiency" for the planned lifetime of the data centre and the provision of effective facilities and infrastructure. Additionally, it introduces the concepts of Key Performance Indicators (KPIs) for resource management of data centre facilities and infrastructures. It also includes a compilation of recommended practices for improving the energy management (i.e. reduction of energy consumption and/or increases in energy-efficiency) of data centres (CENELEC-CLC/TR, 2019). As stated in the European Green Deal (European Commission, 2019e), the Commission will continue to work on new standards for sustainable growth and use its economic weight to shape international standards that are in line with EU environmental and climate ambitions. It will strive to facilitate trade in environmental goods and services, in bilateral and multilateral forums, and in supporting open and attractive EU and global markets for sustainable products. In addition, to legally binding as well as non-binding formal standards, informal standards (e.g. intra-company standards) exist mainly in bigger companies. Semi-standards or informal standards might be developed more quickly but they need to be evaluated and not used as a marketing tool only. Nevertheless, some ideas and impulses coming from informal standards might be worth considering so that informal standards become formal standards after all. As a first step, standardisation initiatives might be needed where clear differences or uncertainties exist (e.g. standardised measurement of PUE). A standardised approach can support especially European small- and medium-sized companies in measuring progress in energy-efficiency. Recommendations for standards from recent research publications (e.g. Masanet et al., 2020) should be considered. As a next step, elements of the EU Code of Conduct on Data Centre Energy efficiency for data centres (which is to be developed further so that a Code of Conduct for energy-efficient cloud computing will be available in the future) might be selected for standardisation, or parts of the guideline for energy-efficient cloud computing (recommendation No 5) might be used for SMEs.		

Table 23 - Recommendation 10 Cooperation on the development of standards

Incentives

<table>
<tr><th colspan="2">Recommendation</th><th>Main target groups</th></tr>
<tr><td>11</td><td>Incentives to support energy-efficiency in data centres</td><td>Companies, providers</td></tr>
<tr><th colspan="3">Goal</th></tr>
<tr><td colspan="3">• To foster the take-up of maximum standards in data centres.</td></tr>
<tr><th colspan="3">Short description</th></tr>
<tr><td colspan="3">Incentives (e.g. tax breaks or subsidies) if data centres fulfil a certain set of ambitious maximum criteria for KPI (e.g. use of renewable energy only, reuse of waste heat, PUE value) to optimise the energy use. Incentives might not necessarily be monetary, but take the form of land use concessions (e.g. for the construction and operation of data centres).

Incentives have to be integrated in existing funding schemes to support existing energy saving efforts of Member States and to avoid unintended parallel funding.

The stakeholders have ranked this recommendation on incentives as the second most important policy instrument, which is understandable, as it is an instrument that promises financial benefits.

As stated in the European Green Deal (European Commission, 2019e), taxes play a direct role as they send the right price signals and provide the right incentives for sustainable behaviour among producers, users and consumers. While a general CO2 tax can be seen as the most important and efficient market based policy instrument when it comes to dealing with negative externalities and improving energy-efficiency, incentives are an alternative to a missing CO2 tax.

Due to the fact that cloud computing is characterised as being very dynamic, fast-paced and innovative, the question of appropriate criteria for granting incentives arises. Criteria development and definition need time and therefore, criteria might not be as efficient as a driver in such a highly innovative sector as a CO2 tax.

Additionally, it might very difficult to prove how much energy-efficiency is due to an incentive only and whether it might not have occurred anyway especially when taken into consideration that, when interviewed for the study, cloud providers stated that energy-efficiency is in their very own interest given their high-energy demand. It must be ensured that “the aid changes the behaviour of the undertaking(s) concerned in such a way that it engages in additional activity which it would not carry out without the aid”. (European Commission, 2014d)

Incentives can be monetary (subsidies, tax breaks, loans) or include e.g. services such as providing infrastructure, utility rebates (Masanet et al., 2020) or cheaper prices for building area. Funding schemes already exist for the use of renewable energy and the reuse of waste heat in most Member States and they should not be duplicated. Existing regulations of the European Union, e.g. the Guidelines on state aid for environmental protection and energy 2014-2020 (European Commission, 2014d) must be considered.</td></tr>
</table>

Table 24 - Recommendation 11 Incentives to support energy-efficiency in data centres

Legislative framework

Recommendation		Main target groups
12	Ecodesign Directive: update of regulations for the "immaterial" component of data centres and cloud services	Companies, providers
Goal		
• Assurance that minimum standards for the immaterial (= service) component of cloud computing are met.		
Short description		
Up to now, the Ecodesign Directive and the Commission Regulation have regulated products but not services (like cloud services). Regulatory efforts - especially of the Commission Regulation on servers and data storage products - should be evaluated and updated regularly. Member States might need support to implement control mechanisms. The focus of regulations or directives is on removing the least environmentally friendly technologies, but they are not innovation drivers. Additionally, 4-5 years of negotiations are needed to formulate the text of a directive, existing directives are updated regularly. As a first step, a statement done by legal experts should be obtained about the possibility of amending a directive or a regulation so that it also includes services.		

Table 25 - Recommendation 12 Ecodesign Directive: update of regulations for the "immaterial" component of data centres and cloud services

<table>
<tr><th colspan="2">Recommendation</th><th>Main target groups</th></tr>
<tr><td>13</td><td>Establishment of minimum criteria for energy-efficiency of newly built data centres in the EU legislation</td><td>Companies, providers</td></tr>
<tr><th colspan="3">Goal</th></tr>
<tr><td colspan="3">Criteria for minimum requirement regarding energy-efficiency of data centres and server rooms in the legislative framework.</td></tr>
<tr><th colspan="3">Short description</th></tr>
<tr><td colspan="3">Criteria for minimum requirements regarding the energy-efficiency of newly built data centres and server rooms shall be included in the legislation.

The requirements might be included in the amended energy-efficiency directive (2018/ 2002) or in the Commission Regulation 2019/424- laying down ecodesign requirements for servers and data storage products- and shall include provisions on minimum energy-efficiency requirements for the PUE of newly built data centres and server rooms. The minimum PUE value for new data centres should be also progressively adapted along the years (i.e. 1.4 until 2025; 1.2 until 2030, etc.).</td></tr>
</table>

Table 26 - Recommendation 13 Establishment of minimum criteria for energy-efficiency of newly built data centres in the EU legislation

GPP related measures

Recommendation		Main target groups
14	Include GPP criteria for green data centres in the National Action Plans (NAPs)	GPP national groups
Goal		
• EU GPP criteria on cloud computing are included in national plans for GPP. • Improve the inclusion of energy-efficient cloud computing in the political agenda.		
Short description		
The gap analysis included in this study, highlights that despite substantial work being carried out by the EC on green data centres and server rooms in public procurement (namely the Code of Conduct for data centres and server rooms and the GPP Criteria for data centres and server rooms), implementation in the national action plans for GPP has not started yet, and none of the NAPs includes the two EC documents as yet. Therefore, Member States should be encouraged to implement the EC documents on green public procurement and data centres in their NAPs. This will in turn stimulate the uptake of energy-efficient cloud computing in GPP processes.		

Table 27 - Recommendation 14 Include GPP criteria for green data centres in the National Action Plans (NAPs)

Recommendation		Main target groups
15	Promote knowledge sharing among the GPP groups	GPP
Goal		
• Increase awareness among the GPP groups.		
Short description		
There seems to be a knowledge gap in GPP groups (GPP competence centres, GPP procurement platforms, Advisory Groups) when it comes to energy-efficient cloud computing. In addition, people in these groups are mostly not those in charge of procuring cloud-based services. The topic of energy-efficiency in cloud computing should be made more prominent in the GPP discourse and awareness of the topic should be raised, e.g. by organising seminars or workshops. This will in turn speed up the dissemination and uptake of good practices and speed up innovation.		

Table 28 - Recommendation 15 Promote knowledge sharing among the GPP groups

Recommendation		Main target groups
16	Stimulate the inclusion of the GPP criteria for Green Data Centres in national criteria for GPP	GPP
Goal		
• EU GPP criteria on cloud computing are included in national plans for GPP. • Improve the inclusion of energy-efficient cloud computing in the political agenda.		
Short description		
The gap analysis included in this study highlights that no Member State has adopted GPP criteria for green data centres, or for cloud computing in general. The European Commission document on GPP criteria for data centres and server rooms is finalised. The proposed criteria should be included in national criteria for GPP. Therefore, Member States should be encouraged to implement the EC documents on green public procurement and data centres in their NAPs. In addition, regional funds are available for regions, which develop “smart specialisation” strategies. The European Commission GPP criteria should be included as a requirement in the tendering process for obtaining these funds. This will in turn stimulate the uptake of energy-efficient cloud computing in GPP processes.		

Table 29 - Recommendation 16 Stimulate the inclusion of the GPP criteria for Green Data Centres in national criteria for GPP

Recommendation		Main target groups
17	Consider Public Procurement for Innovation (PPI)	GPP

Goal

- To promote energy-efficient innovation in public procurement of cloud services.
- To foster the market offering of energy-efficient cloud services.

Short description

The analysis included in this study shows that there is currently no market for energy-efficient PAAS or SAAS deployment models, nor are energy-efficiency criteria available. On the other hand, energy-efficient cloud applications usually need to be developed on an ad-hoc basis.

This poses the question if GPP and in particular, the development of criteria are suitable instruments to stimulate public procurement of energy-efficient cloud services.

Public Procurement for Innovation is a type of procurement where contracting authorities act as a launch customer for innovative goods or services which are not yet available on a large-scale commercial basis, and may include conformance testing. The public procurer and the contracted entity work together to develop ad-hoc solutions. The risks for market failure are mitigated by support measures, and work is carried out to create the right framework conditions. The European Commission also published a guideline for Public Procurement for Innovation. (European Commission, 2018d)

Therefore, Public Procurement for Innovation should be considered as an alternative approach to GPP, especially to foster innovation in fields where currently no market response exists, such as energy-efficient cloud computing.

This will in turn speed up the innovation process and the uptake of energy-efficient solutions in practice and in public procurement.

Table 30 - Recommendation 17 Consider Public Procurement for Innovation (PPI)

Recommendation		Main target groups
18	Promote GPP in the development of an EU cloud infrastructure 71	Policy makers, GPP, SMEs
Goal		
• To develop an EU cloud infrastructure.		
Short description		
The EC has recently announced that 2 billion Euros will be invested in a European High Impact Project, to develop data processing infrastructures, data sharing tools, architectures and governance mechanisms for thriving data sharing and federated energy-efficient and trustworthy cloud infrastructures and related services, as part of the EC Digital Agenda. The development of an EU cloud infrastructure will: • Open up possibilities for public administrations to be involved and for the promotion of GPP. • It is recommended that the following aspects should be considered when planning investments. • Funded projects should include the criteria for GPP Data Centres and Server Rooms. The criteria for renewable energy can in particular contribute to speeding up the development of a carbon neutral cloud (see dedicated recommendation). Public procurement should be stimulated by financial aid for technical projects targeting public administration, research, and healthcare on the one hand, and sectors with a higher potential for using energy-efficient criteria data centres on the other, as well as the development of big data analysis software. For projects in the first group, the application of EC GPP criteria should be mandatory, whereas the projects in the second group should aim to explore the development of energy-efficient software to reduce the energy need of an analysis of large data pools. Public Procurement for Innovation should be explored, and SMEs should be encouraged to take part in the process. This will in turn increase the possibility of energy-efficient cloud solutions becoming a necessary part of the infrastructure, by working together with the industry and SMEs and contribute to the objectives of the Digital Single Market agenda.		

Table 31 - Recommendation 18 Promote GPP in the development of an EU cloud infrastructure 11

7 Previously: Consider the cloud as a critical EU infrastructure (and build one)

Recommendation		Main target groups
19	Bring together public research & healthcare institutions to develop ad-hoc cloud solutions which also target energy-efficiency	GPP, healthcare, sector, research sector
Goal		
• Strengthen partnerships among public research & healthcare stakeholders in cloud service procurement. • Stimulate the implementation of energy-efficient cloud services.		
Short description		
The public research & healthcare sector has a growing demand for cloud services, e.g. to share data and perform analyses of large data pools. Both of these activities are highly energy demanding. Public research institutes, universities, medical centres, hospitals etc. will increasingly need these types of services, which also require data connectivity and compatibility. Regarding energy-efficiency, a one-size-fits-all solution does not exist, so solutions need to be developed on an ad-hoc basis (e.g. the EC HELIX-NEBULA project). Stimulating cooperation and partnership between public research and healthcare organisations, e.g. by developing and sharing cloud infrastructures, would provide opportunities to address these issues. Therefore, public research and healthcare institutions should partner up to develop ad-hoc cloud solutions for big data storage and analysis, so that energy-efficiency principles can also be included. This will in turn speed up the innovation process and the uptake of energy-efficient solutions in practice and in public procurement.		

