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Green Economics: a Roadmap to Sustainable ICT Development

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Abstract— **The paper discusses a systematic approach to sustainable development. It puts forward an idea of analysing energy efficiency and sustainability of a particular product, service or even a process during the whole life-cycle. Minor carbon footprint or low energy consumption of a product during its operation or exploitation does not necessary mean that the product manufacturing, decommissioning and disposal are also sustainable. In this paper, we discuss a set of sustainable principles and propose a graphical notion describing key factors of product/process sustainability. We also consider information and communication technologies (ICT) as essential tools of sustainable development in various application domains. On the other hand, ICT themselves should be considered as an object of energy efficiency improvement. The paper discusses ICT impact on the environment and identifies the fundamental green ICT trade-off between dependability, performance and energy consumption. Finally, we consider problems and propose approaches to building green clouds and datacenters.**

Keywords—green ICT technologies; trade-offs; energy consumption; dependability; performance; green data centres

I. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC)[1] recommends limiting global temperature rise to 2°C in order to prevent disastrous consequences of climate change. In November 2014, China and United States, the two biggest emitters of greenhouse gases in the world negotiated a pact to cap carbon emission by 2030. In October 2014, to address the IPCC recommendations, the European Council agreed on the following targets for 2030 [1]: 40% Reduction of Greenhouse Gas Emissions, 27% of Power Consumption from Renewable Energies, 27% Improvement in Energy Efficiency. Moreover, IPPC declared in November 2014 that the climate change is almost entirely caused by human activity.

Recent years demonstrate significant improvements in developing sustainable technologies and products. Probably, the most impressive results have been achieved in the automotive industry. In 2016, the cumulative global sales of pure electric vehicles reached one million cars in total [2]. Tesla Model 3 presented this year shows that electric cars has reached technological maturity and can successfully compete (both in price, acceleration, speed, distance and other technical characteristics) with traditional cars. Electric cars, as compared to cars equipped with internal combustion engines, have no tailpipe emissions. It is assumed that electric vehicles can reduce greenhouse gas emissions compared to internal combustion engines. However, it can be true only if electric vehicles are recharged by low-emission electrical power sources, like nuclear power plants (NPP), solar or wind power generators.

Thus, electric cars themselves, cannot provide significant reduction of carbon emission. Moreover, taking into account the whole cycle of energy generation, it can be found that electric vehicles might be responsible for generating even more greenhouse gases. For instance, Singapore's Land Transport Authority found that the Model S was not environmentally friendly. Model S was estimated to use 444 Wh/km (instead of 210 Wh/km claimed by manufacturer) which corresponds to 222 grams of CO_2 "upstream" emission during the electricity generation process [3]. This exceeds direct CO_2 emission of a car petrol engine with the same power.

Besides, lithium-based batteries used by many modern electric cars may suffer thermal runaway and cell rupture or even can lead to combustion if overheated or overcharged. Moreover, their shelf life and cycle lifetime are quite limited while manufacturing and recycling is costly and is not environment-friendly. There are no doubts that alternatives to traditional internal combustion engines are of a great demand. However, energy efficiency and sustainability of new technologies that are coming on as substitute should be analyzed throughout the whole technology/product life cycle from manufacturing and energy generation to disposal and recycling.

Another crucial aspect of sustainable society development is advances in Information and Communications Technologies (ICT) which both contribute to, and offer opportunities to mitigate the world's carbon emissions.

According to the SMART 2020 report [4], ICT sector is responsible for, approximately, 2% of global carbon emissions and thus, contributes to climate change. It is, for example, equivalent to the CO_2 emissions of the whole

[1] https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/WGIIIAR5_SPM_TS_Volume.pdf

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aviation sector of the world economy. At the same time, the report highlighted that the ICT sector can save up to 15% of global emissions in 2020, mainly through enabling energy efficiency in sectors like transport, energy, industry and buildings.

The purpose of this paper is to consider information and communication technologies as, on the one hand, one of the contributors to the global carbon footprint and, on the other hand, as effective means for improving energy efficiency of other human activity sectors. In this paper, we discuss sustainability principles of the global economics and analyze fundamental trade-off and research activities aimed at improving energy efficiency of ICT.

