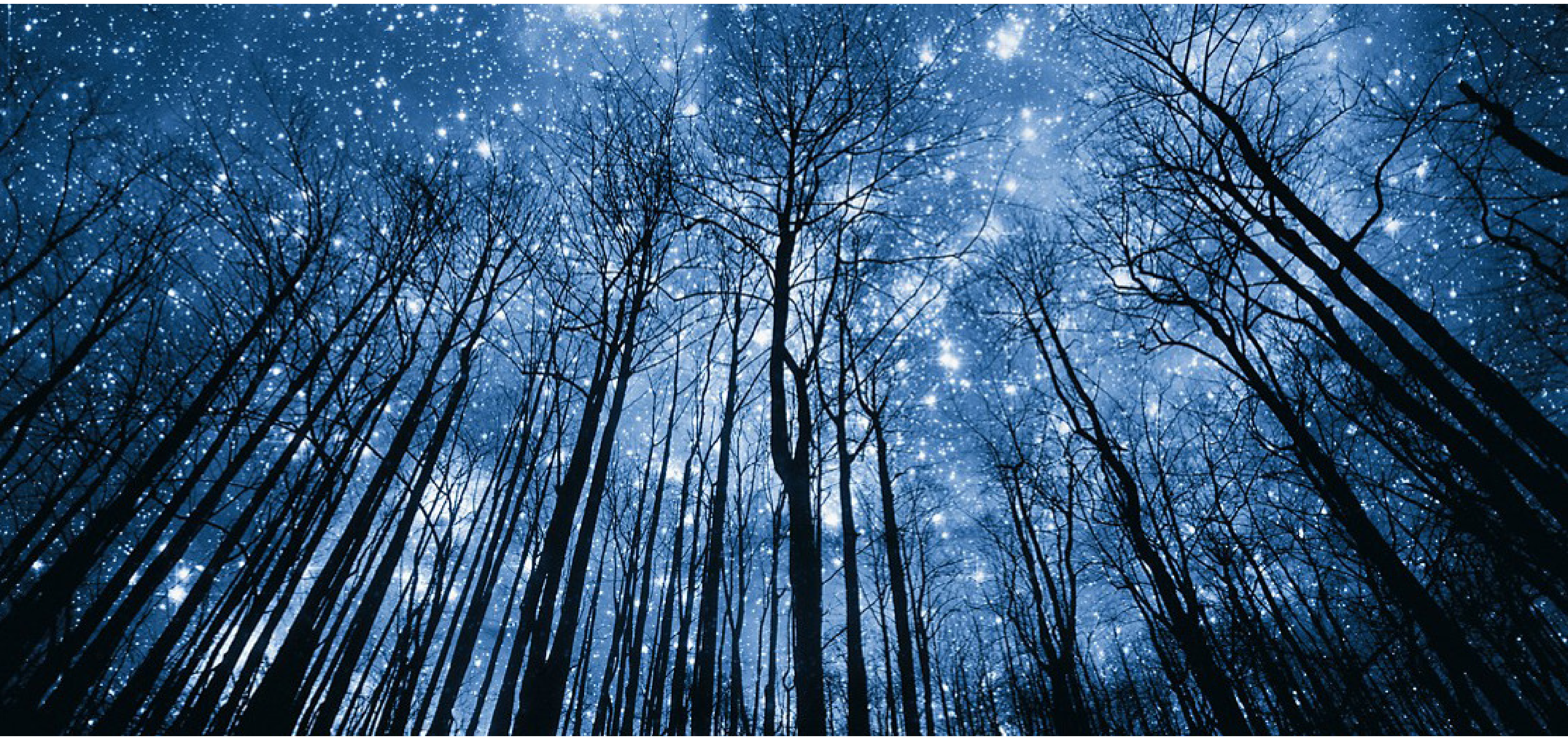
HOW IT CHANGES TO ADVANCE SUSTAINABILITY



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1. Introduction

While the science on climate change is complex and debates on some aspects continue, everyone agrees that the climate is changing and humans influence the climate. Reducing greenhouse gas (GHG) emissions ideally to net-zero is the main way to remediate the climate change impact.

In this article I review how energy efficiency improvements and renewable energy use in Information Technology (IT) or broader – in Information Communications Technology (ICT) – can contribute to this goal. I consider new technologies to reduce the IT carbon footprint. New methods of server high-density liquid cooling and intelligent power management in data centers are also discussed. From a sustainability perspective, how can data center engineering focus on renewable energy to substitute traditional carbon-intensive energy sources? How can environmentally sustainable data centers be built? I compare carbon footprint of data centers versus public cloud, and cloud-focused IT sustainability standards are reviewed.

Growth in data traffic such as video streaming requires additional internet infrastructure, leading to higher emissions. Various initiatives to address this challenge are presented in the article, and approaches for improving energy efficiency in IT such as Adiabatic Reversible Computing, use of direct current, and dematerialization are explored. I also consider Circular Economy and how IT Asset Management and Disposition programs can contribute to sustainability goals of companies.

Innovations in software development that contribute to GHG emission reductions such as Rust programming language are covered. As more efficient code requires fewer resources to run, it results in less energy usage in datacenters. Attention should be also paid to mitigate the impact of power-hungry cryptocurrency mining on the climate.

2. IT Sustainability: Definition, Standards & Measurements

2.1 IT Sustainability Terminology

For many companies and organizations, IT sustainability is becoming important in the environmental category of Corporate Social Responsibility (CSR). There are various definitions of sustainable computing. In this article, I use the definition of Sustainable Computing as a methodology having a broad spectrum from efficient energy use in IT to green storage, sustainable power-aware software, Adiabatic Reversible Computing and to Circular Economy.

The growing importance of sustainable computing is demonstrated by establishing a scientific journal: Sustainable Computing: Informatics and Systems (SUSCOM). This journal publishes research on energy-efficient and environmentally friendly computing technologies.[2] "Green Computing" and “Green IT” are the related terms. They can be defined as policies and practices to reduce the environmental impact of IT by making appropriate changes in the system life cycle starting with design, manufacturing, service implementation and finally to asset disposition. Energy-efficiency and circular economy are the key directions in green computing.[3]

The main terms used in sustainable IT are:

- Carbon neutral: a company’s carbon dioxide emissions are reduced as much as possible and then balanced by offsets.
- Zero carbon: no carbon dioxide gas was emitted in the first place.
- Carbon negative: a company removes more carbon dioxide gas than it emits.
- Net-zero emissions: there are net-zero emissions of all greenhouse gases, not just carbon dioxide.

2.2 IT Sustainability Standards

While the IT industry generates only about 1.4% of the global carbon-containing gas emissions,[4] rapidly growing digitalization is estimated to increase IT power consumption from 2% to 3% of the global electricity supply to 20% by 2030. To reduce future emissions and power consumption, several global international and country-local standards have been introduced. For example, the ISO TC 207 standard applies to environmental management systems, auditing, verification/validation and related investigations, environmental labelling, environmental performance evaluation, life cycle assessment, etc.[5] Standardization in the field of life cycle assessment, eco-efficiency assessment and related environmental management tools for products and organizations is provided by the ISO/TC 207/SC 5 Standard.[5] IEEE 1922.2 is a new standard for electricity emission calculations. Its goal is to improve the accuracy of electricity emissions modeling.[6]

There are also several Projects Authorization Requests (PARs) in development by the IEEE Standards Association as part of the IEEE Green ICT Initiatives Standards. Some examples are PAR 2, standard for calculations near real-time emissions of ICT infrastructure; PAR 4, recommending practice for developing energy-efficient power digital architectures; and PAR 7, proving a standard for the energy-efficient Orchestration and Management of Virtualized Distributed Data Centers Interconnected by a Virtualized Network.[6]

The ITU Telecommunication Standardization Sector has developed recommendations on sustainable development. For example, L.1471 provides guidance and criteria for ICT organizations on setting Net Zero targets and strategies.[7] Best practices for energy-efficiency without impacting the provided data center services are outlined in the EU Code of Conduct for energy consumption in data centers.[8,9]

The UK Department for Environment, Food and Rural Affairs (Defra) has initiated a project for “cloud sustainability”. The project goal is to create a standard that government departments and private sector companies can use in developing their cloud computing strategies.[10]

Governing by these standards, IT companies have developed their own IT sustainability programs. For example, Kyndryl implementing its Environment Sustainability Program will have 46 data centers that are part of the European Union Code of Conduct for Energy Efficiency in Data Centers.[11]

2.3 IT Sustainability Metrics

To manage environmental impacts of the IT industry, we need to be able to measure them first so that we can implement actionable sustainability metrics. Carbon footprint measured in tCO_2eq (metric tons of CO_2 equivalent) is the most common metric. It is based on the source of energy, manufacturing, and logistics impacts as well as product life cycle impact (e-waste).[12] Product carbon footprint (PCF) helps in understanding product impact on the environment throughout the entire life cycle of the product. PCF guides the design of sustainable IT equipment.[13] For example, Dell provides a collection of PowerEdge PCF documents listing the carbon emissions from the main life cycle phases of Dell servers.[14] The Dell PowerEdge R740 Full Life Cycle Assessment is a detailed and multi-factor impact analysis.[15]

In addition to PCF, Corporate Carbon Footprint (CCF) includes all GHG emissions related to a company’s business. In addition to direct emissions, CCF also considers all indirect emissions associated with a given business activity.[12]

The electricity carbon emission factor is used for correlating power consumption with the related carbon emissions. The weighted average electricity emission factor is determined by the average CO_2 emitted per unit of electricity generated in the grid.[16]

The Power Usage Effectiveness (PUE) is calculated as the ratio of the total data center power consumption to the amount of energy utilized by critical IT infrastructure systems (servers, storage, network equipment, etc.). The closer the PUE is to 1, the better the overall efficiency. The overall average PUE tends to be around 1.8. Data centers focusing on efficiency typically achieve PUE values of 1.2 or less.[17] While PUE is a popular metric, the way it is defined encourages critical systems using more energy in the data center, not less. Indeed, replacing old servers with more energy-efficient servers could increase PUE values.