Table 32 - Recommendation 19 Bring together public research & healthcare institutions to develop ad-hoc cloud solutions which also target energy-efficiency

Policy awareness raising

Recommendation		Main target groups
20	Promote the carbon footprint/carbon neutrality as a topic in the cloud computing and energy efficiency discourse	Policy makers
Goal		
• Put energy-efficient cloud computing on the political agenda.		
Short description		
Using the term "energy-efficiency" in the political agenda has some implications. Energy-efficiency is mostly translated into decreasing the energy demand of data centres, but a) it does not put particular requirements on the type of energy employed (e.g. renewable or not), and b) it does not put any particular restrictions on the total amount of energy required by the cloud (e.g. rebound effect), nor on the CO2 emissions or the impact on global warming. The demand for energy of the cloud, which is already considerable, will grow further (and quickly), and therefore it is of vital importance to decrease it; but this objective should be paired with the goal to decrease CO2 emissions and reduce the impact on climate change, and explicitly contribute to international political agendas such as the Paris Agreement and the SDGs. Therefore, it would be important to put energy-efficiency and the carbon footprint/neutrality of the cloud on the political agendas. This will in turn support the implementation of measures which will ensure the energy-efficiency and carbon neutrality of the cloud. A starting point is offered by the work of the EC on GPP Criteria for Energy-efficient Data Centres and Server rooms, which already includes criteria on the reduction of GHG emissions (Criteria Area 3). These criteria are to be given priority in the process of implementing the EC GPP criteria at the national and the local level, e.g. in the NAPs. Note: this recommendation has been written prior to the European Data Strategy (European Commission, 2020a) from February 2020. This data strategy states that in the period 2021-2027, the Commission will invest in a High Impact Project on European data spaces and federated cloud infrastructures. A Memoranda of Understanding with Member States on cloud federation is planned for Q3 2020.		

Table 33 - Recommendation 20 Promote the carbon footprint/carbon neutrality as a topic in the cloud computing and energy efficiency discourse

Recommendation		Main target groups
21	Put energy-efficiency for cloud computing on national digital agendas	Policy makers
Goal		
• Put energy-efficient cloud computing on the political agenda.		
Short description		
Several Member States are adopting national digital agendas. This study has highlighted that digital agendas cover topics including data security, protection, privacy and the digitalisation of public administration (among others); but not the topic of energy-efficiency. On the other hand, it can be argued that digital agendas are mostly adopted for the very first time and cover many topics already; thus, it could be ensured that the inclusion of energy-efficient cloud computing goes hand in hand with the digitalisation process. Therefore, Member States should be stimulated to include the topic of energy-efficient cloud computing in their national digital agendas. This will in turn stimulate the uptake of energy-efficient cloud computing in the political agenda. Note: this recommendation has been written prior to the European Data Strategy (European Commission, 2020a): One of the key actions in this strategy is, to invest in a high impact project on European data spaces, encompassing data sharing architectures (including standards for data sharing, best practices, tools) and governance mechanisms, as well as the European federation of energy-efficient and trustworthy cloud infrastructures and related services, with a view to facilitating combined investments. Other key actions are e.g. the signing of a Memoranda of Understanding with Member States on cloud federation or a proposal for a legislative framework for the governance of common European data spaces.		

Table 34 - Recommendation 21 Put energy-efficiency for cloud computing on national digital agendas

Overview on feasibility for implementation and stakeholders' priorisation

In the following table, an overview of the proposed recommendations, a rough assessment of the expected efforts for the implementation (e.g. feasibility for implementation) and the results from the stakeholders´ priorisation and validation exercise is provided.

No.	Recommendation	Type of policy instrument	Feasibility for implementation (expert judgment) (easier - higher efforts required)	Prioritised by the stakeholders: n. of votes
18	Including the term carbon footprint/neutrality in the cloud computing and energy-efficiency discourse	Policy awareness raising	easier implementation	23
11	Incentives to support energy-efficiency in data centres	Incentives	higher efforts required	19
10	Cooperation on the development of standards	Standards	higher efforts required	18
3	Cloud footprint or virtual smart meter	Enhance transparency/ information raising	higher efforts required	16
5	Guideline for energy-efficient cloud computing	Guidelines	easier implementation	14
19	Include energy-efficiency for cloud computing in national digital agendas	Policy awareness raising	easier implementation	11
2	Information campaign on energy-efficient cloud computing for providers & companies & universities and politicians	Information/ awareness raising measures	easier implementation	10
20	Consider the cloud as a critical EU infrastructure (and build one)	Development & Innovation	higher efforts required	8
6	Code of Conduct for cloud computing	Soft certification	higher efforts required	7
13	Establishment of minimum criteria for energy-efficiency of newly built data centres in the EU legislation	Legislative Framework	higher efforts required	7
9	Label "ECO-Cloud": a service label	Labels	higher efforts required	5
16	Stimulate the inclusion of the GPP criteria for Green Data Centres in national criteria for GPP	GPP related measures	easier implementation	5
1	Information campaign(s) on the impact of cloud computing on energy demand	Information/ awareness raising measures	easier implementation	3
12	Ecodesign Directive: update of regulations for the "material" component of data centres and cloud services	Legislative Framework	higher efforts required	3

17	Consider Public Procurement for Innovation (PPI) instead of GPP	GPP related measures	higher efforts required	2
4	Digital Environmental Repository (DER)	Enhance transparency/ information raising	higher efforts required	1
8	Label for cloud computing – high threshold provider endorsement label	Labels	higher efforts required	1
14	Include GPP criteria for green data centres in the National Action Plans (NAPs)	GPP related measures	easier implementation	1
7	Label for cloud computing – low threshold provider endorsement label	Labels	higher efforts required	0
15	Promote knowledge sharing among the GPP groups	GPP related measures	easier implementation	0
21	Bring together public research & healthcare institutions to develop ad-hoc cloud solutions which also target energy-efficiency	Development & Innovation	higher efforts required	0

Table 35 - overview of the proposed recommendations

Prioritisation of recommendations and conclusions

The proposed recommendations are drafted based on the evidence collected for this study. They consist of different instruments, have diverse target groups, and they require different resources and efforts for their implementation, with different levels of feasibility.

The recommendations whose implementation has been rated as “easier implementation” (see table above), are, generally speaking, “low hanging fruits” and should be prioritised. However, they might not be the most effective measures. An impact assessment has not been carried out as it did not come within the scope of the study.

Based on the results of this study and expert judgment, the following recommendations are proposed:

- Communicate the need for energy-efficient cloud computing: recommendations No. 1 and No. 2 concerning information campaign(s) on the impact of cloud computing on energy demand, with different target groups can be used as stand-alone measures or combined, i.e. the recommendations can also be used as instruments accompanying other recommendations. A well designed information campaign on energy-efficient cloud computing with different roll-outs should be closely coordinated with, or even incorporated into, information activities carried out under the European Green Deal, the European Data Strategy and the Digital Strategy “Shaping Europe’s Digital Future” (European Commission, 2020c) that formulates the goal that data centres should become climate neutral by 2030 (European Commission, 2020c).
- Ensure transparency for companies and the broad public to support informed decision making. Better metrics are needed to provide important knowledge for the development of a cloud footprint or a virtual smart meter in order to visualise and communicate the energy demand of cloud services.
- Proceed with cooperation on the development of standards of the European Union with international standardisation initiatives.

- Support and motivate companies to implement energy-efficient cloud computing. Build on the knowledge of existing initiatives (EU Code of Conduct on Data Centre Energy efficiency, Blauer Engel,..), develop in a stakeholder dialogue and together with the scientific community a flexible and adaptable tool set (e.g. guidelines, best practices) for the needs of SMEs as well as big companies. This tool set has to be adapted regularly to ensure that it is state-of-the-art and needs to be evaluated to measure the success of the activities. Support information flow and experience exchange by supporting networking and motivational activities (e.g. awards).
- As stated in the European Green Deal (European Commission, 2019e), taxes play a direct role as they send the right price signals and provide the right incentives for sustainable behaviour among producers, users and consumers. A general CO2 tax can be seen as the most important and efficient market based policy instrument to deal with negative externalities and to improve energy-efficiency.
- The adaptation of legislation is regarded as a priority, and in particular the setting of minimum requirements for data centres and server rooms: establishment of minimum criteria for energy-efficiency for existing data centres and server rooms and establishment of minimum criteria for the energy-efficiency of newly built data centres in the EU legislation.

Regarding GPP, the following recommendations should be prioritised:

- Promote the inclusion of GPP Criteria in the NAPs: public procurement expenditures contribute substantially to national GDPs. The EC Code of Conduct on Data Centre Energy efficiency and GPP Criteria for Data Centres documents are an opportunity for Member States to put energy-efficient cloud computing on their procurement agendas. In the medium term, this will stimulate the market so that it offers solutions which are compliant with the GPP criteria.
- Promote GPP in the development of an EU cloud infrastructure: according to the budgets and expenditures planned, there is a window of opportunity for stimulating energy-efficient cloud computing in public procurement and the inclusion of GPP criteria.

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14. ANNEX 1 – TOR DESCRIPTION OF TASKS

Objectives

The main objective of the study is:

- To analyse and assess the current and future energy consumption of cloud computing services in Europe, including edge computing, sensors, networks, hardware, software, and rapidly emerging technologies such as Blockchain. To identify and propose measures to drive the cloud market towards energy-efficiency in terms of future research and technology development, green public procurement and the provisioning of energy-efficient cloud services.

Tasks

The minimal requirements are provided in the following tasks:

1. Analyse and model across the EU28, using an appropriate classification of regions, the energy consumption of the cloud computing data centre infrastructure and forecast the energy-consumption for providing cloud-based services by 2025.

2. Technological analysis: compile and analyse the spectrum of technologies for providing full cloud computing services from the edge, intermediate networking and processing up to cloud data centres to determine typical and representative energy consumption patterns, the state of the art of energy-efficiency and the scope for further technological development to improve the energy-efficiency. This analysis should include relevant technologies, edge devices, networking, software, hardware, Blockchain as well as architectures and management approaches.

3. Policy analysis: compile and analyse the impact of current ap-proaches for stimulating or imposing eco-friendly procurement, use and provisioning of digital technologies. Relevant standards for digital services in this area should be mapped out, identifying possible gaps. The feasibility and effectiveness of policy measus (e.g. awareness raising, codes of conduct, voluntary schemes and self-regulation, labels, legislation etc.) driving the market towards energy-efficient digital services should be compiled and assessed, possibly using experience from other areas.

4. Research and technological development: investigate RTD policy options identifying key technological areas for further improving the energy-efficiency of providing cloud computing services. Consult relevant stakeholders, provide recommendations on future RTD and execute a validation workshop with a wide range of relevant stakeholders.

5. Green Public Procurement (GPP): compile and analyse the impact of existing (GPP) schemes and recommend policy options for Green Public Procurement (GPP) of cloud computing services. In particular reference should be made to work done in this area. The recommendations should result in a deliverable that could be used in the existing initiative on GPP, focusing on energy-efficiency of the cloud computing for a variety of relevant use cases. A validation workshop with relevant stakeholders should be organised.

6. Providers of cloud computing services: compile, analyse and recommend policy options for stimulating the provisioning of energy-efficient cloud computing services. This should include the identifica-tion of relevant standards and gaps, awareness raising, labels and certificates, self-regulation and legislation. The feasibility and effec-tiveness of different options should be analysed, if needed with experience

from other areas. A validation workshop with relevant stakeholders should be organised.

The overall outcome of this study will directly contribute to defining policies in the area of energy-efficient cloud services, including Blockchain, and for fu-ture research, innovation and deployment programmes for digital technologies. The study will directly contribute to policy development on Green Public Procurement of digital services in the cloud and the provisioning of such services. Overall this will contribute to realising the goals of the Paris Agreement on climate change.

15. ANNEX 2 - Modelling the energy consumption of data centres in the EU28

The energy consumption of data centres in the EU28 was determined using a calculation model available at Borderstep Institute. This Annex describes the calculation model and the assumptions and partial results derived from it. The calculation model is based on a structured and optimised quantitative survey of the equipment used in data centres. Energy-relevant technology and usage parameters were assigned to equipment technology, and the resulting electrical power consumption is thus calculated as annual energy consumption of data centres in EU28. Figure 16 shows an overview of the structure of the adapted calculation model.

The multi-layered calculation model contains three basic parameters:

- Type and number of devices (product groups)
- Load profiles (usage parameters)
- Load-dependent electrical power consumption (technical parameters).