II. GREEN ECONOMICS METHODOLOGY

A. Green Economics Principles

Emerging technology breakthroughs in big data, artificial intelligence, robotics, the Internet of Things, autonomous vehicles, 3D printing, nanotechnology, etc. has triggered so-called the fourth industrial revolution (4IR). 4IR integrates the physical, digital and biological worlds in the global society, economy and industry. The main driver of all industrial revolutions including 4IR has already been human's desire for improving productivity of labour by advancing manufacturing method and technologies.

Unfortunately, the ecological and environmental aspects have never been in the primary focus of the industrial development. We believe that understanding the fact that Earth could reach the critical climate threshold even in a decade [5, 6] should put sustainability forward as a cornerstone of the next industrial revolution and global society development.

In this paper, we introduce a term 'Green economics' assuming that sustainability, environmental friendliness and liability should be considered as major factors in the global economics and industry development in the coming decades. Preferences must be given to those technologies, manufacturing method and products which will help to reduce global warming and environmental pollution despite the higher cost. Governments, economists and company owners should accept the necessity to reduce profits in favor of saving Earth environment.

We propose a set of principles creating a foundation of the Green economics:

- ***Reduce***. Manufacturers should focus on reducing: (i) resource/material utilization, (ii) energy consumption, and (iii) waste/pollution emission per unit of a product or a service;
- ***Increase***. Manufacturers should focus on increasing/improving: (i) quantity of produced products/services, (ii) their durability, and (iii) performance/quality indicators per unit of used resources/materials, energy and generated waste/pollution. However, in some cases, implementation of the 'increase principle' does not mean becoming greener. Due to the rapid growth of a power of consumption, all extra-results can be absorbed very fast without leaving any trace for the future. Besides, it can lead to the crisis of economic glut and over-production. This is why manufacturer should extend durability of their products that can contradict the principle of programmed/planned obsolescence which is widely adopted these days [7].
- ***Reuse and Recycle***. From the very beginning of product design and development, manufacturers have to provide for products reparability, reuse, disposal and recycling. Nowadays, manufacturers are usually oblivious of this important aspect which results in producing 'disposable' products which are not suitable for further recycle and reuse. It is noteworthy that Apple and Samsung products have been ranked among the least repairable in new Greenpeace and iFixit assessment [8]. Thus, manufacturers should take on full responsibility for disposal and recycling of their products while enhanced reparability should be prioritized in product design. On the other hand, making products reusable and recyclable can increase their cost and reduce some performance characteristics. However, this is a necessary price for achieving sustainability. Besides, products manufacturers should be obliged to widely adopt trade-in programmes for their customers.
- ***Recover and Renew***. Extracting materials from disposed products for the future use is an important part of recycling. Besides, manufacturers should be concerned about recovering of resources sources (e.g. wood, water, etc.) and switch to using renewable energy sources. In EU, renewable energy generation (biomass, biofuels: ethanol and biodiesel, wood, hydropower, hydrothermal, wind, solar) varies from 5% (Malta, Luxembourg) up to 50% (Sweden). In particular, in Germany about 34% of net generated electricity came from renewable sources in 2016 [9], while U.S. energy consumption from renewable energy sources is only about 10% of total [10].

These principles are less specific than, for instance, those, proposed in [11, 12, 13]. They define general approaches to sustainable development and can be concretized and adapted to a particular application domain.

B. Green Economics Life-Cycle and Lightweight Sustainability Analysis

The Tesla Model S example discussed in the introduction section highlights the importance of accounting all environmental impacts during the whole product's life cycle as well as considering the whole chain of energy generation/consumption and CO_2/waste emission. ISO 14040:2006 introduces a framework for life cycle inventory analysis and impact assessment.

It aims at compilation and quantification of inputs and outputs (energy, raw materials, atmospheric emissions, water borne emissions, solid wastes, etc.) for a given product system throughout its *life cycle* [14].

There is a number of tools supporting life cycle inventory analysis [15, 16, 17]. However, most of them are tailored for experts, and too complicated for non-specialists and SMEs. We propose a lightweight approach to perform a life cycle inventory analysis.

Particular process, product or a system can be represented as a block with the two inputs and two outputs (see Fig. 1):

- ***resources*** (input): it includes raw materials (e.g. water, iron, wood, etc.) and other resources which are necessary to manufacture a product;
- ***energy*** source (input): electricity and/or fuel such as such as coal, gas, oil, wood which are necessary to provide power for light, heat and running of machines etc.
- ***outcome*** (output): manufactured products or useful activities/work performed by a system;
- ***waste*** (output), including toxicants and pollutants released to air, land, and water (e.g. greenhouse gases).