The Data Center infrastructure Efficiency (DCiE) metric is the accepted benchmarking standard proposed by the Green Grid for determining the energy-efficiency of data centers.[18] "Dematerialization" is a term describing the reduction in the total energy and material use for product manufacturing or service delivery to lower its environmental impact. It covers the entire product life up to the disposal stage.[19]

The Life Cycle Assessment (LCA) metric is used to identify the main factors such as energy sources, raw materials, etc., contributing to key environmental impacts for the entire product life cycle.[20] It enables establishment of a benchmark to measure further improvements in environmental sustainability. Product Attribute to Impact Algorithm (PAIA) is a streamlined LCA tool that is used to perform PCF analyses. PAIA provides an estimate of the carbon impact of a product class, including notebooks, desktops, monitors, servers, network switches and storage.[21]

3. IT Sustainability and Innovations in Data Center Technologies

3.1 General Solutions for Optimizing Power Usage Effectiveness in Data Centers

The IT industry is energy-intensive, and this is exemplified by data centers. More efficient energy use and increasing the use of renewable energy from solar, wind, and hydrogeneration (Section 3.10) are seen as two main ways to reduce the related environmental impact. We will discuss various ways to increase energy efficiency use first.

While data centers (DCs) themselves do not generate GHG, electric power suppliers to DCs often send GHG pollutants into the atmosphere. To reduce the environmental impact, data centers must be designed to be efficiently utilize the infrastructure resources and minimize energy consumption.[22]

Electricity consumption by data centers globally is estimated to be approximately 200 terawatt-hours (TWh) of electricity. This is almost one percent of global electricity demand and it results in contributing to 0.3% of all global CO_2 emissions, according to the International Energy Agency. While this amount does not appear significant, it is important to bear in mind that the energy usage by data centers in some countries can increase to levels of 15 to 30 percent of their total domestic electricity consumption by 2030, according to predictive models by Eric Masanet and Nuoa Lei of Northwestern University.[23]

While the amount of data center computing workloads has increased almost 5 times from 2010 to 2018, data center electricity consumption has only risen by 6% due to significant improvements in energy efficiency. However, it is unclear whether energy efficiency improvements can continue to offset the growing energy demand of data centers as the number of data centers is expected to increase greatly over the next decade.[24]

The main ways for increasing energy efficiency in data centers are presented in Table 1.[25] They can be categorized as:

1. Energy-efficient IT equipment – reducing the energy consumed by IT equipment (e.g., servers, storage, network switches, etc.)
2. Power infrastructure – reducing losses from power distribution units (PDU) and uninterruptible power supplies (UPS)
3. Air flow management – improving cooling by preventing hot and cold air from mixing
4. Heating, ventilation, and air conditioning (HVAC) – optimizing cooling and humidification systems

Energy Efficiency Solution	Description & Examples	Article Section
Raising data center	Most IT equipment can tolerate higher operating temperatures. Every 1°F increase in temperature can save 4% to 5% in energy costs.	3.1
Server virtualization	Server virtualization results in fewer physical servers to power and cool. For example, a university that virtualized just 35 physical servers saved more than $280,000 over 3 years.	3.4
Increase server utilization	Most servers are not running anywhere near capacity. Consolidate and remove unneeded hardware. Data center surveys show that up to 30% of servers aren't doing any useful work, yet they consume electricity 24/7. According to the Uptime Institute, decommissioning a single server can save $500 in energy, $500 in operating system licenses, and $1,500 in hardware maintenance costs annually.	3.4; 7
Use of containers		3.5
Sustainable green storage	Deduplication software, for example, can reduce the amount of data stored at many organizations by more than 95%.	3.6
Sustainable software		3.7
Automation of data center operations	Using automated policies to data tier management can have a very positive impact on sustainability objectives.	3.2
Utilizing built-in server power management features	Modern servers come with features that can save energy. For example, server processors can reduce power consumption during times of low utilization.	3.3
Manage airflow for cooling efficiency	Inexpensive grommets, diffusers, and blanking panels can keep cold air from mixing with hot exhaust air. One large data center saves $360,000 annually thanks to inexpensive air flow management measures.	
Use innovative cooling technologies	Liquid cooling.	5
Migrating applications to cloud (cloud data centers)		6
Reduce energy losses from power distribution units (PDUs)	Look for more efficient PDUs and "smart" PDUs that monitor power usage. High efficiency PDUs are 2% to 3 % more efficient than conventional units.	
Reduce energy losses from uninterruptable power supply (UPS) systems	Energy-efficient UPS systems minimize electrical losses and may feature an "eco-mode." Properly loading UPS systems can save energy as well.	

	Running UPS systems in eco-mode can reduce data center energy costs by as much as 2%.	
Utilize containment/enclosures	Curtains or Plexiglas panels can keep cold air from mixing with hot air exhaust from the backs of servers, reducing overall cooling costs. In data centers with hot/cold aisle arrangements, containment systems can reduce energy expense by 5% to 10%.	
Use sensors and controls to match cooling capacity & airflow with IT loads	Data Center Infrastructure Management (DCIM) is the convergence of IT and building facilities functions so that energy, equipment and floor space are used as efficiently as possible. DCIM provides information to allow you to "right-size" the infrastructure and reduce energy costs by as much as 30 percent.	
Consider a water-side economizer	Use a cooling tower instead of a mechanical chiller to supply chilled water for cooling the data center. Reduce the cost of chilled water by up to 70%.	
Use an air-side economizer	Cool your data center for (almost) free by using air from outside, weather permitting.	
Install in-rack or in-row cooling	These systems bring cold air closer to (or directly to) servers. Can use 3 times less energy in high-energy density server rack than conventional cooling systems	
Make humidification adjustments	Modern IT equipment can tolerate wider ranges of humidity. BNY Mellon expanded humidification set points, reducing humidification run-time from 80% to 20% of the time. If you must add humidity, use energy-efficient technologies such as misters, foggers, and ultrasonic units. eBay's ultrasonic humidification units save $50,000 annually, a 2-year payback.	
Replace standard fans with variable speed fans	Variable speed fans optimize data center cooling and save energy. eBay's investment in variable speed fan retrofits had a 1.6-year payback.	
Institute ENERGY STAR purchasing policy	Always purchase ENERGY STAR-certified servers, data storage, networking, and uninterruptible power supplies. ENERGY STAR-certified servers can save $60 to $120 annually in electricity per host.	

Table 1. Main Ways to Increase Energy Efficiency in Data Centers (Adapted from Ref.25)

Some IT service providers, for example, Kyndryl, offer Data Center Consulting Services enabling visibility of carbon emission levels from data center infrastructure and its operation. Customers are provided with a report with recommendations for reducing carbon emission levels to align with their organization's strategic carbon emission target.[11]

Optimizing Temperature in Data Centers. Typically, cooling and IT equipment (servers, network devices, etc.) in a data center consume about 40% and 50% of the electric energy used by DCs, respectively. However, increasing the set-point temperature in data centers enables reduction in power consumption.[23] This improves power usage effectiveness (PUE) and energy efficiency, while hardware is continuously monitoring for temperature-related issues.

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommendations (2008), the operating temperature range measured at the server inlet (or front) can be expanded from 20°C - 25°C (68°F-77°F) to 18° - 27°C (64.4°F-80.6°F). ASHRAE studies have shown that increasing the operating temperature has little effect on server component temperatures but can result in significant energy savings. By 2011, the inlet temperature for each server in the Facebook Prineville and Forest City data centers were raised from 26.6°C (80°F) to 29.4°C (85°F). The operating temperature in Google data centers is 26.6°C (80°F).[26]

Using a higher operating temperature is possible because most recent data center equipment is certified for the highest inlet temperature of 95 °F. For example, Dell Power Edge R730 server has the standard operating temperature of 10°C to 35°C (50°F-95°F) with no direct sunlight on the equipment.[27] According to some estimates, data centers can save 4% to 5% in energy costs for every 1°F increase in server inlet temperature.