The energy consumption of data centres was calculated in billion kWh per year (TWh/a). The model is suitable for determining the current energy consumption of data centres. However, it can also be used to forecast the development of future energy consumption.

The model was adapted and extended for the purposes of the study. The following changes and revisions were necessary in particular:

- Adaptation of existing data sets to the data available for the EU28. Server and storage sales figures for the EU28 regions were obtained from a market analyst to extend the model. These sales figures only partially corresponded in structure and scope to those of the market analysts, whose data formed the basis for the Borderstep model.
- Extension to include different regions in the EU28
- Adaptation of the model for the energy consumption of the data centre infrastructure for cooling/air conditioning, power supply, etc. to the needs of the present study.
- Checking and updating the data records used.

In the model, the EU28 countries were divided into the following regions:

- Eastern Europe: Bulgaria, Czechia, Hungary, Poland, Romania, Slovakia,
- Northern Europe: Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Sweden, United Kingdom of Great Britain and Northern Ireland,
- Southern Europe: Croatia, Greece, Italy, Malta, Portugal, Slovenia, Spain,
- Western Europe: Austria, Belgium/Luxembourg, France, Germany, Netherlands

The main parameters and assumptions of the model are briefly explained below. The calculation model has been used by the Borderstep Institute for about ten years. A description of the model and the individual model parameters has already been published many times Fichter & Hintemann, 2014; Hintemann et al., 2010; Hintemann, 2017b, 2018; Hintemann & Hinterholzer, 2019; Stobbe et al., 2015).

Type and number of devices in stock (product groups)

Please note: As mentioned in Chapter 5 , the results of the studies on the energy consumption of data centres vary, in some cases very significantly. One reason for this is the fact that there are often differences in the available market data on the sale of data centre components such as servers and storage or network technology. For example, the sales figures from Techconsult market analysis for volume servers in Germany differ by more than 20% from the data from IDC or Gartner. The deviations can be explained, among other things, by different research methods. The various market data are currently being reviewed for consistency and validated via stakeholder consultation. Therefore, detailed calculation results cannot be provided yet.

Different types of servers are used in data centres; they can be differentiated, for example, according to design, application purpose, size, number of processors or price. The following three categories were used in the present study:

- volume server
- mid-range server
- high-end server.

This distinction was chosen because the Borderstep Institute has market figures, some of which date back to 2007, for these three categories. Specially developed hardware is used for certain applications such as crypto mining and increasingly, in the future, the field of AI. Therefore, the category “application specific hardware” was added to the server categories mentioned above. The number of devices was estimated based on the available information on the energy requirements of crypto mining and the hardware typically used for it. Table 36 shows the inventory figures for servers in the EU28 calculated with the model.

EU28	2010	2015	2018	2020	2025
High-end servers	21	19	18	17	14
Mid-range servers	516	482	453	418	339
Volume servers	9,001	10,456	10,613	10,722	12,456
Application specific hardware	0	73	135	159	245
Total	***9,538***	***11,030***	***11,219***	***11,316***	***13,054***

Table 36 - Servers (stock) in the EU28 in thousands of servers (2020, 2025: forecast)

Data storage is becoming increasingly important in data centres. Trends such as Big Data, Internet of Things or Industry 4.0 are leading to a multiplication of the data volume. According to Cisco, global Internet traffic will reach 150,700 GB per second in 2022. In 2002 it was 100 GB per second. In Western Europe there will be four billion networked devices/connections in 2022. Internet traffic in Western Europe is growing at an annual rate of 22%. Data is stored in different ways in data centres. The servers usually have internal hard disks. These are already taken into account in the energy requirements of the servers. In addition, there are external storage systems in which data is stored. These usually have one or more storage controllers. With such external storage systems, a distinction is usually made between Direct Attached Storage (DAS), Network Attached Storage (NAS) and Storage Area Networks (SAN). With DAS systems, the external storage systems are connected directly to one (or more) server(s). NAS and SAN systems make central storage available to a network. External storage systems are also differentiated according to how they perform. The international organisation SNIA (Storage Networking Industry Association) differentiates between the categories online storage and near online storage according to access speed. For backup systems, a distinction is made between Removable Media Library and Virtual Media Library. Within these systems, different tier levels are differentiated according to performance.

The calculation model follows an approach that is very closely based on the hardware of the systems, i.e. the installed hard disks and the number of storage controllers, to determine the energy demand of the external storage systems. A distinction is made between 2.5" and 3.5" hard disks in classic design (rotating hard disks) and SSD hard disks. Storage systems with optical drives or tape drives are not considered due to their low market share and low share of energy consumption.

New shipment figures for storage systems are unfortunately not available. The calculation of hard disks for the EU regions was based on existing figures for storage capacities and on storage system sales (market values). The definition of a typical storage system was based on the Ecodesign Preparatory Study on Enterprise Servers and Data Equipment (Bio by Deloitte & Fraunhofer IZM, 2016). Table 37 shows the inventory figures for hard disks and storage controllers in the EU28 calculated with the model.

EU28	**2010**	**2015**	**2018**	**2020**	**2025**
3.5" hard disk	35,498	37,480	39,703	39,639	34,726
2.5" hard disk	10,711	34,374	47,439	50,210	45,425
SSD	1,419	13,400	34,638	50,224	88,570
Storage Controller	1,020	1,003	982	925	666

Table 37 - Hard disks and storage controllers (stock) in the EU28 in thousands of devices (2020, 2025: forecast)

To determine the number of network ports, it was assumed that the useful life of network technology in data centres was comparable to that of the servers and storage technology, i.e. that the sales figures for network ports can be derived directly from the sales figures for servers and storage. Table 38 shows the inventory figures for network ports in the EU28 calculated with the model.

EU28	**2010**	**2015**	**2018**	**2020**	**2025**
1 GBit	42,413	22,908	7,515	2,974	953
10 GBit	0	18,171	26,344	22,830	10,348
40/100 GBit	0	1,059	6,905	13,583	26,149
Storage ports	23,936	26,640	27,499	27,749	29,469
Total	**66,349**	**68,778**	**68,263**	**67,136**	**66,919**

Table 38 - Network ports (stock) in the EU28 in thousands of ports (2020, 2025: forecast)

Load profiles (usage parameters)

The average useful life is assumed to be five years for volume servers, eight years for mid-range systems and 12 years for high-end systems[8]. These assumptions also take account of the fact that servers in data centres are frequently reused after the end of their initial use.

Like other components of data centres, servers are in operation 365 days a year. Even today, average volume servers are often only used to a limited extent. A study conducted by Stanford University together with the Anthesis Group concluded that 30% of all servers in data centres are switched on, but practically idle (Koomey & Taylor, 2015). A 2008 McKinsey survey estimated average server utilisation at approximately 6% (Kaplan et al., 2008).

The Ecodesign Preparatory Study on enterprise servers [ENTR Lot 9] assumed an average utilisation of 20% over 24 hours across all server categories (Bio by Deloitte & Fraunhofer IZM, 2016). The same level of capacity utilisation was assumed in the Borderstep model for the year 2015, based on an average of 19 hours in active mode and 5 hours in idle mode. As a rule, mid-range and high-end servers are used at significantly higher capacity. Therefore, average utilisation for mid-range and high-end servers of more than 50% was assumed in the present study. It was assumed that average utilisation increases over time and that the utilisation of servers in hyperscale cloud data centres is significantly higher than in other data centres. These assumptions were also made in the US data centre energy usage report (Shehabi et al., 2016) (Table 39).

Space type	2000-2010	2020
Internal	10%	15%
Service provider	20%	25%
Hyperscale	45%	50%

Table 39 - Average active volume server utilisation assumptions in the US data centre energy usage report (Shehabi et al., 2016)

Similarly to the usage patterns for volume servers, it was also assumed for the storage systems and the network infrastructure of data centres that they are operated 365 days a year, with 19 hours in active and five hours in idle mode. Based on the investigations made for the Ecodesign study (Bio by Deloitte & Fraunhofer IZM, 2016), a useful life of six years was assumed for storage systems.

[8] According to IBM, the zSeries is supported for an average of 11 to 12 years (IBM, 2018).

Load-dependent electrical power consumption (technical parameters)

The electrical power consumption of servers is determined not only by the load, but also by the type and number of processors, the working memory capacity, the power supply design and the efficiency of the power supplies. These parameters affect both the level of power consumption in idle mode and the power consumption in active mode.

In an EU study on the energy demand (Prakash et al., 2014), an average volume server in the EU was assumed to consume 162 watts of power (24 hours, 365 days). According to this study, the maximum power consumption of a volume server increases over time. Mid-range systems are assumed to account for 22% of server power consumption.

The Ecodesign Preparatory Study on Enterprise Servers and Data Equipment assumes average idle power consumption of 150 watts for the year 2012 and 2-socket rack servers in the EU and active power consumption of 200 watts at 25% utilisation. The preliminary study shows a slight increase for the temporal development of the maximum power consumption of a server (Bio by Deloitte & Fraunhofer IZM, 2016).

The US data centre energy usage report assumed that the maximum energy requirement of an average server would remain constant between 2007 and 2020. 365 watts were assumed for a 2-socket server. The average energy requirement of the servers in operation would fall continuously over time because of improved efficiency rates in partial load operation (Shehabi et al., 2016).

Like other studies of EU data centres, the present study assumed an increase in the maximum power consumption of an average server. This assumption is in line with increasing power densities (measured in kW per m^2) , which are mainly due to virtualisation significantly increasing the amount of RAM in the server systems, the increasing use of graphics processing units (GPUs) and the increasing maximum power consumption of server processors. This assumption was confirmed in interviews and surveys of data centre operators and equipment providers. Figure 28 shows the development of the Thermal Design Power (TDP) of Intel server microprocessors between 1998 and 2019. TDP is a measure of the maximum power consumption of a microprocessor. As the graph shows, there has been a significant increase in maximum power consumption of server microprocessors in recent years.

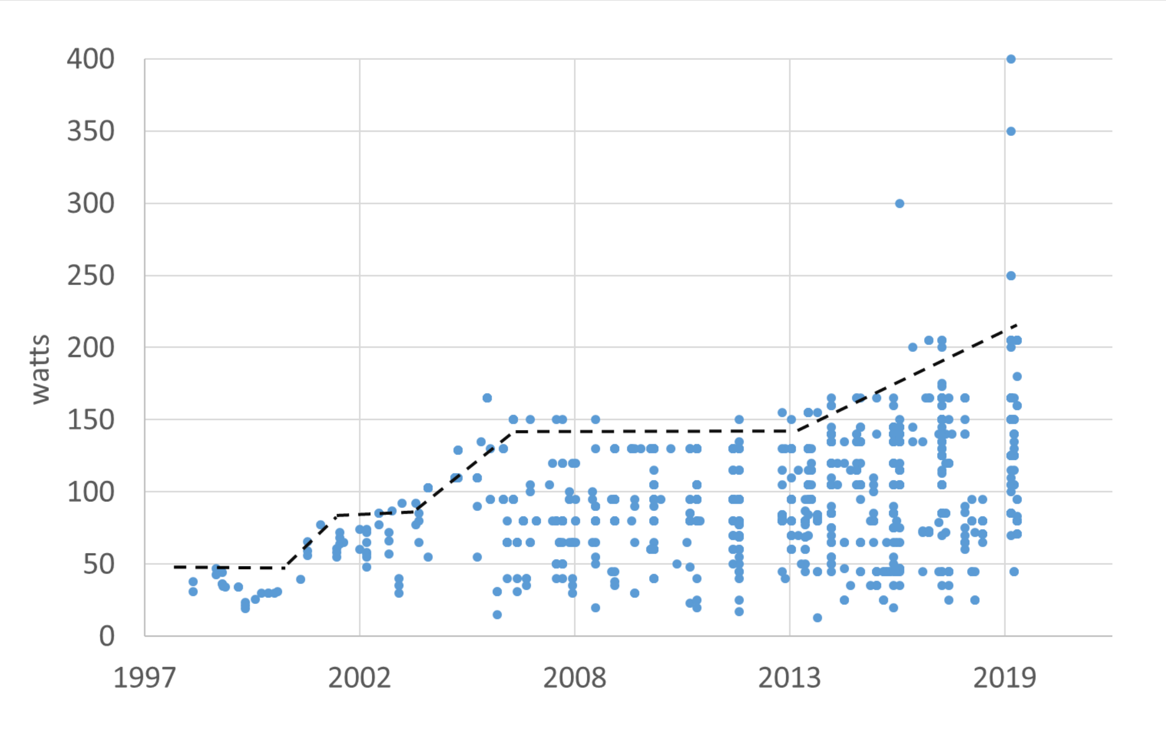

Figure 28 - Thermal Design Power (TDP) of Intel server microprocessors in the years 1998 to 2019 (Source: Intel)

Table 40 shows the average power consumption of servers in the EU28 based on the calculation method presented and the assumptions in the model.