All the inputs and outputs can be split into different categories and quantified per unit of manufactured product or performed activity. Blocks can be pipelined in more complex chains or workflows.

Let us consider Tesla Model S which was estimated by Singapore's Land Transport Authority to produce 222 grams of CO_2 "upstream" emission during the electricity generation by fuel (coal, oil, and natural gas) power stations (see Fig. 2).

For comparison, tail-pipe CO_2 emissions of Audi A8 3.0 TDI diesel car are estimated at the level of 149–157 g/km [18]. Besides, cost and environmental aspects of producing and disposing/recycling of massive electrical accumulators used by electrical cars should be accounted.

It is in our plan to develop a graphical tool implementing the proposed approach. The aim of such tool is to be integrated into daily routines of process/product managers to help them in finding more sustainable and energy/resource efficient solutions.

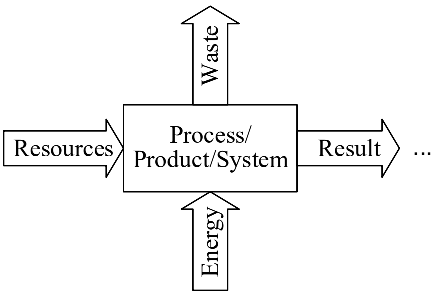

Figure 1. Inventory model for lightweight sustainability analysis

C. Green ICT and Greening by ICT

Information and communication technologies are responsible for approximately 2–2.5% of global CO_2 emission which is equivalent to the aviation industry carbon footprint [19]. This estimate covers the design, manufacture, distribution and in-use phases of PCs, servers, printers, cooling systems, fixed and mobile telephony and all commercial and governmental IT and telecommunications infrastructure worldwide.

On the other hand, information and communication technologies play the key role in developing smart and sustainable systems (Smart Grids, Cities, Buildings, Logistic, etc.). The ICT sector could help to mitigate the carbon footprint of other human activity sectors such as logistics, building, power transport and industry by 15% and reduce power consumption by 10% [20, 21]. Employing the best of ICT can dramatically improve energy efficiency of urban environment and services via developing smart systems taking into consideration the three pillars: planet, people and profit.

Thus, two the most important theses of the Green Economics approach can be formulated as: (i) ***Greening ICT*** and (ii) ***Greening by ICT*** meaning that ICT have to be considered as both an object and an important tool to advantage sustainability in various application domains and economic sectors.

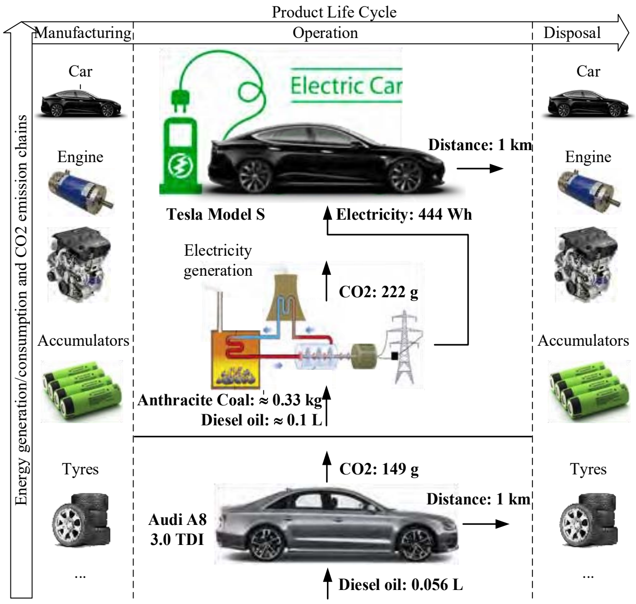

Figure 2. Example of a graphical notion for sustainability analysis

III. GREEN ICT

A. ICT Impact on the Environment

The total power supply of the all computing and communication equipment in the world accounts for 160 GW per year that is about 8% of the total generated energy in the world [22]. Besides, in 2011, Borderstep reported more than 1 billion EUR of total expenses were spent in the world for power supply of servers and data centers (DC).