While some IT equipment vendors have increased the operational temperature ranges to allow for higher inlet temperatures, the data center should be cooled to the lowest operating temperature among all the installed equipment. For instance, you may have a large number of Dell servers with a cooling range of 85º to 95ºF but end-of-the-row Cisco Nexus switches may require the operating temperature lower than 95ºF. Setting different temperature zones can help but not in all cases.[28] Furthermore, setting the highest recommended server inlet temperature may not be the most efficient. As a study by Dell Technologies has found, higher server inlet temperatures can cause internal server fans to automatically speed up and this results in increased overall energy consumption.[28]

Raising operating temperatures can result in occurrence of hot spots. To address this, Dell PowerEdge servers are equipped with Fresh Air 2.0-capable systems and cooled by clean outside air to meet ISA-71 G1 quality.[28]

3.2 Role of Automation in Improving Energy Efficiency in IT

Automation in IT services has the potential to advance the sustainability of enterprise data centers and cloud operations. For example, estimates show that data storage accounts for 10% to 15% of data center energy consumption. Using intelligent storage tiering can significantly reduce this. Automated cost optimization tools (FinOps for clouds) can minimize consumption of cloud resources by a given application without impacting its performance. This is not just cost savings. FinOps tools ensuring that only the optimal set of resources is used by cloud-based applications support sustainable cloud IT practices.[29] Energy consumption by IT infrastructure can also be reduced by automating management of on/off states of resources to scale-out/in by demand while simultaneously sustaining the required performance.

3.3 Utilizing Built-in Server Power Management Features

In general, newer servers are more energy-efficient than older servers. Indeed, they have more efficient power supplies, modern processors with less power consumption and more energy-efficient cooling fans. In addition, new servers have built-in power management features, reducing power consumption for server workloads. Let us look at some types of server power management.

<u>CPU Throttling,</u> also known as dynamic voltage and frequency scaling, can reduce server energy use by automatically adjusting the speed of the CPU during times of low utilization. This reduces heat generation and enables slower cooling fan operation.

<u>Core Parking</u> allows for dynamically disabling CPU cores to conserve power when the CPU load is low. When the CPU load increases, disabled cores are re-enabled.

<u>Power Profiles</u> are pre-defined groups of power management settings. A power profile defines the server power management options. There are typically four basic selections: (1) Balanced mode for the power management having a negligible impact on system performance. (2) Maximum Performance. (3) Maximum Energy Efficiency minimizes system power use, but it can impact system performance. (4) Power Metering and Budgeting uses server power metering software to set power limits, or caps.

Dell's Open Manage Power Center is an example of a software solution to measure and manage server power consumption. Enhanced Dell Energy Smart Architecture reduces power consumption by using intelligent power management.[30]

3.4 Role of Server Virtualization in Improving Energy Efficiency in IT

Because server virtualization results in using fewer physical servers, energy consumption decreases and the data center needs less air conditioning. According to some estimates,[25] reducing the server electricity consumption by one watt-hour typically results in an additional reduction by 1.9 watt-hours at the data center level.

Embodied energy is a term describing the energy required to manufacture, and supply to the point of use, a product, material, or service. Embodied energy for a server is about 25% of the life cycle emissions.[31] Therefore, in addition to direct energy consumption savings by reducing the number of servers, server virtualization results in a reduction of embodied energy.

3.5 Containerized Applications and Energy Consumption Reduction

Just ss server virtualization is an essential way to reduce energy consumption, application containerization goes to the next step to generate even larger energy savings. Running several containers on one virtual machine (VM) enables more efficient use of VM resources and decreases the number of required VMs.[32] Furthermore, modern containerized applications are based on microservice architecture and utilize infrastructure resources more efficiently.[33,34]

3.6 Green Data Storage

According to IDC, by 2025, more than 11 zettabytes of data will be generated globally. This growth in data storage will impact the environment.[35] The Storage Networking Industry Association (SNIA) has developed the Green Storage Initiative (GSI) with a goal of advancing energy efficiency in all networked storage technologies and minimizing the environmental impact of data storage operations. The GSI establishes and maintains data center energy efficiency related programs, test and measurement methods, and standards.[36]

The SNIA Emerald Power Efficiency Specification has been created by the SNIA Green Storage Technical Work Group (TWG). The Emerald specification is used in national and regulatory testing programs for energy efficiency. The Energy Star Program (United States Environmental Protection Agency [EPA]) for Data Center Storage references the SNIA Emerald Specification. The SNIA Emerald Program describes the use of storage system measurement procedures and test metrics documented in the SNIA Emerald Power Efficiency Specification.

The study[37] has found that using intelligent data management policies to identify and archive cold data to offline cold storage can significantly reduce data center energy consumption. Needless to say, moving data to the secondary storage targets is not only environmentally friendly; it is also budget friendly.[38]

There are several storage capacity optimization solutions reducing the overall amount of operational power:

- Thin provisioning systems can save potentially half of the energy required per TB of required storage, as systems can be sized smaller at original purchase time and scaled up as data needs grow.
- Data deduplication replaces multiple copies with a source copy and multiple pointers to it, resulting in space savings quoted to be as high as 99%.
- Compression – used in conjunction with deduplication.
- Delta Snapshots generally save 80% up to 98% of the size of the raw capacity required to hold the target data set, per snapshot. Depending on how heavily they are used, the potential energy savings can be significant.
- Automated Storage Tiering decreases the power usage because both SSDs and SATA drives use less power than SAS or FC drives.
- Cloud Storage Services. Cloud offers the potential to significantly increase storage energy efficiency by using the flexible, scalable model that is resource efficient.

3.7 Green and Sustainable Software

Recent years have shown that the energy consumption of software is gaining attention in green IT initiatives. Indeed, as a result of the constantly increasing digitalization, the general power consumption generated by software is also growing. Terms such as “Green and sustainable software” and “power-aware software” are becoming popular.[39] As software products are immaterial goods, how can the indirect material impacts of these products be assessed in conceptual and methodological terms?

Various criteria have been proposed to assess software ‘‘sustainability’’. One of the questions is how to link observable properties of a software product to conditions defining whether it can be considered as “green” or (more generally) “sustainable.” Some definitions suggest considering a software product if it requires significantly lower hardware and energy flows than competing products with similar functionality. While it seems at first glance that software is an environmentally friendly type of product, in reality software products with the same or similar functionality can differ substantially in their environmental impact.

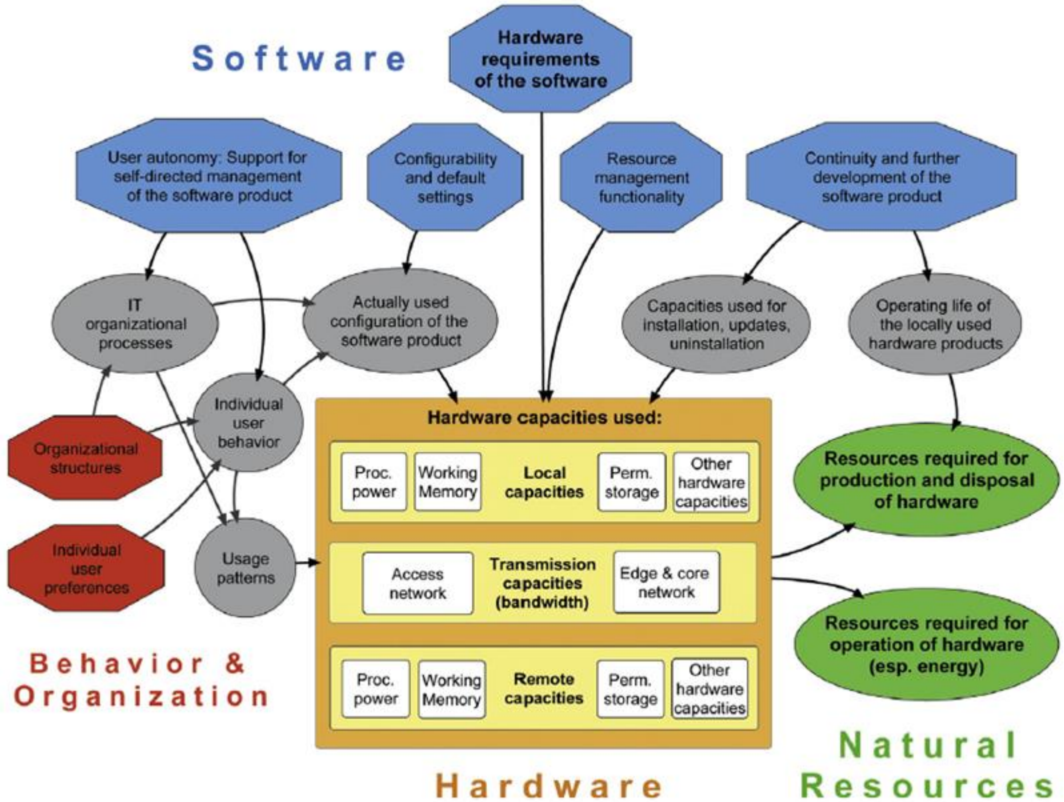

Figure 1. The Model Describing the Causal Chains Leading from Software Properties (blue) to the Natural Resources Required for Using the Software (green) (Ref. 40).