EU28	2010	2015	2018	2020	2025
High-end servers	12,409	16,585	19,241	21,303	26,302
Mid-range servers	845	1,213	1,564	1,873	2,616
Volume servers	153	182	210	228	268
Application specific hardware	n,a,	1,560	2,539	2,880	3,540

Table 40 - Average power consumption of servers in the EU28 in watts (2020, 2025: forecast)

The assumptions concerning the average power consumption of hard disks were based on the surveys carried out as part of the Ecodesign Preparatory Study on Enterprise Servers and Data Equipment. It was assumed that the energy consumption of hard disks will initially decrease slightly, but will increase again somewhat by 2025 due to increasing utilisation in active operation (Table 41).

EU28	2010	2015	2018	2020	2025
3.5" hard disk	8.9	8.6	8.5	8.4	8.5
2.5" hard disk	5.9	5.4	5.2	5.2	5.3
SSD	5.6	5.2	4.9	4.8	4.4
Storage Controller	320.1	312.9	302.2	298.7	301.5

Table 41 - Average power consumption of hard disks and storage controllers in the EU28 in watts (2020, 2025: forecast)

For the present study, the amount of power consumed by network ports was determined by evaluating the Code of Conducts for Broadband Communications Equipment and the technical data on currently available devices and conducting interviews with network manufacturers. No distinction was made between copper and fibre optic technology due to a lack of available data on the dissemination of these technologies in data centres. Energy consumption per port for data centre technology was assumed as shown in Table 42.

EU28	2010	2015	2018	2020	2025
1GBit	3.7	2.4	1.8	1.5	1.2
10GBit	n.a.	4.4	3.8	3.4	2.4
40/100GBit	n.a.	12.9	11.7	10.9	8.3
Storage ports	3.7	3.6	4.8	5.9	6.5

Table 42 - Average power consumption of hard disks and storage controllers in the EU28 in watts (2020, 2025: forecast)

For the ports in storage networks, the average values of ethernet ports in the respective years, weighted by the number of units, were assumed for the purpose of simplification.

Energy consumption of the data centre infrastructure

The Borderstep calculation model was adapted to determine the energy demand of the data centre infrastructure in the EU28 regions. In the previous Borderstep model, the energy demand of the infrastructure components was determined on the basis of sales figures from individual years and assumptions for the development of the energy efficiency achieved with the new installations in question. The model was adapted to now use data on the PUE values and partial PUE values of the data centres for the calculations. The data set of the Borderstep Institute was adapted accordingly and compared with other available data sources.

Table 43 shows the assumptions made in the US data centre energy usage report on the PUE values of data centres, broken down by different data centre types. These assumptions are largely consistent with the model assumptions of the present study.

Space type	IT	Transformer	UPS	Cooling	Lighting	Total PUE
Closet	1	0.05	-	0.93	0.02	2.0
Room	1	0.05	0.2	1.23	0.02	2.5
Localised	1	0.05	0.2	0.73	0.02	2.0
Mid-tier	1	0.05	0.2	0.63	0.02	1.9

High-end	1	0.03	0.1	0.55	0.02	1.7
Hyperscale	1	0.02	-	0.16	0.02	1.2

Table 43 - PUE by space type (2014) in the United States (Shehabi et al., 2016)

The data collected as part of the Code of Conduct for Energy Efficiency in Data Centres are of a comparable magnitude. They also provide information on the regional distribution of PUE values in the EU28 (Table 44).

Geographical zones	Countries	Temperature range (°C)	Average PUE	Number of data centres
Nordic countries	Denmark, Finland, Norway, Sweden	18-26	1.71	13
UK and Republic of Ireland	England, Scotland, Wales, Northern Ireland, Republic of Ireland	17-30	1.83	116
Northern/Central Europe	Austria, Belgium, France, Germany, Hungary, Luxembourg, The Netherlands, Portugal, Poland, Switzerland	14-28	1.72	122
Southern Europe/Mediterranean	Gibraltar, Greece, Italy, Malta, Spain, Turkey, Monaco, Romania, Bulgaria	16-26	2	30
Non-EU	Republic of Mauritius, US	-	-	5

Table 44 - Geographical zones of data centres giving temperature, average relative humidity data and average PUE. Data source: participants of EU Data Centre Code of Conduct (Avgerinou et al., 2017)

According to a study for the German Federal Ministry for Economic Affairs and Energy, the assumed PUE value for Germany for 2018 is approx. 1.7 (Stobbe et al., 2015). Table 45 shows the breakdown of PUE values in Germany by data centre type in the year 2015.

Data centre type	PUE in 2015
Server closets and server rooms (under 100 m^2 whitespace)	2.1
Small data centres (100 to 500m^2 whitespace)	1.9
Medium data centres (500 to 5,000 m^2 whitespace)	1.7
Large data centres (more than 5,000 m^2 whitespace)	1.6

Table 45 - PUE by data centre type in Germany (Stobbe et al., 2015)

The average partial PUE values and the regional distribution of PUE values in the EU28 were determined on the basis of the information on average PUE values presented and additional expert interviews. The table shows the average PUE values thus obtained in the EU28.

EU28	**2010**	**2015**	**2018**	**2020**	**2025**
pPUE Cooling	1.67	1.58	1.51	1.48	1.31
pPUE UPS	1.30	1.25	1.20	1.19	1.17
pPUE other	1.06	1.06	1.05	1.05	1.04
PUE	**2.03**	**1.89**	**1.75**	**1.71**	**1.51**

Table 46 - Partial PUE values (pPUE) and PUE values used for modelling in the present study (2020, 2025: forecast)

16. ANNEX 3 – SCREENED INITIATIVES FROM TASK 5

Title	Type	Le vel	Website	Relevance to cloud computing	Relevance for energy-efficiency related to ICT
ARCADIA	Project	EU	https://www.cloudwatchhub.eu/serviceoffers/arcadia-novel-reconfigurable-design-highly-distributed-applications-development	Yes	Yes
ASCETiC - Adapting Service lifeCycle towards EfficienT Clouds	Project	EU	http://www.ascetic-project.eu	Yes	Yes
Buying green! Handbook	Guideline	EU		No	Not specifically for energy efficiency
CEPS - Digital Single Market	Platform for innovation	EU	https://www.ceps.eu	No	No
CEPS - Digital Single Market - case studies	Best practice	EU	https://www.ceps.eu/wp-content/uploads/2019/06/Sustainability-in-the-Age-of-Platforms-2.pdf	Alibaba (platform) and the establishment of energy-efficient data centres	Yes
Chartered Institute of procurement supply	National and regional Public Procurement Agencies and Centres	EU	https://www.cips.org	Some articles related to the cloud	-
CLOUD FOR EUROPE: REALIZZARE UN MERCATO UNICO EUROPEO PER I SERVIZI CLOUD DELLA PA	Project	EU	https://appaltinnovativi.gov.it/appalti/cloud-for-europe-realizzare-un-mercato-unico-europeo-per-i-servizi-cloud-della-pa	Yes	No
CloudLightning	Project	EU	https://cloudlightning.eu/	Yes	Yes

CloudWATCH2	Project	EU	https://www.cloudwatchhub.eu/cloudwatch2-think-cloud-services-government-business-and-research-0	Yes	Yes
Cloudwatchhub	Procurement platform	EU	http://www.cloudwatchhub.eu/	Yes	Yes
Code of Conduct for Energy-efficiency in Data Centres	GPP criteria	EU	https://ec.europa.eu/jrc/en/energy-efficiency/code-conduct/datacentres	Data Centres	Energy-efficiency of data centres
Communication on a European Cloud Initiative-Building a competitive data and knowledge economy in Europe	legislation	EU	https://ec.europa.eu/digital-single-market/en/news/communication-european-cloud-initiative-building-competitive-data-and-knowledge-economy-europe	Yes	-
Communication on an EU e-Government Action Plan 2016-2020. Accelerating the digital transformation of government	legislation	EU	https://ec.europa.eu/digital-single-market/en/news/communication-eu-egovernment-action-plan-2016-2020-accelerating-digital-transformation	Yes	No
Digital Roadmap Austria	digital roadmaps & cloud strategies	AT	https://www.digitalroadmap.gv.at/	Yes	Not in terms of energy-efficiency of the cloud
Communication on Digitising European Industry: Reaping the full benefits of a Digital Single Market	legislation	EU	https://ec.europa.eu/digital-single-market/en/news/communication-digitising-european-industry-reaping-full-benefits-digital-single-market	Relevant for the cloud, but energy-efficiency of the cloud is not considered	-
UK Digital Market Place for Public Procurement	National and regional Public Procurement Agencies and Centres	UK	https://www.digitalmarketplace.service.gov.uk/	Yes	No

UK Digital Services Standards	standards	UK	https://www.gov.uk/service-manual/service-standard	Yes	Not in the terms of energy-efficiency of the cloud
Communication on Priorities of ICT Standardisation for the Digital Single Market	legislation	EU	https://ec.europa.eu/digital-single-market/en/news/communication-ict-standardisation-priorities-digital-single-market	No	No
Data Centre - EURECA	GPP toolkit	EU	https://tool.dceureca.eu/	Yes	Yes
Driving energy-efficient innovation through procurement - A practical guide for public authorities	Project	EU	http://www.smart-spp.eu/index.php?id=7633	No	Focusing on energy-efficiency. - Lighting systems (LED indoor and outdoor (street) lighting), - Electric vehicles systems (charging points and cars), - Vending machines.
Eafi p (European Assistance for Innovation Procurement) Toolkit	GPP toolkit	EU	www.eafip.eu/toolkit	No	No
EcoProcura	Best practice	EU	http://www.ecoprocura.eu/	No	No
Energy Innovation Procurement (ICLEI, 2018)	Guideline	EU	http://www.ceppi.eu/fileadmin/user_upload/guidance_learning/CEPPI_Guide.pdf	No	guidance to support pro-innovation procurement for energy-efficiency

ETSI 103 199: Environmental Engineering (EE); Life Cycle Assessment (LCA) of ICT equipment, networks and services; General methodology and common requirements	standards	EU	https://www.ictfootprint.eu/en/etsi-103-199-factsheet	ICT Equipment, Networks and Services	Yes
ETSI ES 205 200: Access, Terminals, Transmission and Multiplexing (ATTM); Energy management; Global KPIs; Operational infrastructures	standards	EU	https://www.ictfootprint.eu/en/etsi-205-200-factsheet	Data centres; Fixed broadband access networks; mobile access networks; cable access networks	Yes
ETSI GS OEU 008: Operational energy-efficiency for Users (OEU); Global KPI for Information and Communication Technology Nodes	standards	EU	https://www.ictfootprint.eu/en/etsi-oeu-008-factsheet	Data centres or operator sites (ICT node operations)	Yes
EU GPP Criteria	GPP criteria	EU	http://ec.europa.eu/environment/gpp/alert_en.htm	Half way- Code of conduct for data centres is part of the EU criteria but is treated as single cases	Yes
Eu GPP criteria for data centres	GPP criteria	EU	http://susproc.jrc.ec.europa.eu/Data_Centres/documents.html	Criteria for data centres	Energy use and efficiency in data centres
EU GPP Criteria for Data Centres and Server Rooms	GPP criteria	EU	https://susproc.jrc.ec.europa.eu/Data_Centres/docs/181128_Draft%20Technical%20report%20EU%20GPP%20Data%20Centres%20-%20v3.0%20JRC%20Nov2018%20clean.pdf	Yes	Yes

EURECA Project – EU Resource Efficiency Coordination Action	Project	EU	https://www.dceureca.eu/?page_id=11	Data centres	Energy-efficiency of data centres
European Electronic Communications Code (EECC),	guideline	EU	https://www.accesspartnership.com/introducing-the-new-european-electronic-communications-code-eecc/	partially	No
Purchase of Thin Client Systems in Oeste Cim , PT	Best practice	PT	http://www.gpp2020.eu/fileadmin/files/Tender_Models/GPP_2020_Tender_Model_Thin_Clients_OesteCIM_Portugal_Jan_2016.pdf	No	Yes
Purchase of energy efficint IT and computing equipent in OesteCIM, PT	Best practice	PT	http://www.gpp2020.eu/fileadmin/files/Tender_Models/GPP_2020_Tender_Model_IT_OesteCIM_2014_revised_2015-06-15.pdf	No	Yes
Purchase of Thin Client Computer Systemsand connected services in Germany	Best practice	DE	http://www.gpp2020.eu/fileadmin/files/Tender_Models/GPP_2020_BeschA_Tender_Model_Thin_Clients.pdf	No	Yes
IÖB - Innovation Platform	Platform for innovation	AT	https://www.ioeb-innovationsplattform.at/challenges/	Yes	Not in relation to the cloud. Best practices are presented, but the proposed solutions are related to the energy savings that cloud solution can enhance.