However, 1W of application computing requires 27W of data center power and the aggregated energy loss can reach up to 97% [23]. For instance, while generating electricity by burning fossil fuels such as coal, up to 60% of energy are leaked as heat. Additional 5-10% is lost during energy transmission over high-voltage lines from a power plant to consumers. 55-65% of the rest can be lost in server's power supply units, for data centers cooling, ventilation and lighting. Up to 70% of the remaining energy are used to supply HDD discs, memory cards, mother board chips, input-output devices and coolers. Finally, only about 30% is spent by the CPU.

Thus, approximately, the only one of every 27 Watts consumed by DC is spent directly on performing user tasks (considering the average CPU utilization is up to 20%).

Considering environmental impact of servers, clients and computer networks Dr Alex Wissner-Gross has estimated that browsing a basic website generates about 0.02g of CO_2 for every second it is viewed [24]. Websites with complex video can be responsible for up to 0.2 g per second. Moreover, he claimed that the CO_2 generated to perform a single Google search is about 7grams (though, Google claimed [25] that typical Google search is equivalent to about 0.2 grams of CO_2).

Anyway, there is no doubt that the negative effect of using ICT is quite significant and will likely rise in the future. Thus, ICT industry needs to develop and adopt initiatives leveraging it to reduce the environmental impact.

B. *Green ICT Trade-off Model*

Energy efficiency of modern IT should be enhanced simultaneously at ***different scales*** (from the low-power chips and embedded systems up to the green communications and sustainable datacenters; from micro- and milliwatts to kilo- and megawatts) and at ***different levels*** (sustainable principles, models and algorithms, hardware, networking and software solutions). Fig. 3 shows the fundamental interplay between ICT power consumption, performance and quality (QoS or QoE, including dependability). For instance, switching to the 3D "Tri-Gate" 22 nm transistors [26] reduces CPU energy consumption by 50 percent at the same performance level, as the 2D 32nm generation. Alternatively, new processors can provide 37% more speed than their counterparts.

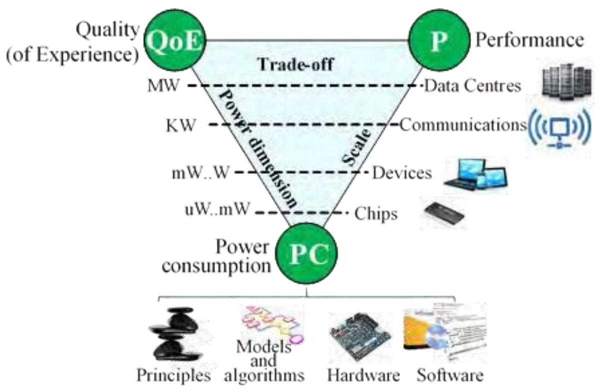

Figure 3. Green ICT: scales, dimensions and trade-offs

Quality in Experience (QoE) is a relatively new term defining the level of system/service quality and dependability, which is acceptable (i.e. good enough) for most of the end users [27]. QoE paradigm expresses objective and subjective user satisfaction and is in line with the ALARA (As Low As Reasonably Applicable) principle [28] widely used in safety-critical application domain.

Development of design principles for sustainable computing is based on but not limited to (1) approximate computing, e.g. lightweight encoding or cryptography, (2) power-modulated computing, (3) run-time interplay between power consumption, performance and QoS considering dependability, safety and security requirements.

Development of innovation techniques, models, architectural solutions and technologies for sustainable computing should be done at the scale of: (1) low-power chips and FPGA, (2) power-effective embedded computing systems and mobile devices, (3) green wired and wireless communications, and (4) sustainable data centers and cloud computing.

C. *Green Clouds and Datacenters*

Enhancing power effectiveness of information and communication equipment, servers and data centers is one of the key issues in modern IT industry. Energy efficiency, performance and dependability of applications running in data centers should be optimized at different levels – from developing energy-efficient applications to optimal VMs placement, dynamic tasks scheduling and proactive software rejuvenation enabling sustainable coexistence of virtual instances.

Virtualization of computing resources significantly reduces energy costs with denser placement (consolidation) of virtual machines on the physical servers. Sun Microsystems and Emerson Network Power have reported [29] that increasing the average load of a physical server from 10% to 70% (by increasing a number of virtual machines hosting on it from 2 to 8) will reduce the total number of servers in a data center by 4 times and will decrease the total energy consumption almost by 3 times.