Figure 1 presents the model linking software properties (blue) to the natural resources required for using the software (green). A link means ''has impact on''. The central node, ''Hardware capacities used'', consists of several types of local, transmission, and remote hardware capacities required to run the software product. The Green Software Foundation[41] places its focus on carbon footprint reduction rather than neutralization. Indeed, it is better to never have emitted the carbon dioxide in the first place. However, as GHG reduction is more difficult than offsetting, more investment is required. To incentivize investment into green software products, the Green Software Foundation creates an ecosystem of standards, tools, and best practices for the reduction of GHG emissions caused by software use. The Foundation suggests the following actions:

- Using fewer physical resources
- Using less energy
- Using energy more efficiently

Measuring the energy consumption of software is not a trivial task. The Software Carbon Intensity (SCI) specification offers a methodology for calculating the rate of carbon emissions by a software system. The methodology allows users and developers to make informed decisions for selecting software architectures and development approaches for green software development.[42]

Various software energy profilers are available, for example, Intel Power Gadget[43] and Perf.[44] The nvidia-smi tool[45] enables measuring the Nvidia GPUs' power consumption of GPU-intensive applications such as training a deep learning model, watching a video, and so on.

An interesting question that frequently arises in analysis of software energy efficiency is whether a faster program is also an energy-efficient program. If it is true, then optimizing a program for speed also means optimizing it for energy. However, energy consumption depends not only on execution time but also on the power consumed by the computational system running the program.

A similar question comes up in comparing software languages: is a faster language a greener one? Comparing environmental friendliness of software languages is a mammoth undertaking since the language performance is determined by the compiler quality, garbage collector, available libraries, etc. While an application can be faster after improving its source code, the execution time can also be improved by optimizing its libraries and/or its compiler.

The energy efficiency of 27 software languages has been analyzed by Rui Pereira.[46] C has been found to be the most energy efficient and Rust comes close behind with just 3% more energy use (Table 2). Rust consumes less energy than other programming languages such as Python (98% less), Java (50% less), and C++ (23% less) (Table 2).

Total					
	Energy		Time		Mb
(c) C	1.00	(c) C	1.00	(c) Pascal	1.00
(c) Rust	1.03	(c) Rust	1.04	(c) Go	1.05
(c) C++	1.34	(c) C++	1.56	(c) C	1.17
(c) Ada	1.70	(c) Ada	1.85	(c) Fortran	1.24
(v) Java	1.98	(v) Java	1.89	(c) C++	1.34
(c) Pascal	2.14	(c) Chapel	2.14	(c) Ada	1.47
(c) Chapel	2.18	(c) Go	2.83	(c) Rust	1.54
(v) Lisp	2.27	(c) Pascal	3.02	(v) Lisp	1.92
(c) Ocaml	2.40	(c) Ocaml	3.09	(c) Haskell	2.45
(c) Fortran	2.52	(v) C#	3.14	(i) PHP	2.57
(c) Swift	2.79	(v) Lisp	3.40	(c) Swift	2.71
(c) Haskell	3.10	(c) Haskell	3.55	(i) Python	2.80
(v) C#	3.14	(c) Swift	4.20	(c) Ocaml	2.82
(c) Go	3.23	(c) Fortran	4.20	(v) C#	2.85
(i) Dart	3.83	(v) F#	6.30	(i) Hack	3.34
(v) F#	4.13	(i) JavaScript	6.52	(v) Racket	3.52
(i) JavaScript	4.45	(i) Dart	6.67	(i) Ruby	3.97
(v) Racket	7.91	(v) Racket	11.27	(c) Chapel	4.00
(i) TypeScript	21.50	(i) Hack	26.99	(v) F#	4.25
(i) Hack	24.02	(i) PHP	27.64	(i) JavaScript	4.59
(i) PHP	29.30	(v) Erlang	36.71	(i) TypeScript	4.69
(v) Erlang	42.23	(i) Jruby	43.44	(v) Java	6.01
(i) Lua	45.98	(i) TypeScript	46.20	(i) Perl	6.62
(i) Jruby	46.54	(i) Ruby	59.34	(i) Lua	6.72
(i) Ruby	69.91	(i) Perl	65.79	(v) Erlang	7.20
(i) Python	75.88	(i) Python	71.90	(i) Dart	8.64
(i) Perl	79.58	(i) Lua	82.91	(i) Jruby	19.84

Table 2. Normalized Global Results for Energy, Time, and Memory (Ref.46)

Garbage-collecting languages are inherently less efficient. This means languages such as Java, C# and JavaScript can never be as efficient and performant as C and Rust.

3.8 Can Direct Current Power Make Data Centers More Energy Efficient?

While alternate current (AC) power distribution systems are used in most data centers, recent years have witnessed a growing interest to explore and utilize direct current (DC) power distribution systems as another option. There are servers on the market that can operate on both DC and AC power. Telecommunication companies such as Comcast and Verizon already use DC power in their central offices. Nearly every telco central office uses a 48V DC power plant to power directly its telecommunications equipment and UPS systems.[47]

A further example of expanding the use of DC power is the Google announcement in 2016 of the development and use of a 48V rack solution.[48] In addition, Google announced a joint project with Facebook and others about further development of DC power within the Open Compute Project.[49] As every AC-to- DC conversion leads to power losses and heat generation (Figure 2), using DC power as much as possible throughout the power chain results in energy savings.

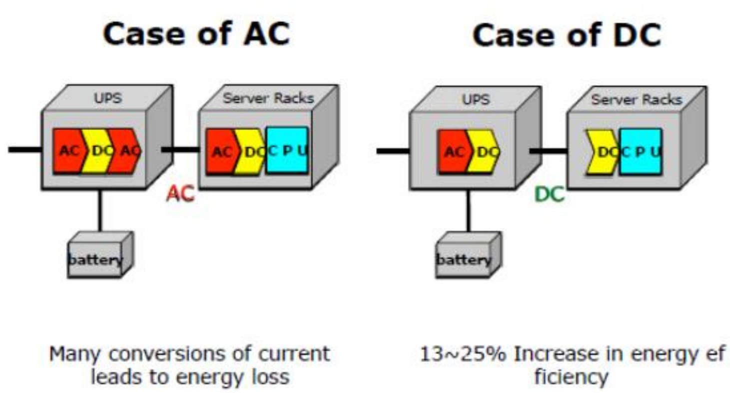

Figure 2. Energy Efficiency of Direct Current Power (Ref.47)

Benefits of DC Power[47]

Less complex. DC power conversion is less complex when compared to AC power. Therefore, less data center space and equipment are required. In addition, DC power systems having a simpler design do not need phase load balancing.

Uses less space. Using DC power equipment results in 25% reduction in the raised floor use compared to an AC power data center. As this saved space allows for installation of more racks and servers, the cost of space is less in a DC power data center.

Power quality. The power quality is better in DC and the power loss is less compared to AC (Figure 2).

Modular and scalable. DC power systems are more scalable as they can be built over time as the load increases by adding more battery strings. Adding energy storage devices such as batteries can be done as needed without changing the existing architecture. In contrast, for AC power use, a UPS needs to be installed with maximum power capacity from the very beginning.

Integration with other sources. Integration of energy sources such as solar panels and fuel cells with DC power systems in data centers is easier.

Longer run time. The run time provided by batteries in DC power data centers in case of power failure is longer compared with a UPS for the same load.

Limitations of DC Power

Lack of knowledge and experience. Since very few companies have their data centers run by DC power, there is a lack of experience among data center owners and operators. Similarly, the lack of knowledge and experience limits the hardware vendor support.

Lack of standard. There is no industry-defined standard design for a DC power data center yet. The International Electrotechnical Commission (IEC) has standardized plug and socket devices according to TS 62735 (the IEC TS 62735-1 standard for power distribution systems up to 2.6 kW and IEC TS 62735-2 for power distribution systems with outputs of up to 5.2 kW).[50]

Refactoring cost. Since most data centers use AC power, there is a cost involved in retrofitting the existing architecture. The data center industry may not be in favor of DC power because changing the existing AC power architecture to support DC power can be expensive. However, DC power is a promising option in designing new data centers.

Limited DC power resources. Vendors offer only a limited number of servers running on DC power supplies. The lack of air conditioning systems and fire protection systems running on DC power slows adoption of DC power distribution systems in the data center.[51]

Nevertheless, better integration of DC power with renewable sources of energy such as solar and wind, as mentioned above, can be a factor that overrides the discussed DC limitations. Since renewable sources generate power intermittently (when the sun shines or the wind blows), storage (batteries) is required as part of the system for providing reliable power supply. Solar photovoltaic device is inherently a DC energy supply, as are batteries, making DC a more naturally compatible interface.[52]

3.9 Environmental Water Footprint of DCs: Cooling and Water Consumption

Data centers directly and indirectly consume water in their operation. Indeed, electricity generation is the second largest water consumer and the second largest emitter of GHGs in the US.[53]

As most of the water used by data centers typically comes from potable sources supplying homes and businesses with drinking water, data centers compete with other users for access to local water resources. For example, a medium-sized data center (15 MW) uses as much water as three average-sized hospitals or more than two 18-hole golf courses.[54] As estimated, data centers globally consume enough water for cooling purposes to fill 120,000 Olympic-sized swimming pools each year.[55]

In addition to the electricity consumed directly by data centers, the indirect consumption includes the electricity used for supplying treated water to data centers and treating the wastewater discharged by data centers. The electricity required in the provisioning and treatment of water as well as treatment of discharged wastewater emits GHGs and this GHG emission can be attributed to data center operations. Water may also be used directly within a data center for cooling.