Product group IT of the German GPP criteria	GPP criteria	DE	http://www.nachhaltige-beschaffung.info/SharedDocs/DokumenteNB/Produktbl%C3%A4tter/Informationstechnik.pdf?__blob=publicationFile&v=8	No	Yes
Nachhaltige Beschaffung - Informationen zu Produktgruppen	GPP criteria	DE	http://www.nachhaltige-beschaffung.info/DE/Home/home_node.html	No Computer, Monitore, Notebooks)	Yes
Green Cloud Computing-Lebenszyklusbasierte Datenerhebung zu Umweltwirkungen des cloud-Computing	Project	DE	https://www.umweltbundesamt.de/sites/default/files/medien/421/dokumente/groeger_indikatoren_fuer_cloud_180829.pdf	Use of KPIs for cloud computing. There is a research project for green cloud - computing as well a part concerning the further development of KPIs for cloud services	Yes
Austrian Action Plan for GPP (Österreichischen Aktionsplan zur nachhaltigen öffentlichen Beschaffung)	NAP	AT	www.nachhaltigebeschaffung.at	No - just IT appliances	Yes - related to IT appliances
ÖkoKauf Wien - Programm für die ökologische Beschaffung der Stadt Wien	National and regional Public Procurement Agencies and Centres	AT	www.oekokauf.wien.at	Criteria for thin clients	Yes - related to IT appliances
Österreichisches Umweltzeichen	Label	AT	https://www.umweltzeichen.at/de/home/start	No	Yes - green energy
Umweltverband	National and regional Public Procurement Agencies and Centres	AT	www.umweltverband.at	No	Yes

GPP Lower Austria	National and regional Public Procurement Agencies and Centres	AT	https://www.ncheck.at/start/	No	No
NEU	National and regional Public Procurement Agencies and Centres	AT	www.enu.at	No	No
GemNova	National and regional Public Procurement Agencies and Centres	AT	www.gemnova.at	No	
Guide des achats durable	NAP	BE	http://www.guidedesachatsdurables.be/	No	Yes
Vlaanderen Actieplan 2012-2014	NAP	BE	http://www.bestuurszaken.be/vlaamse-overheid	Yes	No
Portail des marchés publics	National and regional Public Procurement Agencies and Centres	BE	https://marchespublics.wallonie.be/de/home.html	No	No
Agency for a Digital Italy (AgID),	digital roadmaps & cloud strategies	IT	https://www.agid.gov.it/en	Yes -but not to ist efficiency	No
Appaltinnovativi.GOV	National and regional Public Procurement Agencies and Centres	IT	https://appaltinnovativi.gov.it/	Yes	No

European sustainable procurement network (Procura+)	GPP network	EU	http://www.procuraplus.org/	No	No - energy use in public buildings
Google	Best practice	EU	https://ictfootprint.eu/en/google-worldwide https://www.ellenmacarthurfoundation.org/case-studies/circular-economy-at-work-in-google-data-centres	Yes - energy-efficiency of data centres	Yes - energy-efficiency of data centres
GPP 2020 – Procurement for a low-carbon community	Procurement platform	EU	http://www.gpp2020.eu/home/	1 case study	supply of energy-efficient IT equipment
Green Digital Charter	Project	EU	http://www.greendigitalcharter.eu/	ICT solutions, not specified if could	Yes
GreenitAmsterdam	Best practice	EU	http://www.greenitamsterdam.nl/wp-content/uploads/2019/02/AGIT-LB-Whats-up-in-Green-IT-2018.pdf	Yes	Yes
HELIX NEBULA - The Cloud of European researchers	Project	EU	https://www.helix-nebula.eu/	Yes	No
ICLEI global platform (ICLEI Local Governments for Sustainability (ICLEI, n.d.)	Procurement platform	EU	https://www.iclei .org/	No	No - energy use in public buildings
ICT Footprint EU - European Framework Initiative for Energy & Environmental Efficiency in the ICT Sector	Platform for innovation	EU	https://www.ictfootprint.eu	Yes	Yes
PIANOo	National and regional Public Procurement Agencies and Centres	NL	https://www.pianoo.nl/nl	Yes	No

ictfootprint.eu - ICT carbon and energy footprint Standards	Best practice	EU	https://www.ictfootprint.eu/en/ict-standards/sdos-ict-standards	Development of ICT Standards	Yes
INPUT's OpenVolcano platform	Project	EU	http://openvolcano.org/	Yes	Yes
Lessons Learnt from a joint EC Co-funded PCP - Cloud for Europe	article	EU	https://www.pianoo.nl/sites/default/files/documents/documents/lessonlearned-evaluatiecloudforeuropeproject-november2015.pdf	Yes - relevant to pre-commercial procurement	
PICSE PROJECT ON CLOUD SERVICES PROCUREMENT	Project	EU	http://www.sustainable-procurement.org/resource-centre/	procurement for cloud services	No
PPI platform – Public procurement for innovations	Procurement platform	EU	www.innovation-procurement.org	a couple of case studies/ projects related to digitalisation and procurement, but not to energy-efficiency aspects	No
private business for circular IT (remnaufacturing)	Best practice	EU	http://www.circularcomputing.com/	end users devices	-
Flemish Cloud Strategy	digital roadmaps & cloud strategies	BE	https://overheid.vlaanderen.be/nieuws/vlaamse-overheid-keurt-cloud-strategie-goed	Yes	No
VÝPOČETNÍ TECHNIKA	GPP criteria	CZ	https://www.mzp.cz/C1257458002F0DC7/cz/setrna_verejna_sprava/$FILE/OFDN-List_1_Vypocetni_technika-20180314.pdf.002.pdf	No - just for IT appliances	Yes
Šetrná veřejná správa	NAP	CZ	https://www.mzp.cz/cz/setrna_verejna_sprava	No - just for IT appliances	Yes

National Action Plan for GPP Cyprus	NAP	CY	INVALID : http://www.moa.gov.cy/moa/environment/environment.nsf/3D37FFD63B3D335CC2257953004368E1/$file/GPP2012-2014.pdf	No	No
Strategi for intelligent offentligt indkøb	NAP	DK	https://naturstyrelsen.dk/media/nst/10636202/strategi_for_intelligent_offentligt_indk_b2.pdf	No	
Dutch Responsible Procurer	GPP criteria	DK	www.csr-indkob.dk	Yes	Yes
Partnership for Public Green Procurement	Best practice	DK	https://ansvarligeindkob.dk/viden-og-vaerktoejer/cases/; www.gronneindkob.dk	No - not on cloud	Yes
Spaerenergy Denmark	GPP criteria	DK	https://sparenergi.dk/offentlig/vaerktoejer/indkoebsanbefalinger	Not on cloud but on Network equipment and broadband equipment	Yes
keskkonnahoidlikud-riigihanked	NAP	EE	https://www.envir.ee/et/keskkonnahoidlikud-riigihanked	No	No
Free of charge Helpdesk and training	GPP criteria	FI	http://www.motivanhankintapalvelu.fi/in_english	No	No
Finnish NAP	NAP	FI	www.motivanhankintapalvelu.fi/tietopankki	just to PCs	related to PCs
National Action Plan on Sustainable Public Procurement	NAP	FR	http://www.ecoresponsabilite.ecologie.gouv.fr	No	Yes
National Action Plan on Sustainable Public Procurement	GPP criteria	FR	http://www.ecolabels.fr/fr/	No	No

National Action Plan on Sustainable Public Procurement	NAP	FR	https://www.ecologique-solidaire.gouv.fr/sites/default/files/Plan_national_d_action_pour_les_achats_publics_durables_2015-2020.pdf	No	No
National Action Plan Germany	NAP	DE	http://www.verwaltungsvorschriften-im-internet.de/bsvwvbund_13022013_B1581643321841199.htm	relevant also to cloud computing	Yes
Gesetzliche Anforderungen an Server in Büroumgebungen	guideline	DE	https://www.itk-beschaffung.de/Leitf%C3%A4den/Gesetzliche-Anforderungen-Server-Bueroumgebungen	Yes	No
Ecolabel Germany	Label	DE	http://www.blauer-engel.de/	Yes	Yes
German procurement centre	Best practice	DE	www.beschaffung-info.de	some best practices related to data centres are listed here	Yes
National Competence Centre for Sustainable Public Procurement	National and regional Public Procurement Agencies and Centres	DE	https://www.nachhaltige-beschaffung.info/	information technology	Yes
Federal Ministry of Economic Affairs and Energy on public procurement	article	DE	http://www.bmwi.de/DE/Themen/Wirtschaft/oeffentliche-auftraege-und-vergabe.html	Digitalisation, IT	in a bigger context
Federal Ministry of Economic Affairs and Energy on energy-efficient procurement:	article	DE	http://www.bmwi.de/DE/Themen/Energie/energieeffizienz.html	Digitalisation, IT	in a bigger context

Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety on GPP:	article	DE	http://www.bmub.bund.de/themen/wirtschaft-produkte-ressourcen/produkte-und-umwelt/umweltfreundlichebeschaffung/	Digitalisation, IT	in a bigger context
Kompass Nachhaltigkeit	National and regional Public Procurement Agencies and Centres	DE	http://oeffentlichebeschaffung.kompass-nachhaltigkeit.de/	IT products	Yes
Centre of Excellence for Innovative Procurement	National and regional Public Procurement Agencies and Centres	DE	www.koinno.de	also some project relevant to cloud; but not necessarily to ist efficiency	Yes
Procura+ Case	Best practice	EU	http://www.procuraplus.org/case-studies/	No	energy use for buildings
ICT procurement platform that cooperates with the German Environment Agency on GPP issues related to ICT	National and regional Public Procurement Agencies and Centres	DE	www.itk-beschaffung.de	Yes	Yes
Hungarian National Ecolabel	Label	HU	http://www.kornyezetbarat-termek.hu/en/#.VzMXZdKLSUk	No	No
NAP & criteria Ireland	NAP	IE	https://www.dccae.gov.ie/en-ie/environment/topics/sustainable-development/green-public-procurement/Pages/default.aspx	just for office IT equipment	Yes
Italian GPP criteria	GPP criteria	IT	https://www.minambiente.it/pagina/i-criteri-ambientali-minimi	No	No

Italian GPP NAP	NAP	IT	http://www.minambiente.it/pagina/il-piano-dazione-nazionale-il-gpp-pan-gpp	No	No
National action plan	NAP	LV	http://www.iub.gov.lv/lv/node/63	No	related to computers
National Action Plan Lithuania	NAP	LT	https://www.e-tar.lt/portal/lt/legalAct/0947df20d3b311e583a295d9366c7ab3	No	No
National Action Plan Lithuania	GPP criteria	LT	https://www.e-tar.lt/portal/lt/legalAct/TAR.EAC62D7F8C15/TAIS_396083	No	No
Criteria Lithuania GPP	GPP criteria	LT	https://www.e-tar.lt/portal/lt/legalAct/7a673940158f11e58569be21ff080a8c	No	No
Ökotopten	National and regional Public Procurement Agencies and Centres	LU	http://www.oekotopten.lu/	No	No
GPP expertiese centre Netherland	National and regional Public Procurement Agencies and Centres	NL	https://www.pianoo.nl	some articles related to the cloud	-
National Action Plan Poland	NAP	PL	https://www.uzp.gov.pl/baza-wiedzy/zrownowazone-zamowienia-publiczne/zielone-zamowienia	General NAP	general
NAP Portugal	NAP	PT	https://encpe.apambiente.pt/	generic document	generic document
NAP Slovakia	NAP	SK	http://www.rokovania.sk/File.aspx/ViewDocumentHtml/Mater-Dokum-205132?prefixFile=m_	generic document	generic document
GPP criteria Slovakia	GPP criteria	SK	http://www.sazp.sk/public/index/go.php?id=2454	No- just to IT products	Yes - for IT products