Nevertheless, the consolidated deployment of virtual instances in practice leads to a decrease of their performance and stability of operation. Besides, it increases a risk of the appearance of a so-called 'Noisy neighbor' – a virtual machine, located on the same server, where applications are aggressively using shared physical resources (CPU, memory, disc or network I/O operations). Existence of a 'noisy neighbor' can lead to a significant performance degradation of the applications running on co-located virtual machines, and even cause a suspension of their operation or system failures [30].

Moreover, an effect called 'software ageing' can add complexity to the problem [31, 32]. This phenomenon refers to software tendency to fail, degrade performance and increase system power consumption after running continuously for a certain time.

It happens mainly due to memory leaks, memory and disc fragmentation, data corruption, numerical error accumulation, etc.

Development of Green clouds and datacenters is impossible without creating a strong engineering methodology. We believe the most promising research activities in this area will focus on improving energy efficiency of computer software rather than hardware. In particular, we put forward the following research and engineering frameworks:

- *Software power consumption measurement and billing*; this framework will provide useful tools for software power effectiveness measurement, prediction and optimization. Besides, it will introduce a new billing model based on measuring power consumed by a particular service or virtual instance;
- *Software power rejuvenation strategy*; we will examine a power ageing phenomenon related to virtual instances and particular software services running on them. As a result, we will develop a proactive strategy for software power rejuvenation (via VM reboot or services restart) to reduce the amount of energy consumed by a particular VM or a service, increase stability of operation and prevent performance degradation;
- *Smart task scheduling and virtual instances allocation for sustainable coexistence*. The framework will provide tools aiming at sustainable coexistence and effective consolidation of virtual resources through optimal task scheduling and allocation of virtual instances taking into account system resources utilization profiles of neighbouring VMs. This will effectively reduce the overall power consumption without affecting performance and dependability of different VMs by avoiding noisy neighbourhood.

The proposed frameworks will aim at decreasing electricity bills paid by DC owners and Cloud providers and providing more flexible billing model for cloud customers taking into account energy consumed by virtual instances. In turn, as the side effect we will stimulate ICT companies developing software to create more energy efficient applications.

D. *Interplay Between Energy Consumption and CAP Properties in Distributed Fault-Tolerance Systems*

Many studies (e.g. [33, 34, 35]) report that failures occur regularly on the Internet, clouds and in scale-out data centre networks. Thus, developers of large-scale distributed systems consider the Internet as a poor communication medium, which requires the introduction of fault-tolerance techniques. However, when developers apply replication in the Internet- and cloud-based systems, they need to understand energy overheads and have to consider additional delays and their uncertainty.

Similarly, providing consistency among replicas is another major issue in distributed fault-tolerant computing. The CAP theorem defining a trade-off between system *Availability*, *Consistency* and *Partition tolerance* [36] first appeared in 1998-1999. It states that the only two of the three properties can be preserved at once in distributed replicated systems. Gilbert and Lynch [37] consider the CAP theorem as a particular case of a more general trade-off between consistency, availability and latency [38] in unreliable distributed systems.

Necessity to run several system replicas as part of the fault-tolerance strategy increases the overall power, consumed by the system. The more replicas we run, the better availability can be achieved at higher energy expenses. Moreover, the more replicas we invoke simultaneously to increase data consistency, the more energy we spend in addition for parallel request processing and transferring larger amount of data over the network.

The interplay between Energy Consumption (EC), Fault-Tolerance (FT) and other CAP properties is shown in Fig. 4. Replication factor defines the main trade-off between fault tolerance and energy consumption which is proportional to the number of replicas.

Replication (i.e. redundancy) is introduced to the distributed computer systems with the two main purposes. Firstly, it is an effective approach to tolerate errors, failures and other abnormal situations, occurred in such systems. Secondly, replication increases performance of high loaded client-server systems by balancing users' requests between server's replicas. At the same time, the high degree of redundancy (large replication factor) which assumes better fault-tolerance does not necessary ensure high availability, which can be treated as a probability of a system to return response before time-out (see Fig. 4).

The second important trade-off is the consistency level, defining a number of replicas invoked simultaneously during the execution of a particular read or write request to return the adjudicated (consistent) result to a client application. Higher consistency level increases system latency especially if replicas are distributed over the Internet (hosting all replicas in the same data center, in general case, reduces the deviation between their response times; though the probability of common-mode failure is increased).