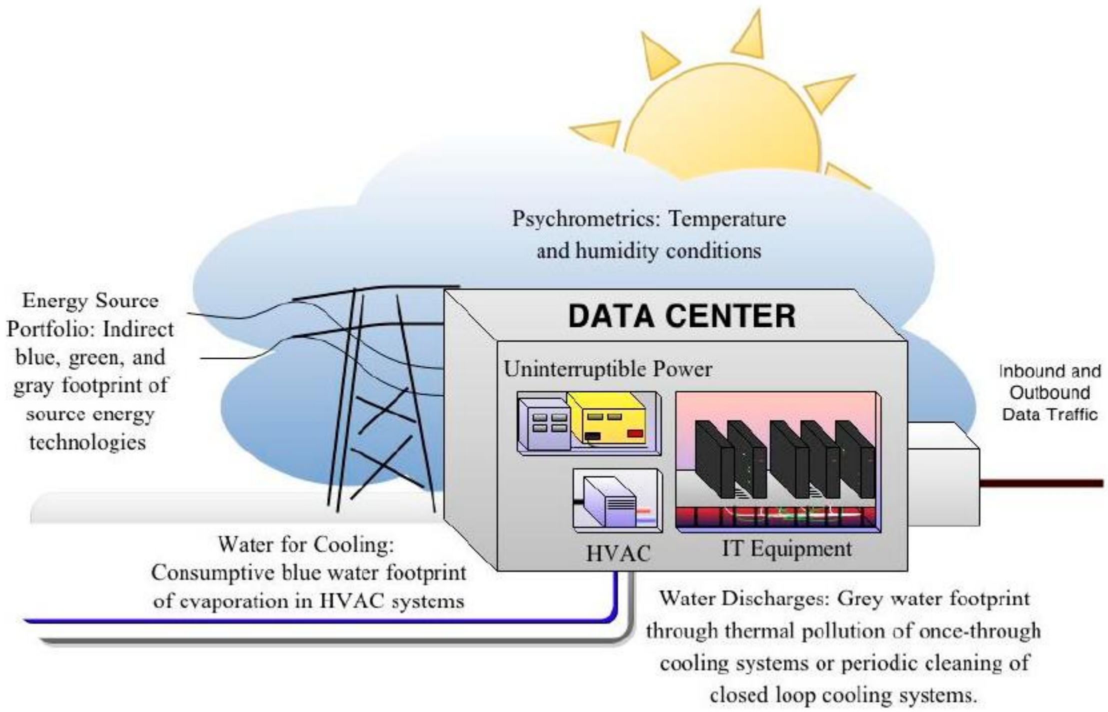

Figure 3. Data Center Components and Water Footprint Drivers: HVAC, Climate, and Energy Sources (Ref.53).

The Water Use Effectiveness (WUE) metric developed by the Green Grid[56] is emerging as the industry standard for measuring DC water use. WUE is defined as the total facility water use divided by the energy consumed exclusively by the IT systems. The higher WUE is, the more water-intensive DC is. According to the US Department of Energy, the average data center has the WUE of 1.8 L per 1 kWh. If a data center WUE is 0.2 L/kWh or less, it uses less than one cup of water for every kWh consumed by IT infrastructure. Along with PUE (Section 2.3), WUE provides an estimate of DC energy efficiency.[57]

Water Footprint (WF) is a measure of direct and indirect water usage.[58] Since it considers the water usage attributed to the consumer rather than the producer, it is a consumption-based metric. Combined WUE and WF are useful indicators of water-usage effectiveness.[59]

There are a number of approaches for reducing water usage by data centers. More efficient cooling technologies like liquid water cooling are gaining interest. Liquid immersion cooling is predicted to be capable of lowering energy consumed by IT equipment by a minimum of 5% to 15% while also using less water than chilled-air cooling.

The Hamina data center in Finland opened in 2011 uses seawater for cooling. The cold seawater that is kept separate from the freshwater circulating within the heat exchangers is pumped into heat exchangers within the data center. The expelled hot water is mixed with cold seawater before being returned to the sea.
Some IT vendors, for example, Dell Technologies report to the CDP water program (formerly the Carbon Disclosure Project).[60] Innovative closed-loop and rainwater collection systems are used at Dell Technologies facilities.[61]

4. ICT Transitioning to Renewable and Clean Energy Sources

4.1 Renewable and Clean Energy in Data Center Operations

Along with more efficient energy use we discussed above, transitioning to renewable energy sources is another key approach in reducing the environment impact of data centers. Increasing the use of clean energy for data center operations is essential in achieving the goal of carbon neutrality by the ICT industry. It is not an easily achievable goal since availability and reliability of IT services that are of utmost importance for DC operators should not be impacted by transitioning to renewable energy.[62]

The IDC identifies three directions for data centers to increase their usage of renewable and clean energy sources:

1. Increasing the use of renewable energy generated onsite and offsite.
2. Aligning renewable energy supply with demand by using time-of-day workload optimization.
3. Utilizing fuel cells as a cleaner energy source of primary or backup power.

Data center operators are making significant progress in transitioning to clean and renewable energy sources. For example, Equinix achieved 92% of its long-term goal of using 100% clean and renewable energy for the Equinix global platform in 2019. While their data center footprint and energy consumption doubled, Equinix has reduced the carbon footprint of its data centers by 60% since 2015. The deployed on-site fuel cells reduce reliance on the power grid and provide reliable power that is 20% to 45% cleaner than the equivalent natural gas-powered electricity generation from an electric utility. Another example is three large Kyndryl data centers having installed solar arrays in partnership with local energy suppliers. In late 2018, two solar arrays went into operation at Kyndryl data centers in Bastogne and Vaux-sur-Sûre, Belgium, which generated approximately 2,800 MWh of solar power in 2019. The third onsite solar array is a 10 MW project hosted at a Kyndryl facility in Boulder, Colorado, which went into production in July 2019 and produced 5,700 MWh of solar power by year end.[11]

4.2 Use of Microgrids for Data Centers

Microgrids can be considered as a distribution network that manages distributed energy resources (DERs), such as renewables and interconnected energy loads, within a defined electrical boundary. A microgrid provides local generation and can operate as a single controllable entity working in parallel with the utility grid. It can also work in island mode when it disconnects from the grid and operates under its own power. Therefore, microgrids provide electricity to data centers regardless of available utility services. They allow data center operators to balance their supply and demand in both on-grid and island modes and provide business continuity by switching back and forth as needed.

Many data centers have traditionally relied on UPS systems and diesel generators to maintain uptime. However even some new, modern Tier-4 diesel generators using low sulfur diesel and additional pollution controls are not emission-free. Diesel fuel produces more carbon emissions and more volatile organic compound (VOC) and NO_x emissions when compared to natural gas. In contrast, microgrids can include a wide variety of DERs, such as renewables, energy storage systems, backup generators, and fuel cells. The advanced microgrid solutions have artificial intelligence (AI) features for integrating external data, such as weather predictions for availability of solar and wind as well as energy market pricing.

To meet environmental protection goals as well as resiliency needs, microgrid solutions for backup generators combine a wide variety of DERs including renewables. For example, hybrid microgrid solutions for backup generation use a combination of renewables (e.g., wind and solar), battery storage and natural gas or renewable natural gas generation. Solar and storage microgrids utilizing renewables to provide environmentally friendly power are limited in the number of hours of their backup capacity. Adding a natural gas generating element to the DERs enables customers to receive long-duration backup power for extended utility outages that last days or even weeks. Furthermore, these microgrids can be made even cleaner with options like renewable natural gas or Neste renewable diesel.[63]

Depending on the source and process used to produce hydrogen, hydrogen fuel cells can be a sustainable energy solution for data centers. These fuel cells use electrochemical processes to cleanly and efficiently capture energy and provide it back to the data centers. Hydrogen fuel cells produce short-term backup power under peak loads that would reduce the demand on the grid without emitting carbon. The hydrogen fuel cells can also generate electricity two times more efficiently than combustion engines.

If transitioning to hydrogen fuel cells is not an option for some data centers, transitioning from diesel to natural gas natural gas reduces CO_2 emissions by 28.6% and does not require any alterations to current generators.

Grid-interactive Battery Energy Storage Systems (BESS) and UPS batteries that can be charged with renewable power significantly reduce emissions. In contrast to lead acid batteries, grid-interactive BESS and UPS batteries store energy with up to 90% efficiency. To use stored power, an algorithm regulates frequency between batteries and the grid by determining microbursts of electricity in either direction based on need in any given moment. Returning power to or taking it off the grid also serves as a potential source of monetary income for data center operators enabling them to sell excess renewable energy.[64]

4.3 Turning Flare Gas Waste into Electricity for Data Centers

Natural gas coming from oil wells is typically called “associated gas” or flare gas. Flare gas considered a waste byproduct can be a valuable source in an appropriately designed generator set. While a data center powered by burning natural gas might not appear very environmentally friendly, several data center operators using flare gas claim that they reduce emissions. For example, Crusoe Energy operates 40 data centers powered by burning natural gas. Crusoe Energy uses Digital Flare Mitigation® technology generating power from flare gas that is otherwise burned off by flaring. In Norway, Earth Wind & Power plans to offer data processing located on North Sea oil platforms.[65,66]

5. Energy efficient High-Performance Computing: Liquid Cooling

High-Performance Computing (HPC) is major consumer of energy with a significant environmental footprint and making HPC environmentally sustainable will require considerable effort. Direct-liquid hot-water cooling and adsorption chilling that both allow for reducing the energy required to cool computer systems, as well as energy-aware scheduling that can help in reducing the power consumption of supercomputers are promising technologies for energy-efficient HPC.