Decree on green public procurement	NAP	SL	http://pisrs.si/Pis.web/pregledPredpisa?id=URED7202	Not for the cloud	Yes, but not in relation to cloud computing
GPP criteria Slovenia	GPP criteria	SL	http://www.djn.mju.gov.si/sistem-javnega-narocanja/zeleno-jn	IT products	Yes , but not for the cloud
Criteria Spain GPP	GPP criteria	ES	http://www.boe.es/boe/dias/2008/01/31/pdfs/A05706-05710.pdf	No	No
National procurememnt strategy	NAP	SE	http://www.government.se/information-material/2017/11/national-public-procurement-strategy/	generic document	generic document
Local Government Sustainable Procurement Strategy	National and regional Public Procurement Agencies and Centres	UK	http://www.idea.gov.uk	No	No
Scottish NAP	NAP	UK	http://www.scotland.gov.uk/Publications/2009/10/sspap	General NAP	general
Welsh Assembly Government's Procurement Policy	NAP	UK	https://gov.wales/written-statement-public-procurement-wales	No	No
Northern Ireland NAP	NAP	UK	http://www.cpdni.gov.uk/sustainabl e-procurement-action-plan-ni.pdf	best practices are mentioned	-
Public procurement UK	NAP	UK	https://www.gov.uk/guidance/public-sector-procurement-policy	there is a section dedicated to procurement of technologies and cloud, but not to ist energy-efficiency	-
Difi's webpage on public procurement	National and regional Public Procurement	NO	https://www.anskaffelser.no/	No	No

	Agencies and Centres				
National Action Plan	NAP	NO	https://www.regjeringen.no/contentassets/4a98ed15ec264d0e938863448ebf7ba8/t-1562b.pdf	The importance of renewable energy and the rol of Norvegia for greening data centres is recognized in this up-to-dat document	Yes
GPP criteria	GPP criteria	NO	https://www.anskaffelser.no/gjore-anskaffelser/hva-skal-du-kjope	Yes, but not to green cloud	
Consip	National and regional Public Procurement Agencies and Centres	IT	http://www.consip.it/azienda/chi-siamo	Not on cloud	Yes
Procura+ Network	guideline	EU	http://www.procuraplus.org/	No	no - energy use in public buildings
Public Procurement as a Driver of Innovation in SMEs and Public Services	guideline	EU	https://www.ffg.at/sites/default/files/public-procurement-driver-of-innovation.pdf	No	Not specifically for energy efficiency
Produktneutrale Leistungsbeschreibung x86-Server	guideline	DE	https://www.itk-beschaffung.de/Leitf%C3%A4den/Produktneutrale-Leistungsbeschreibung-x86-Server	Yes	Yes
Public Procurement for a Circular Economy	guideline	EU	http://ec.europa.eu/environment/gpp/pdf/Public_procurement_circular_economy_brochure.pdf	No	Not specifically for energy efficiency
Public Procurement of Innovation Guidance	guideline	EU	https://www.ffg.at/sites/default/files/public-procurement-driver-of-innovation.pdf	No	Not specifically for energy efficiency

REC	National and regional Public Procurement Agencies and Centres	EU	http://www.rec.org/	No	No
Innovationsplat-form Austria	Platform for innovation	AT	http://www.innovationspartnerschaft.at	NoT for green cloud	
SPP IN HELSINKI	Best practice	FI	http://www.procuraplus.org/public-authorities/helsinki/	No - just related to ICT products such as PCs	
Ecosistemi	National and regional Public Procurement Agencies and Centres	IT	https://www.fondazioneecosistemi.org/	No	No
Rijkswaterstaat and Netherlands Enterprise Agency	National and regional Public Procurement Agencies and Centres	NL	https://english.rvo.nl/	No	No
Ecoinstitut SCCL	National and regional Public Procurement Agencies and Centres	ES	http://www.ecoinstitut.coop/index.html	No	No
EnergieSchweiz - Switzerland	Best practice	CH	https://ictfootprint.eu/en/energieschweiz-switzerland	Yes - energy-efficiency of data centres	Yes - energy-efficiency of data centres
Design4Green Challenge	Best practice	FR	https://ictfootprint.eu/en/design4green-esaip-france	Yes	Yes
RECAP	Project	EU	https://recap-project.eu/	Yes	Yes

GPP criteria Portugal	GPP criteria	PT	https://encpe.apambiente.pt/content/lista-de-bens-e-servi%C3%A7os-priorit%C3%A1rios?language=pt-pt	for IT desk product	Yes, but not in relation to cloud computing
Guidelines for environmental friendly public procurement of data centres and servers (Leitfaden zur umweltfreundlichen öffentlichen Beschaffung: Produkte und Dienstleistungen für Rechenzentren und Serverräume)	guideline	DE	https://www.umweltbundesamt.de/publikationen/leitfaden-zur-umweltfreundlichen-oeffentlichen-14	Yes	Yes
Green IT initiative of the Federal Government	Best practice	DE	https://www.bmu.de/themen/wirtschaft-produkte-ressourcen-tourismus/produkte-und-konsum/produktbereiche/green-it/green-it-initiative-des-bundes/	Yes	Yes
Contract for the NI public sector data centres	Best practice	UK	https://www.finance-ni.gov.uk/articles/contract-ni-public-sector-data-centres	Yes	No
Guide to Cloud Computing for Governments	guideline	NL	https://www.pianoo.nl/nl/document/14610/handreiking-cloudcomputing-voor-overheden	Yes, but not to energy-efficiency!!	No
SMART SPP LCC-CO2 Tool	GPP toolkit	EU	http://www.smart-spp.eu/fileadmin/template/projects/smart_spp/files/Guidance/Final_versions/EN_SMART_SPP_Tool_User_Guide_2011_FINAL.pdf	No	focusing in energy-efficiency. - Lighting systems (LED indoor and outdoor (street) lighting),

					- Electric vehicles systems (charging points and cars), and - Vending machines.
Sun Microsystems (Oracle) - USA	Best practice	USA	https://www.ictfootprint.eu/en/sun-microsystems-oracle-usa	Yes - data centres	Yes
Capgemini - UK	Best practice	UK	https://www.ictfootprint.eu/en/capgemini-uk	Yes - data centres	Yes
EARLHAM Institute - UK	Best practice	UK	https://www.ictfootprint.eu/en/earlham-institute-uk	Yes - computation power for genomics	
Equinix - UK	Best practice	UK	https://www.ictfootprint.eu/en/equinix-uk	Yes - data centres	Yes
FCO Services - UK	Best practice	UK	https://www.ictfootprint.eu/en/fco-services-uk	Yes - data centres	Yes
Bedford Drive Primary School - UK	Best practice	UK	https://www.ictfootprint.eu/en/bedford-drive-primary-school-uk	no - IT appliances	Yes
Digital3rd - UK	Best practice	UK	https://www.ictfootprint.eu/en/digital3rd-uk	no - IT appliances	Yes
Malmö, SWEDEN	Best practice	SE	https://www.ictfootprint.eu/en/malm%C3%B6-sweden	no - (IT devices)	
EURECA project - UK	Best practice	UK	https://www.ictfootprint.eu/en/eureca-project-uk	Yes - GPP and green data centres	Yes
Linköping, SWEDEN	Best practice	SE	https://www.ictfootprint.eu/en/link%C3%B6ping-swedenLinköping City Council	Yes - GPP and green data centres	Yes
Telia Sonera - Sweden	Best practice	SE	https://www.ictfootprint.eu/en/telia-sonera-sweden	Yes - cooling from data centres	
Atman - Poland	Best practice	PL	https://www.ictfootprint.eu/en/atman-poland	Yes - free cooling in data centres	Yes
Digiplex and Stockholm Exergi - Sweden	Best practice	SE	https://www.ictfootprint.eu/en/digiplex-and-stockholm-exergi-sweden	Yes - heat reuse from data centres	Yes

University of Coimbra - Portugal	Best practice	PT	https://www.ictfootprint.eu/en/university-coimbra-portugal	Yes - free cooling in data centres	Yes
KPN - The Netherlands	Best practice	NL	https://www.ictfootprint.eu/en/kpn-netherlands	Yes - green energy in data centres	Yes
Schuberg Philis - The Netherlands	Best practice	NL	https://www.ictfootprint.eu/en/schuberg-philis-netherlands	water consumption in data centres	No
Green Data Centre Platform - The Netherlands	Platform for innovation	NL	https://www.ictfootprint.eu/en/green-data-centre-platform-netherlands	Yes - collection of best practices	Yes
Aperam - Luxembourg	Best practice	LU	https://www.ictfootprint.eu/en/aperam-luxembourg	Assessment	Yes
GreenServe - The Netherlands	Best practice	NL	https://www.ictfootprint.eu/en/greenserve-netherlands	Yes - data centres , virtualisation, query scripts	Yes
Politecnico di Milano - Italy	Best practice	IT	https://www.ictfootprint.eu/en/politecnico-di-milano-italy	IT devices	Yes
Verne Global - Iceland	Best practice	IS	https://www.ictfootprint.eu/en/verne-global-iceland	Yes	Yes
RVX - Iceland	Best practice	IS	https://www.ictfootprint.eu/en/rvx-iceland	Yes - Low carbon data centres	Yes
Microsoft - Ireland	Best practice	IE	https://www.ictfootprint.eu/en/microsoft-ireland	Yes - implementation of the EU code of conduct	
Jerlaure - France	Best practice	FR	https://www.ictfootprint.eu/en/jerlaure-france	Yes - Green Data Centres	
EDF - France	Best practice	FR	https://www.ictfootprint.eu/en/edf-france	Yes - ISO certifications for data centres (50001)	Yes
TELEHOUSE - France	Best practice	FR	https://www.ictfootprint.eu/en/telehouse-france	Yes - ISO certifications for data centres (50001)	Yes
Walhalla - Spain	Best practice	ES	https://www.ictfootprint.eu/en/walhalla-spain	Yes -improve energy-efficiency by optimising the UPS's energy consumption	Yes

GreenConcept Project - France	Best practice	FR	https://www.ictfootprint.eu/en/greenconcept-project-france	Yes - life cycle analysis methodology including data centre, telecom network, and end-user devices	Yes
CENTRE OF REGISTERS AND INFORMATION SYSTEMS - Estonia	Best practice	ES	https://www.ictfootprint.eu/en/centre-registers-and-information-systems-estonia	No - IT appliances	Yes
BMW Group - Germany	Best practice	DE	https://www.ictfootprint.eu/en/bmw-group-germany	Yes - data centres in Iceland (renewable, temperature favourable)	Yes
Blauer Engel for data centres	Label	DE	https://www.blauer-engel.de/de/produktwelt/elektrogeraete/rechenzentren	Yes	Yes
Deutsche Telekom - Germany	Best practice	DE	https://www.ictfootprint.eu/en/deutsche-telekom-germany	Yes - data centres and software virtualisation	Yes
Postbank - Germany	Best practice	DE	https://www.ictfootprint.eu/en/postbank-germany	Yes - data centres and firewall servers	Yes
Goethe University Frankfurt - Germany	Best practice	DE	https://www.ictfootprint.eu/en/goethe-university-frankfurt-germany	Yes - data centres	Yes
Altron - Czech Republic	Best practice	CZ	https://www.ictfootprint.eu/en/altron-czech-republic	Yes - virtualisation	Yes
STMicroelectronics - Switzerland	Best practice	CH	http://www.altron.net/en/	No	Yes
COOP - Switzerland	Best practice	CH	https://www.ictfootprint.eu/en/coop-switzerland	Yes	Yes
Network Energy St.Gallen - Switzerland	Best practice	CH	https://www.ictfootprint.eu/en/network-energy-stgallen-switzerland	No	Yes
solutions for circular IT (remnaufacturing)	Best practice	EU	https://tcocertified.com/news/circular-it-in-practice-real-world-solutions/	on end users devices	-

SPP Best practices - SPP Regions Tender Models	Best practice	EU	http://www.sppregions.eu/tenders/tender-models/	No	No - Energy use for buildings, public lightning
SPP Regions – Regional network for sustainable procurement	GPP network	EU	http://www.sppregions.eu/home/	No	No - Energy use in public buildings
SUNFISH	Project	EU	http://www.sunfishproject.eu/	Yes	Yes
Sustainable Procurement Platform - Case studies	Best practice	EU	http://www.sustainable-procurement.org/case-studies/	No	For ICT end-user appliances
Swiss Re	Best practice	CH	https://www.energieschweiz.ch/page/de-ch/so-kann-man-es-umsetzen	Yes - data centres	Yes
CR - Network	Best practice	CH	https://www.energieschweiz.ch/page/de-ch/so-kann-man-es-umsetzen	Yes - data centres	Yes
UBS	Best practice	CH	https://www.energieschweiz.ch/page/de-ch/so-kann-man-es-umsetzen	Yes - data centres	Yes
Elektroplan Buchs & Grossen AG	Best practice	CH	https://www.energieschweiz.ch/page/de-ch/so-kann-man-es-umsetzen	Yes - data centres	Yes
Virtualisation and IT Operations for AAA Radiotaxi	Best practice	CZ	https://www.altron.net/?article&id=252	Yes - virtualisation of servers	Yes
The Procurement Forum	Procurement platform	EU	www.procurement-forum.eu	No - not specifically to cloud services	
UNEP SPP implementation guidelines	guideline	EU	https://www.epa.gov/sites/production/files/2015-09/documents/unep_sp_guidance_profile.pdf	No	Not specifically for energy-efficiency

Yandex data centre Finland: Residual data centre heat in Stockholm en Finland	Best practice	FI	https://www.greendatacentreplatform.com/project/royal-haskoning/	Yes	Yes
Telia Helsinki Data Centre	Best practice	FI	https://www.greendatacentreplatform.com/project/royal-haskoning/	Yes	Yes

Table 47 - screened initiatives from Task 5

17. ANNEX 4 - QUESTIONNAIRE FOR THE GPP ADVISORY GROUPS AND PROCURERS OF TASK 5

GPP Advisory Group´s expert Questionnaire

to examine the current paths for public procurement of energy-efficient cloud computing services

In recent years the demand for cloud services has grown exponentially contributing to a sharp increase in the energy demand to manage the cloud. By 2030, data centres could account for around 8% of the world's energy consumption. It is, therefore, necessary to ensure that the digital transformation of the European society can be managed in a way that supports the agreed emission reduction targets set out in the Paris Agreement.