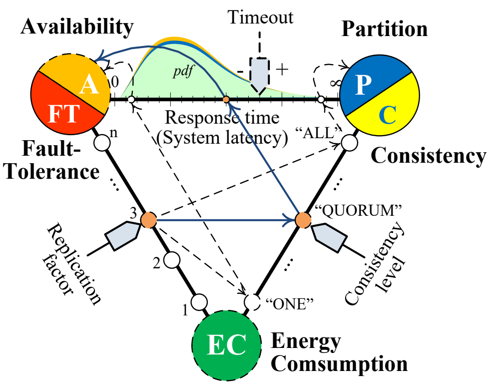

Figure 4. The interplay between energy consumption and CAP trade-offs

Concurrent execution of redundant replicas additionally increases the overall power consumption. If one of the replicas returns its response beyond the specified application timeout, the system enters a partition mode, causing timeout exception, or returns possibly incorrect (or inconsistent) response to the client.

Thus, the replication factor and consistency level contribute together to the overall energy consumption. We can consider the replication factor as the dominating factor in energy increase, while the consistency level is added as a variable component. Besides, in the global sustainability context, the amount of energy spent on network transfer of the increased amount of data also needs to be accounted for. As reported in [39], transporting data between data centers and cloud users can consume even larger amount of energy compared to processing and storing the data on the clouds.

IV. Greening Urban Environment and Services by ICT

The future world challenges include the impact of technological development and new emerging technologies on environment and require an enormous effort to efficiently address energy and GHG challenges. The SMART 2020 [4], SMARTer2020 [40] and SMARTer2030 [41] reports recommend to intensively deploying ICT both for enhancing the management of smart environment and human activities (industry, building, transport, etc.).

One of the crucial technologies is the Smart Grid which combines a traditional electric power grid with an "intelligent" ICT infrastructure to produce a smarter power system. Smart grid is complicated, multilevel and dynamical system of systems comprised of different ICT-based, interconnected and independent components. Enhancement and implementation of smart grid systems is one of the milestones for successful sustainable.

The NRC Report [42] reiterates this and proposes that the sustainability and education should be increasingly blended. Such harmonious and purposeful development can be presented by matrix (see Fig. 5) defining ***type of greening*** (e.g. what type of systems are applied, what activities are implemented) and ***object/level of greening*** (e.g. where systems or initiatives are applied to improve green related products and processes, to popularize green culture values). According to this scheme, the following objectives can be identified:

- Development of a scalable model and specific roadmaps for greening urban environment by ICT at different scales;
- Development of ICT services, monitoring and control systems for Smart urban environment (smart lighting and heating for buildings and campuses, smart lighting systems for city streets and region roads, smart waste collections, etc.);
- Development of the Ukrainian smart grid initiatives to stipulate the Smart Grid concept and vision development;
- Development of models and techniques to estimate and ensure Smart Grids safety and resilience;
- Development of *Green Memorandum* and promotion of *Green Culture* via social networks, by developing thematic web-portals and organizing a series of webinars, workshops and TV programs on Green ICT, business and culture.

Object/ level of greening	Type of greening					
	Smart lighting	Smart heating	Smart grid	Smart waste management	…	Green culture
Country			✓	✓		✓
Region/City	✓		✓	✓		✓
Campuses, Buildings, Houses/Flats	✓	✓		✓		✓

Figure 5. Greening urban environment and services by ICT

Conclusion

In this paper, we have discussed the Green Economics methodology which defines a set of green and sustainability principles aimed at improving efficiency of energy and resources utilization. The lightweight sustainability analysis approach is proposed to estimate and compare energy/resource consumption for various processes, products and systems during their life cycle.

Despite increasing energy directly consumed by the global ICT sector, modern information and communication technologies could help at mitigating the carbon footprint of other human activity sectors. Thus, we highlight the idea of *greening ICT* and *greening by ICT* reflecting the dual nature of such technologies.

This paper also discusses the fundamental trade-off models between energy consumption, performance, dependability and other system properties. In particular, we consider the interplay between energy consumption and CAP properties which is in the very nature of large-scale distributed fault-tolerance systems.

This paper analyzes issues of building green clouds and data centers and proposes a set of research activities focusing on improving their energy efficiency. They include development of power models estimating software energy efficiency; development of software power rejuvenation techniques and smart scheduling algorithms for sustainable coexistence of virtual instances.

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