All the electrical energy consumed by an HPC system is ultimately transformed into heat. Since removing the heat from an HPC system and disposing of it requires additional electrical energy, it is important to have it done in an energy-efficient manner to reduce the overall energy consumption of the HPC system. While most data centers use air cooling according to ASHRAE class A1 specifications (Section 3.1), some sites for HPC have switched to liquid cooling according to ASHRAE W1-W5 standards. This allows for higher compute densities and more powerful processors because of the superior thermal properties of water over air.

Higher temperatures used in data centers (Section 3.1) require the cooling liquid to be delivered as close to the hot components (processor, graphics card, memory modules, etc.) of the servers as possible so that they operate within their thermal specifications. To achieve this, most vendors use technology called Direct Liquid Hot Water Cooling (HT-DLC). In HT-DLC, water-cooled heat sinks are attached directly to the hot components and allow for sufficient heat transfer from them directly to the water. The latest development in HT-DLC is to cover as many IT system components as possible with direct liquid cooling and 100% HTDLC systems are now available. In addition, the racks can be thermally insulated to reduce heat radiation into the computer room.

Let us review some methods of liquid cooling.[67]

Direct to Chip (DTC) or (D2C) is a method of CPU cooling that runs a cold liquid (contained) over the top of a chip. The cooler liquid captures the heat from the chip and is carried away to be cooled elsewhere. Then the cooler liquid is returned to the chip in a closed loop system. The pump circulating the liquid and placed directly on the chip to improve flow is a critical element of the system. While in-rack Coolant Distribution Units (CDUs) may be a good choice in many cases, their downside is the compute density reduction because rack units have to be dedicated to the CDUs. Pumping the hot liquid to an external system chilling the liquid through a liquid-to-liquid process and using an external system to cool the liquid is an alternative method.

Immersion Cooling may be the solution for environments with servers located in a confined space without the data center infrastructure. In this method entire servers are immersed in a dielectric liquid. Non-conductive and non-corrosive dielectric liquids are used for immersion cooling to avoid damage to electronic components.

Rear Door Heat Exchanger (RDHx) is used when data centers cannot modify or add a cooling system as D2C may require. As an alternative, a special rear door containing fans and a coolant can be added to the rack with the hottest servers. This system chills the hot air from the back of the servers and cools it immediately. The coolant absorbs the heat and cooler air is returned to the data center. Similar to the cooling methods discussed above, the hot liquid needs to be chilled before returning to the door. Overall, RDHx can reduce the need in computer room air conditioning (CRAC) units.

Liquid cooling dramatically improves the PUE of data centers. However, organizations need the resources to design or adapt them to use new liquid cooling technologies.

6. Public Cloud

According to the Ericsson report, dematerialized enterprises increase the use of cloud and mobile technologies to make their businesses more sustainable by 2030.[68]

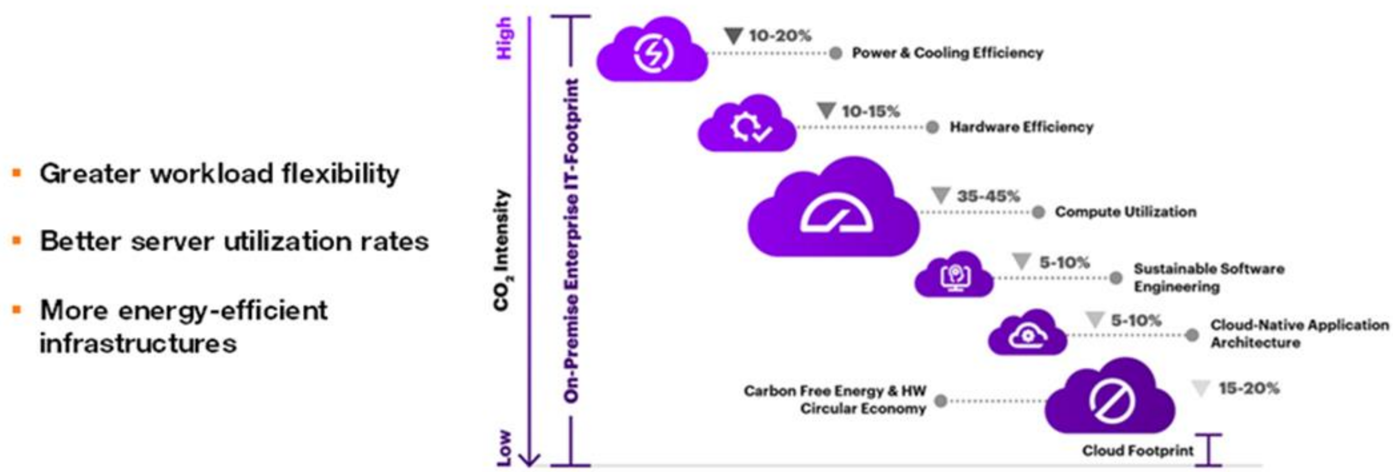

Figure 4. Reducing Carbon Emissions by Moving to Cloud (Accenture, 2020)

Eco-benefits of cloud-native apps and sustainable software engineering (Section 3.7) are presented in Figure 4. The cloud is critical for achieving environmental sustainability in ITC as moving from using many on-premises servers to on-demand scalable cloud IT services reduces overall IT consumption of energy and related carbon emissions. Sustainability is becoming a driver of cloud technology innovations. Most hyperscale cloud providers such as AWS, Microsoft Azure, and Google Cloud Platform have set sustainability goals for making cloud data centers carbon neutral. Let's review hyperscalers' initiatives on environmental sustainability.

AWS. According to the study by 451 Research, AWS data centers are 3.6 times more energy efficient than the median of U.S. enterprise data centers due to using energy-efficient servers and much higher server utilization.[69]

In 2021, AWS joined the data center industry in Europe to create the Climate Neutral Data Centre Pact that demonstrates a commitment of data center operators for the transition to a climate neutral economy. The key approaches for achieving sustainability are maximizing utilization of IT system resources and reducing waste or duplication. For example, AWS Instance Scheduler allows users to optimize their AWS resource cost by configuring start and stop schedules. Another method of cost optimization is to use services managed by AWS (for example, AWS Lambda, RDS, Amazon Managed Streaming for Apache Kafka, Amazon EMR, etc.) as much as possible.[70]

Energy-Proportional Computing requires that compute resources be maximized on average 70% to 80% because energy efficiency quickly decreases when the system resources are close to saturation and performance plummets. Intelligent storage tiering enables AWS customers to store and access data efficiently. Thereby they optimize the storage footprint and cost.[71]

Microsoft Azure. According to the comparison of energy consumption and carbon emissions associated with running four applications in Azure with running them on-premises, Azure is up to 93% more energy efficient than traditional data centers. The Azure data center infrastructure efficiency (PUE) and using renewable electricity are factors contributing to these savings.

The Emissions Impact Dashboard (EID) introduced by Microsoft as the Microsoft Sustainability Calculator provides transparency into GHG emissions associated with using Microsoft Azure cloud services. It enables customers to measure the impact of Microsoft cloud usage on their carbon footprint. The emission data is available by month, service, and data center region. The EID also enables customers to enter on-premises workloads and get an estimate of emissions savings resulting from migrating to Azure.[72]

Google Cloud Platform (GCP). As Google achieved carbon neutrality in 2007, GCP customers have a carbon footprint that is already carbon neutral. Google has recently introduced the option in Cloud Console location selectors to choose a Google Cloud region according to the lowest CO_2 footprint (Figure 5). Regions presented as the "Lowest CO_2" and the leaf have a carbon-free energy (CFE) of at least 75%.[73]