This study “Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market” aims to support the development of energy-efficiency cloud computing services, among others in public procurement. The recommendations, criteria and best practices will target public procurers in the EU member states and will be meant as a supportive tool to pave the way to the procurement of energy-efficient cloud services, i.e. to support the preparation of public tenders for cloud services.

In particular, the scope of this study includes the cloud, which includes different cloud models (SaaS, PaaS, IaaS, FaaS) , the cloud computing infrastructure (such as Datacentre, Switches, Server, Storage, etc.), the cloud service models (Storage, Network, Database, Security, Communication, Collaboration, Video, Integration, File Management, Process as a Service), and the cloud deployment models (Private-, Public-, Community-, Hybrid-, Inter-Cloud). Are excluded from the scope of this investigation IT equipment such as monitors, laptops, PCs, thin systems, scanners, imaging equipment, routers, etc. and more in general end-users devise.

As you are a renowned expert in the field of Green Public Procurement, we would greatly appreciate your expert opinion as a participant in our study. Your input would help to provide specific insights for better implementation of policies and practices in the area of Green Public Procurement for energy-efficient cloud computing services in Europe. In addition, as an expert participant in our study, you would receive first-hand access to our results.

We would like to conduct an expert interview with you by means of this questionnaire. If you are interested to contribute your expertise, please reply to this e-mail by 20.06.2019 indicating a time of your convenience to set up the interview. In alternative, if you prefer to complete the questionnaire on your own, please return it to us compiled by 30.06.2019 the latest. In both cases, the completion of the questionnaire will take about 20-30 minutes.

If you have any questions or would like more information about the study, please do not hesitate to contact the project team at Francesca.montevecchi@umweltbundsamt.at / Corina.dominko@umweltbundesamt.at or visit the following website: https://www.cloudefficiency.eu/home

Questionnaire

A. Inclusion of criteria in National Action Plans and best practices in the purchase of energy-efficient cloud computing services

1. Are you aware of any public procurement initiatives or working groups promoting energy-efficiency for cloud computing services (in your or in another EU country)? If yes, can you please describe them (e.g. core elements)? If not, is there any in preparation?

2. Are you aware of any national strategies or legislation promoting energy-efficiency for cloud computing services (in your or in another EU country)? If yes, can you please describe them (e.g. core ele-ments)? If not, is there any in preparation?

3. Are specific criteria for energy-efficient cloud computing services included in your National Action Plan for green or sustainable public procurement (in your or in another EU country)? If yes, can you please describe them (the wording of the criteria as well as its use as e.g. core criteria, comprehensive criteria)? If not, is there any in preparation?

4. Are you aware of any use-case or best practice example (in your or in another EU country)? If yes, could you please describe them? What criteria related to energy-efficiency are applied? If yes, can you describe them (e.g. core elements, relation to cloud and energy-efficiency)? If not, is there any in preparation?

5. Is there any ongoing discussion (at the political level, in social me-dia, etc.) in your country addressing the topic of energy consumption or energy-efficiency of the cloud? What are the main arguments?

B. Inclusion of energy-efficiency criteria in the preparation of public tenders

A number of tools exist, including standards, labels, guidelines, and legis-lation, which can foster the procurement of more energy-efficient cloud com-puting services. Please mark the statement which best fits each tool accord-ing to your personal experience.

		I never saw it being applied	I saw it being applied for the preparation of public tenders, but not in relation to cloud computing services	I saw it being applied for the preparation of public tenders for cloud computing services
Criteria	EU Code of Conduct on Data Centre Energy-efficiency			
Ecolabel	The Blue Angel (Der Blaue Engel)			
	The ENERGY STAR (expired)			
Directives	The EU Ecodesign Directive (2009/125/EC)			
	The EU Directive on Energy-efficiency 2012/27/EU			
	The EU 2020 Climate & Energy Package „20-20-20“			
Standards	ITU-T Recommendation: L.1321: Reference operational model and interface for improving energy-efficiency of ICT network hosts			
	ITU-T Recommendation:L.1325: Green ICT solutions for telecom network facilities			
	ITU-T Recommendation: L.1501: Best practices on how countries can utilize ICTs to adapt to the effects of climate change			
	ETSI GS OEU 008: Operational energy-efficiency for Users (OEU); Global KPI for Information and Communication Technology Nodes			
	ETSI ES 205 200: Access, Terminals, Transmission and Multiplexing (ATTM); Energy management; Global KPIs; Operational infrastructures			
	ETSI 103 199: Environmental Engineering (EE); Life Cycle Assessment (LCA) of ICT equipment, networks, and services; General methodology and common requirements			

Guidelines	Energy Innovation Procurement. A guide for city authorities (ICLEI, 2018)			
	Buying green! A handbook on green public procurement (European Commission, 2016c)			
	Public Procurement as a Driver of Innovation in SMEs and Public Services (European Commission, 2014c)			
	Guidelines - Leitfaden - Energieeffizienz in Rechenzentren (German Text)			

Table 48 - Questionnaire on GPP

6. Would you see it as particularly challenging to include any of the above- mentioned tools as a requirement in a public procurement tender? Could you please elaborate on that?

7. Are you aware of any other tools to include energy-efficiency in ten-ders for the public procurement of cloud computing services?

C. Market response

8. How would you rank, from poor to extended, the market offer (e.g. from service providers) for energy-efficient could computing services? Could you elaborate on that?

9. How mature would you rank, from poor to extended, the market de-mand for energy-efficient could computing services? Could you elaborate on that?

10. What are the most important barriers in the market? What could be potential drivrs?

D. Gaps and ways forward

11. Which of these gaps hamper the inclusion of energy-efficiency re-quirements in tenders for the procurement of cloud computing ser-vices? Please pick out the three most urgent issues:

a. Lack of know-how by practitioners

b. Lack of interest by practitioners

c. Lack of exchange of knowledge among practitioners

d. Lack of market offer/ interest (e.g. from service providers)

e. Lack of criteria/standards /labels

f. Lack of technological readiness/lack of suitable technologies

g. Lack of research & innovation on the topic

h. Lack of implementation costs

i. Lack of legislative framework

j. Other (please describe)

12. What would be in your opinion the most important actions to tackle these gaps?

18. ANNEX 5 - ALL RECOMMENDATIONS FOR RTD

All the recommendations suggested during the stakeholder process are listed here. The field “workshop priority” indicates the number of stakeholder groups (tables) at the workshop on RTD policy options on 9 September 2019 that considered this recommendation to be important. The numbers reach from zero to five.

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

<table>
<tr><td colspan="2">Recommendation</td><td colspan="2">Direct connected to RTD policy</td><td colspan="2">Workshop priority</td></tr>
<tr><td colspan="4">REC 1: Development of KPI for the energy-efficiency of cloud computing</td><td colspan="2">5</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of transparency, data availability, allocation of energy consumption and standards</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">A simple comparison of the energy-efficiency of cloud computing products is not possible today; a suitable KPI has yet to be developed.</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td></tr>
</table>

Table 49 - Recommendation 1 Development of KPI for the energy-efficiency of cloud computing

<table>
<tr><th colspan="2">Recommendation</th><th colspan="2">Direct connected to RTD policy</th><th colspan="2">Workshop priority</th></tr>
<tr><td colspan="4">REC 2: Detailed system management and monitoring to gather data for adjusting the runtime environment.</td><td colspan="2">1</td></tr>
<tr><th colspan="6">Type of contribution</th></tr>
<tr><td colspan="6">Improvement of transparency, data availability, allocation of energy consumption and standards</td></tr>
<tr><th colspan="6">Short description (interpretation of the study authors)</th></tr>
<tr><td colspan="6">The configuration of the runtime environment has a high impact on how efficiently software can be operated within 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.</td></tr>
<tr><th colspan="6">Impact on specific technological areas</th></tr>
<tr><th>IT equipment</th><th>Infrastructure for IT environments</th><th>Communication networks</th><th>ICT energy metering, control and analytics</th><th>Cloud (scaling) management</th><th>Cloud application software</th></tr>
<tr><td>No impact</td><td>No impact</td><td>No impact</td><td>Indirect impact</td><td>Indirect impact</td><td>Medium impact</td></tr>
</table>

Table 50 - Recommendation 2 Detailed system management and monitoring to gather data for adjusting the runtime environment.

<table>
<tr><td colspan="2">Recommendation</td><td colspan="2">Direct connected to RTD policy</td><td colspan="2">Workshop priority</td></tr>
<tr><td colspan="4">REC 3: Research of the influence of 5G and edge computing on the energy demand of cloud computing.</td><td colspan="2">2</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of transparency, data availability, allocation of energy consumption and standards</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>Medium impact</td><td>No impact</td><td>Large impact</td><td>Indirect impact</td><td>No impact</td><td>No impact</td></tr>
</table>

Table 51 - Recommendation 3 Research of the influence of 5G and edge computing on the energy demand of cloud computing.

Recommendation	Direct connected to RTD policy				Workshop priority
REC 4: Metering tool for software applications regarding their energy consumption/Development of a 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	Direct impact

Table 52 - Recommendation 4 Metering tool for software applications regarding their energy consumption/Development of a dedicated library for accounting at the OS level.

<table>
<tr><td colspan="3">Recommendation</td><td colspan="3">Direct connected to RTD policy</td><td colspan="2">Workshop priority</td></tr>
<tr><td colspan="6">REC 5: New energy measurement/monitoring solutions for existing DCs with moderate installation cost/lead time.</td><td colspan="2">1</td></tr>
<tr><td colspan="8">Type of contribution</td></tr>
<tr><td colspan="8">Improvement of transparency, data availability, allocation of energy consumption and standards</td></tr>
<tr><td colspan="8">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="8">It is much more effort to integrate monitoring technologies into existing data centres than into new buildings. To this end, further technological approaches are to be researched.</td></tr>
<tr><td colspan="8">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td colspan="2">Cloud (scaling) management</td><td colspan="2">Cloud application software</td></tr>
<tr><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td><td>Medium impact</td><td colspan="2">No impact</td><td colspan="2">Indirect impact</td></tr>
</table>

Table 53 - Recommendation 5 New energy measurement/monitoring solutions for existing DCs with moderate installation cost/lead time.

Recommendation	Direct connected to RTD policy				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

Table 54 - Recommendation 6 Development of standards to describe the energy-efficiency of individual components of the cloud computing ecosystem

<table>
<tr><td colspan="2">Recommendation</td><td colspan="2">Support RTD policies</td><td colspan="2">Workshop priority</td></tr>
<tr><td colspan="4">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</td><td colspan="2">0</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of transparency, data availability, allocation of energy consumption and standards</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td><td>Indirect impact</td></tr>
</table>

Table 55 - Recommendation 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

Recommendation		Direct connected to RTD policy, Support RTD policies		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

Table 56 - Recommendation 8 Public information about life cycle of cloud products + comparison of alternatives

Main focus on "Management and operation optimisation"

Recommendation	Direct connected to RTD policy			Workshop priority	
REC 9: Optimised load and resource management to increase relevant utilization of data servers and data centres				4	
Type of contribution					
Improvement of cloud management and operation optimisation					
Short description (interpretation of the study authors)					
Server utilization has long been an important issue as many servers are often idle; 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	Large impact	Indirect impact

Table 57 - Recommendation 9 Optimised load and resource management to increase relevant utilization of data servers and data centres

<table>
<tr><td colspan="3">Recommendation</td><td colspan="2">Direct connected to RTD policy</td><td>Workshop priority</td></tr>
<tr><td colspan="5">REC 10: Artificial intelligence to optimise cloud performance and reduce power consumption</td><td>2</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of cloud management and operation optimisation</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">Artificial intelligence offers great potential for the automatic optimisation of cloud services in terms of performance and (energy-) efficient operation.</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>Medium impact</td><td>Medium impact</td><td>Medium impact</td><td>Large impact</td><td>Large impact</td><td>Medium impact</td></tr>
</table>

Table 58 - Recommendation 10 Artificial intelligence to optimise cloud performance and reduce power consumption

Recommendation	Direct connected to RTD policy				Workshop priority
REC 11: Self-organizing self-managing heterogeneous cloud architectures and extending this paradigm to the edge. / Development of new architectures from cloud to thing with self-management and self-optimisation.					1
Type of contribution					
Improvement of cloud management and operation optimisation					
Short description (interpretation of the study authors)					
Cloud environments are usually operated in a self-organized way. Efficient operation, selection of optimum resource usage and selection of equipment best suited in heterogeneous 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	Large impact	Medium impact

Table 59 - Recommendation 11 Self-organizing self-managing heterogeneous cloud architectures and extending this paradigm to the edge. / Development of new architectures from cloud to thing with self-management and self-optimisation.