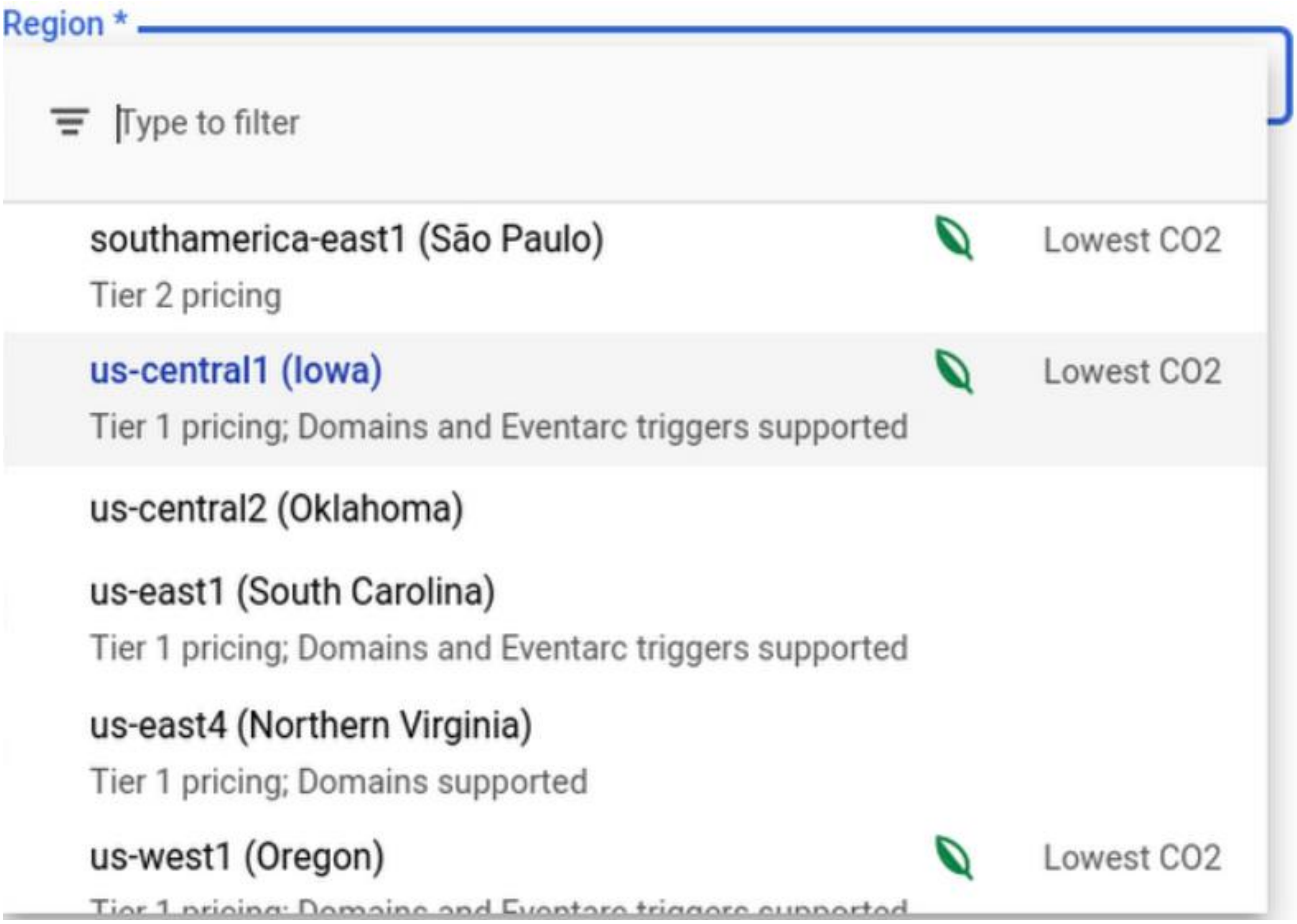

Figure 5. GCP Selection of the Lowest CO_2 Regions (Ref.74)

Google can also show GCP customers the carbon footprint of idle or abandoned projects that continue to run on GCP servers.[75]

In May 2021, Google announced a next-generation geothermal project to add carbon-free energy to the electric grid serving the GCP data centers throughout Nevada, including the GCP region in Las Vegas. GCP also introduced so-called “carbon-intelligent computing” that enables shifting moveable compute tasks between different data centers, based on the relative CFE availability across regions.

7. Circular Economy and Sustainable IT

Environmental sustainability is not limited by GHG emission management. The IT industry produces a growing volume of e-waste/WEEE (waste electrical and electronic equipment), around 54 million tons in 2020. It is very difficult to estimate to how much e-waste is actually recycled: while 17.4% is documented as collected and properly recycled, the remaining 82.6% cannot be accounted for. WEEE decomposition results in release of harmful chemicals into air, water, and land. This causes damage to human health.[55]

To address the e-waste danger, the concept of the circular economy has been developed. The circular economy considers waste and pollution as product design flaws. Recycling as a process of converting waste into reusable material begins at the end of a product’s lifecycle. In contrast, the goal of the circular economy is to address the potential environmental impact right at the source by preventing waste and pollution from being created in the first place. To achieve this, a product’s lifecycle should be managed by modifying the product design and increasing the use of remanufactured products. According to some estimates, a product's design determines around 80% of the product's environmental impacts.[76]

The focus of a circular economy approach on the reuse and maintenance of IT products can results in cost saving for IT organizations. A design philosophy enabling customers to upgrade individual components (CPUs, RAM, storage) reduces e-waste while the customers use the latest components. To decrease e-waste, Microsoft has developed Circular Centers to ramp up reuse and supply chain efficiency.[77]

Dell Technologies is also moving to the circular economy by introducing sustainability lifecycle based on the circular design approach to consider sustainability at every stage of a product's lifecycle. Dell plans to increase the use of recycled and renewable materials. For example, according to estimates, more than 90% of a typical Dell laptop is recyclable. Dell design guidelines target reducing the number of components and their sizes, and the complexity of system assembly.[78]

Dell is using innovative ways of applying circular principles; for example, extending the life of hardware assets by using AI/machine learning (ML) to predict performance issues and enable augmented reality-assisted repairs. The possibility for some hardware devices to have several reincarnations with their components cascading across multiple lifecycles is also being explored. For example, top tier performing processors used in enterprise environments may have a second, and possibly even third, lifetime in home or education environments.[79]

HPE offers Asset Upcycling Services (AUS) to manage IT assets throughout their entire lifecycle.[80] AUS helps customers either prepare the IT assets for resale or destruction into recyclable components. HPE also provides reliable, HPE certified pre-owned IT equipment with a 1-year onsite warranty and authorized operating system licensing eligible for HPE support. This helps HPE customers advance their IT lifecycle strategy by extending the life of legacy systems.

The Circular Economy for the Data Centre Industry (CEDaCI) is part of the European Circular Economy Stakeholder Platform with a goal of helping create a Circular Economy for the data center industry. The developed circular economy solutions allow data center operators to increase reuse of Critical Raw Materials and extend product life through IT equipment reuse and remanufacturing.[81]

8. Remanufactured IT Equipment

The previous section mentioned the HPE program for Certified Pre-owned enterprise IT equipment. Laptops also have an environmental impact. This impact may be not visible unless we look at one-year estimates. For example, a laptop with 8 hours of use every day consumes between 150 and 300 kWh and produces between 44 and 88 kg of CO_2 per year. In addition, manufacturing of each new laptop results in 316 kg of CO_2 emissions.[82]

Remote work during the COVID-19 pandemic increased demand for new laptops. Using remanufactured IT equipment is an environmentally sustainable solution for addressing the laptop demand. Indeed, pre-owned laptops that are still in working condition can be repaired or refurbished to be as good as new. In addition, the laptop remanufacturing process (Circular Computing™ laptop) results in significant cost savings.[83]

9. 5G/6G and IT Sustainability and Innovations in Data Center Technologies

There are two main aspects of how 5G technology affects the environment. The first focuses on improving energy efficiency of the 5G network and making 5G eco-friendly. The second aspect is the positive environmental role 5G can play in combination with Internet of Things (IoT) to reduce air and water pollution and minimize water and food waste. We start with discussing the first aspect.

The radio access network (RAN) has the largest energy consumption in a 5G mobile network (Figure 6). Unlike 4G LTE radio, 5G new radio (NR) design minimizes always-on transmissions to enhance network energy efficiency. Idle mode transmission is designed with very long time gaps (up to 20 ms for standalone operation) enabling significantly deeper and longer sleep modes than the 0.2 ms in LTE. In contrast to the 4G LTE setup, the reference signals in NR are transmitted only when necessary. Despite improvements in energy efficiency, the RAN continues to consume more power than any other part of the network. The large power consumption of 5G RAN (Figure 6) is attributed to new technologies such as mmWave transceivers and multi-carriers massive multiple-input and multiple-output (MIMO) antennas, all of which require more power.

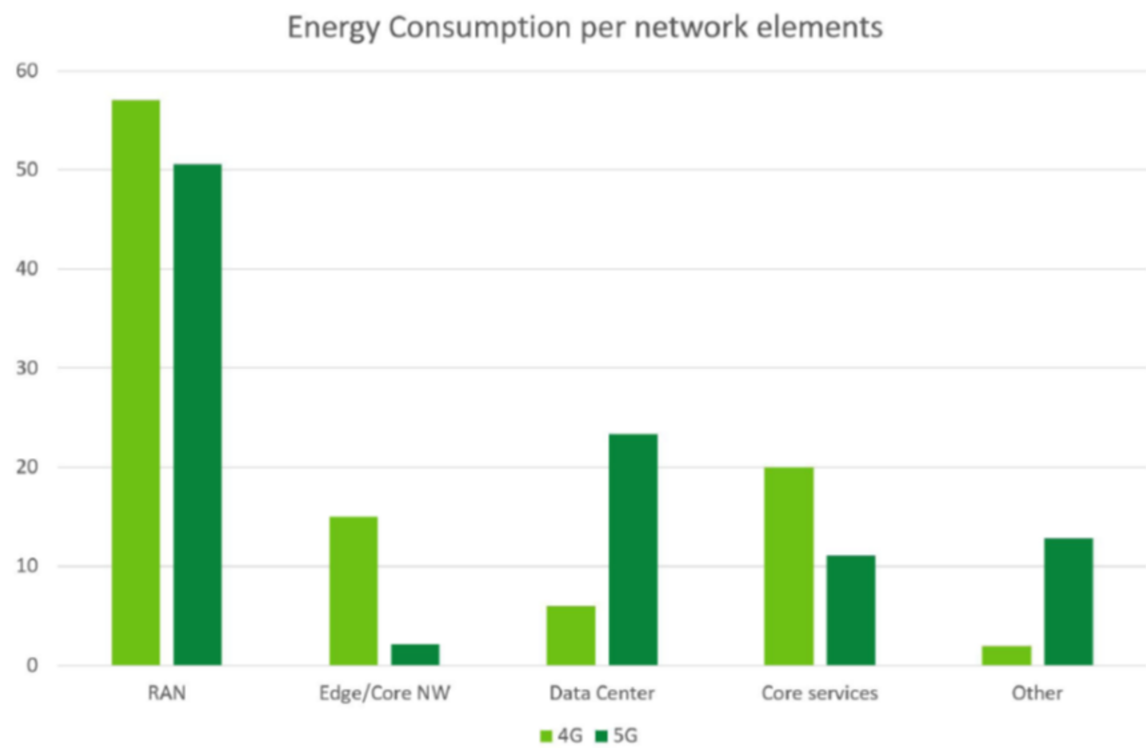

Figure 6. Breakdown of Power Consumption in a 4G/5G Mobile Network (Ref.84)