<table>
<tr><td colspan="2">Recommendation</td><td colspan="2">Direct connected to RTD policy</td><td colspan="2">Workshop priority</td></tr>
<tr><td colspan="4">REC 12: Development of new data centre concepts for the reduction of data traffic (e.g. fog computing)</td><td colspan="2">0</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of cloud management and operation optimisation</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">For many end-user applications, the proximity of the cloud service can help relieve traffic and thus reduce power consumption in core and backbone networks. In certain cases, concepts of fog computing can be a favoured alternative to a central cloud.</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>Medium impact</td><td>Medium impact</td><td>Medium impact</td><td>No impact</td><td>Indirect impact</td><td>No impact</td></tr>
</table>

Table 60 - Recommendation 12 Development of new data centre concepts for the reduction of data traffic (e.g. fog computing)

Recommendation	Direct connected to RTD policy	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 optimisation

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 such as reaction delay are of higher importance, for others it is less important. Analysis tools can help to better fit the parameters to the requirements and thus to improve 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	Large impact	Large impact	Medium impact

Table 61 - Recommendation 13 Improve cloud performance analysis tools to evaluate cloud performance and energy consumption

Recommendation			Direct connected to RTD policy		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 optimisation					
Short description (interpretation of the study authors)					
A permanently installed energy measurement and management system in cloud architectures can be used to support live optimisation 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

Table 62 - Recommendation 14 Development of integrated power measurement and energy management systems for cloud architectures

<table>
<tr><td colspan="3">Recommendation</td><td colspan="2">Direct connected to RTD policy</td><td>Workshop priority</td></tr>
<tr><td colspan="5">REC 15: Communication aware application to decrease data transfers.</td><td>2</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of cloud management and operation optimisation</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">Communication-aware software development can make a contribution to reducing data traffic on the Internet.</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>No impact</td><td>no impact</td><td>Large impact</td><td>Medium impact</td><td>Indirect impact</td><td>Large impact</td></tr>
</table>

Table 63 - Recommendation 15 Communication aware application to decrease data transfers

Recommendation			Direct connected to RTD policy		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 optimisation					
Short description (interpretation of the study authors)					
Application-specific management for comparing the QoS with 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	Large impact

Table 64 - Recommendation 16 Development of software that is able to control its service quality in comparison to energy consumption

<table>
<tr><td colspan="3">Recommendation</td><td colspan="2">Direct connected to RTD policy</td><td>Workshop priority</td></tr>
<tr><td colspan="5">REC 17: Cloud native programming (provisioning, runtime, logging)</td><td>0</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of cloud management and operation optimisation</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">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 ones).</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>No impact</td><td>No impact</td><td>no impact</td><td>No impact</td><td>Large impact</td><td>Large impact</td></tr>
</table>

Table 65 - Recommendation 17 Cloud native programming (provisioning, runtime, logging)

Recommendation		Direct connected to RTD policy		Workshop priority	
REC 18: Decentralised pre-processing of data				0	
Type of contribution					
Improvement of cloud management and operation optimisation					
Short description (interpretation of the study authors)					
The IoT in particular will result in more and more data being generated decentrally; complete processing in a central cloud would mean massive data traffic and thus increasing energy consumption in the communication networks. Decentralised pre-processing can massively reduce data traffic.					
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	Large impact	No impact	No impact	Medium impact

Table 66 - Recommendation 18 Decentralised pre-processing of data

Recommendation			Direct connected to RTD policy, Support RTD policies		Workshop priority
REC 19: Further dissemination and wider use of orchestration/management tools such as Kubernetes for efficient operation					0
Type of contribution					
Improvement of cloud management and operation optimisation					
Short description (interpretation of the study authors)					
Optimised resource management in a cloud environment can provide services more efficiently; well-known 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 metering, control and analytics	Cloud (scaling) management	Cloud application software
No impact	No impact	No impact	No impact	Large impact	Large impact

Table 67 - Recommendation 19 Further dissemination and wider use of orchestration/management tools such as Kubernetes for efficient operation

Recommendation	Support RTD policies				Workshop priority
REC 20: Further improve the publicly available orchestration tools (such as Kubernetes).					2
Type of contribution					
Improvement of cloud management and operation optimisation					
Short description (interpretation of the study authors)					
Kubernetes still has the potential to improve its functions in terms of efficient resource allocation.					
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	Large impact	Large impact

Table 68 - Recommendation 20 Further improve the publicly available orchestration tools (such as Kubernetes).

Main focus on "Improvement of energy-efficiency in individual technological components"

Recommendation		Direct connected to RTD policy, Support RTD policies		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 nearby heat consumers saving energy and cutting CO2 emissions.					
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

Table 69 - Recommendation 21 Reuse of heat generated by data centres

Recommendation	Direct connected to RTD policy				Workshop priority
REC 22: Use of artificial intelligence to optimise data centres, in particular to reduce the energy consumption of cooling systems					0
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 the potential to be further optimised with artificial intelligence, especially machine learning, for example to predict thermal situations in data centres. This will lower the PUE and save more 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	Large impact	Indirect impact	Large impact	No impact	No impact

Table 70 - Recommendation 22 Use of artificial intelligence to optimise data centres, in particular to reduce the energy consumption of cooling systems

<table>
<tr><td colspan="3">Recommendation</td><td colspan="2">Direct connected to RTD policy</td><td>Workshop priority</td></tr>
<tr><td colspan="5">REC 23: Hardware acceleration and new SoC design</td><td>1</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of energy-efficiency in individual technological components</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">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...) are used in cloud environments. It is very important from the perspective of energy-efficiency that the hardware architecture matches the needs of the software.</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>Large impact</td><td>Large impact</td><td>Large impact</td><td>No impact</td><td>No impact</td><td>No impact</td></tr>
</table>

Table 71 - Recommendation 23 Hardware acceleration and new SoC design

Recommendation	Direct connected to RTD policy				Workshop priority
REC 24: New communication strategies such as on-device machine learning and analog transmission					0
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	Large impact	Medium impact	No impact	No impact

Table 72 - Recommendation 24 New communication strategies such as on-device machine learning and analog transmission

Recommendation		Direct connected to RTD policy			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
Large impact	Medium impact	Large impact	No impact	No impact	No impact

Table 73 - Recommendation 25 "Standby ready" equipment and architectures

Recommendation	Direct connected to RTD policy				Workshop priority
REC 26: Modular computing (multiprocessing computer system where processing, memory and peripheral units can be added or removed without disrupting its operation)					0
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 faster renewal of hardware, which usually also has a positive effect on the CO_2 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
Large impact	Medium impact	No impact	No impact	No impact	No impact

Table 74 - Recommendation 26 Modular computing (multiprocessing computer system where processing, memory and peripheral units can be added or removed without disrupting its operation)

Recommendation	Direct connected to RTD policy				Workshop priority
REC 27: Efficient chip cooling					0
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. Taken together, transporting the refrigerant and generating cold consume the same amount of electricity as the chip itself. The limits of miniaturization in CMOS technology and thus a potential end to Moore's 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
Large impact	Indirect impact	Indirect impact	No impact	No impact	No impact

Table 75 - Recommendation 27 Efficient chip cooling

Recommendation	Direct connected to RTD policy			Workshop priority	
REC 28: Water cooling of servers, storage systems and network components				0	
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 guarantees that the water cooling system is 100% leak-proof and that it 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
Large impact	Large impact	Large impact	No impact	No impact	No impact

Table 76 - Recommendation 28 Water cooling of servers, storage systems and network components

<table>
<tr><th colspan="2">Recommendation</th><th colspan="2">Direct connected to RTD policy</th><th colspan="2">Workshop priority</th></tr>
<tr><td colspan="4">REC 29: Use of quantum computers for dedicated applications</td><td colspan="2">0</td></tr>
<tr><th colspan="6">Type of contribution</th></tr>
<tr><td colspan="6">Improvement of energy-efficiency in individual technological components</td></tr>
<tr><th colspan="6">Short description (interpretation of the study authors)</th></tr>
<tr><td colspan="6">The first quantum computers are commercially available. This offers new possibilities in ICT and many applications will profit from it in terms of both performance and energy-efficiency.</td></tr>
<tr><th colspan="6">Impact on specific technological areas</th></tr>
<tr><th>IT equipment</th><th>Infrastructure for IT environments</th><th>Communication networks</th><th>ICT energy metering, control and analytics</th><th>Cloud (scaling) management</th><th>Cloud application software</th></tr>
<tr><td>No impact</td><td>Indirect impact</td><td>No impact</td><td>No impact</td><td>No impact</td><td>No impact</td></tr>
</table>

Table 77 - Recommendation 29 Use of quantum computers for dedicated applications

Recommendation			Direct connected to RTD policy		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 as well as 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

Table 78 - Recommendation 30 General research on central cloud computing vs. decentralised edge computing in terms of energy-efficiency

Main focus on "Software efficiency"

Recommendation			Support RTD policies		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 very similar applications may sometimes require 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	Large impact

Table 79 - Recommendation 31 Energy-efficient programming (in general)

Recommendation	Direct connected to RTD policy	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	Large impact	Large impact

Table 80 - Recommendation 32 Developer guidelines for energy-efficient programming

<table>
<tr><td colspan="2">Recommendation</td><td colspan="2">Support RTD policies</td><td colspan="2">Workshop priority</td></tr>
<tr><td colspan="4">REC 33: Training of software developers, increasing awareness of energy-efficient programming</td><td colspan="2">1</td></tr>
<tr><td colspan="6">Type of contribution</td></tr>
<tr><td colspan="6">Improvement of software efficiency</td></tr>
<tr><td colspan="6">Short description (interpretation of the study authors)</td></tr>
<tr><td colspan="6">More efficient programming requires specific skills that are often not part of the software developers’ training. Targeted training and sensitization to energy-efficiency can make a contribution here.</td></tr>
<tr><td colspan="6">Impact on specific technological areas</td></tr>
<tr><td>IT equipment</td><td>Infrastructure for IT environments</td><td>Communication networks</td><td>ICT energy metering, control and analytics</td><td>Cloud (scaling) management</td><td>Cloud application software</td></tr>
<tr><td>No impact</td><td>No impact</td><td>No impact</td><td>No impact</td><td>Large impact</td><td>Large impact</td></tr>
</table>

Table 81 - Recommendation 33 Training of software developers, increasing awareness of energy-efficient programming

Recommendation	Direct connected to RTD policy				Workshop priority
REC 34: Slim/efficient design of hypervisor					0
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

Table 82 - Recommendation 34 Slim/efficient design of hypervisor

Recommendation	Direct connected to RTD policy				Workshop priority
REC 35: New programming languages for coding energy-efficient cloud application					0
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	Large impact

Table 83 - Recommendation 35 New programming languages for coding energy-efficient cloud application

Recommendation		Direct connected to RTD policy, Support RTD policies		Workshop priority	
REC 36: Development of a dedicated library for accounting at the OS level				0	
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	Large impact

Table 84 - Recommendation 36 Development of a dedicated library for accounting at the OS level

Recommendation	Direct connected to RTD policy				Workshop priority
REC 37: Develop tools that can easily assess the energy consequences of variations of programming (use of accelerators, data locality, data movements, ...).					0
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	Large impact	Medium impact	Indirect impact

Table 85 - Recommendation 37 Develop tools that can easily assess the energy consequences of variations of programming (use of accelerators, data locality, data movements, ...)

Recommendation	Direct connected to RTD policy				Workshop priority
REC 38: Research to increase 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	Large impact	Large impact	Indirect impact	Indirect impact	Indirect impact

Table 86 - Recommendation 38 Research to increase overall network energy-efficiency

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