Other techniques to improve energy efficiency include introduction of dynamic and efficient shutdown of functionalities that are not in use and not required to remain active for purposes such as signaling. This results in keeping fixed energy consumption to a bare minimum.

Solar panels and small-scale wind turbines (i.e. vertical spiral wind turbines) can be installed on the premises of the cellular tower. While they may not be able to supply all the power needed to support communications, the energy generated from renewable sources can be stored in batteries to support other facility needs. The data center strategy in 5G networks can also lead to some power savings. By running more workload in the cloud, virtual networks like Open RAN can benefit from the energy efficiency of cloud data centers (Section 6). AI solutions are used to achieve energy efficiency and lower the carbon footprint of mobile networks.[84]

The second aspect of 5G technology effect on the environment is various opportunities for environmental preservation and protection that are made possible by 5G technology features. 5G technology in IoT solutions can reduce energy use because IoT devices can be powered up and shut down automatically depending on the need. 5G enables expanded use of IoT sensors in appliances, transportation networks, buildings, factories, streetlights, and residences for real-time monitoring and analysis of their energy consumption. As a result, their energy use can be automatically optimized.

The Next Generation Mobile Networks (NGMN) Alliance working on defining 6G technology has initiated the Green Future Networks project for improving energy efficiency, reducing carbon emissions, and increasing the use of renewable sources of energy.

10. IoT and Energy Savings

In 2020, globally IoT devices produced around 2.8 ZB of data.[85] Around 90% of the IoT generated data is transferred to the cloud. The energy consumption for transferring 1 GB of data to the cloud is 3-7 kWh.[86] Taking 5 kWh as the average, this results in the total energy consumption of 635 kWh. Based on these calculations, IoT-generated data transferred to the cloud would be responsible for emitting of 8 billion tons of CO_2 in 2025. Edge computing can help reduce this impact as energy consumption related to network transport is decreased. However, an increase of edge computing devices leads to additional energy consumption. There are several ways to address the projected increase of energy consumptions in edge data centers. One of them is to deploy resource-optimized infrastructure and to use the renewable energy sources.[87]

5G technology used with IoT can modernize all stages of manufacturing including managing energy and water usage, reducing carbon emissions, and leveraging renewable energy to power operations. For example, Ericsson's Smart 5G Factory has been capable of reducing waste by 5%, saving 5% on energy costs, and increasing overall energy efficiency by 24%.

5G and the IoT can bring microgrids (Section 4.2) online if the main grid fails or is unavailable. This will help in integration of intermittent renewable energy sources such as wind and solar into the grid. Furthermore, 5G-enabled smart grids can better monitor energy demands and optimize electrical distribution. According to the Qualcomm report,[88] 5G-connected smart grids will reduce gas and electricity consumption by 12%. Using sensors and cameras, 5G can decrease vehicle emissions by reducing traffic congestion and idling.

11. The Environmental Implications of Remote Working

Remote working enabled by IT services saves energy and reduces GHG emissions from vehicles and airplanes. According to the study from Spain's Institut de Ciència i Tecnologia Ambientals,[89] working from home even not the entire work week but just four days a week would lead to reduction in the amount of NO_2 (the main air pollutant in traffic emissions), by around 10%.

However, remote workers have their own carbon footprint that should be added to the corporate carbon footprint. The study by VMware has found that VMware home-office emissions are close to 0.47 tons of carbon dioxide equivalent per employee.[90] The leading contributors are computers and monitors. Nevertheless, according to the study, the carbon footprints of VMware employees working from home are less than that of traditional employees commuting to the office.

12. Cryptocurrency and Its Impact on the Environment

As cryptocurrency popularity grows, the number of bitcoin or other cryptocurrency miners increases exponentially. Mining cryptocurrencies requires a specialized GPU or an application-specific integrated circuit (ASIC) miner. A cooling system is required for the rig in GPU mining. In addition, a reliable internet connection is always required.

Proof of work crypto mining by hundreds of thousands or more computers is estimated to consume around 707 kWh per transaction. While it is very difficult to accurately estimate the amount of electricity used by proof of work crypto mining because different computers and cooling systems vary in energy efficiency, a University of Cambridge analysis[91] approximated that the annual electricity consumption by proof of work crypto mining is121.36 terawatt hours. This amount is larger than the consumption of Google, Apple, Facebook, and Microsoft combined. Furthermore, proof of work crypto energy consumption increased almost 62-fold between 2015 and March of 2021. Only 39% of this energy comes from renewable energy sources, mostly from hydropower.[92] Even if in the future it will become possible to run all proof of work crypto mining on renewable energy, the mining e-waste problem should be addressed. Indeed, cryptocurrency miners try to use the most efficient hardware. This specialized hardware becomes obsolete every 1.5 years and cannot be repurposed for other uses. As a result, the proof of work crypto network is estimated to produce 11.5 kilotons of e-waste each year.

As China prohibited crypto mining in 2021, miners have started to use the energy sources in neighboring Kazakhstan. These energy sources are based on coal-generated electricity and the large amounts of CO_2 emissions they generate.[93]

Understanding the negative environmental impacts of cryptocurrency mining have led to creating several projects aimed at reducing the cryptocurrency carbon footprint. For example, the goal of the Crypto Climate Accord[94] is to move cryptocurrency mining to the use of 100% renewable energy by 2025. A more ambitious aim is to decarbonize blockchains so that the entire cryptocurrency industry can achieve net zero emissions by 2040.

Moving bitcoin operations next to oil fields and using waste gas flare (Section 4.3) in electricity generators is among many ideas for greening cryptocurrencies. Wind turbines in West Texas can be used as the energy source for bitcoin mining.[95] Crusoe Energy Systems operates 40 modular data centers powered by flared natural gas to generate revenue by bitcoin mining.[96]

13. Adiabatic Reversible Computing

13.1 Power Consumption in IT: Koomey's Law

Koomey's law plays a role in sustainable IT similar to the role of Moore's Law in processor technologies. Koomey's Law states from the 1940s vacuum-tube mainframes to the 1990s laptops the number of computations per joule of dissipated energy doubles about every 1.57 years.[97] However, the industry-wide doubling of energy efficiency described by Koomey's Law has slowed since 2000. This was caused by the end of Dennard scaling (Dennard observed that as transistors are reduced in size, their power density stays constant[98]) and the deceleration of Moore's Law. The updated Koomey's Law points to doubling every 2.6 years.

Landauer showed that the minimum energy needed to erase a bit of information is $kT\ln(2)$, or 285×10^{-23} joules at room temperature (k is Boltzmann constant and T is temperature).[99] It means at least $kT\ln 2$ joules of energy produced for every bit of information are lost due to an irreversible computation.

Applying Landauer's principle and the second law of thermodynamics demonstrates that the growth in the energy efficiency of irreversible computing is not limitless. Using Koomey's observation, one can conclude that Landauer limit will be reached by 2048. It means that Koomey's Law will be no longer valid after 2048. Since power consumption of CMOS (Complementary Metal Oxide Semiconductor) circuits increases with clock frequency determining computation speed, growth in performance results in higher power consumption. Eventually, the amount of heat that must be removed becomes insurmountable and further advancement of computing systems become unsustainable unless novel computing technologies like Adiabatic Reversible Computing are developed.[100]

13.2 Developments in Adiabatic Reversible Computing

Generally speaking, reversible computing means computing using reversible operations. These operations can be easily and exactly reversed or undone. Reversibility does not lead to loss of information because all inputs can be recovered from the output. Loss of information increases entropy dissipated as heat. Hence, if there is no loss of information, entropy is unchanged, and no heat is dissipated (although other sources of energy dissipation such as resistance in wires, displays, and communication remain).

In a closed system, any heat gain or loss is nullified for adiabatic operation. Adiabatic and reversible logic (ARL) combines to minimize heat dissipation. For example, a reversible Metal Oxide Semiconductor (MOS) design performing better than irreversible complementary MOS has been described.[101] However, ARL implementations of digital circuits impose a penalty as the circuits must run slower because the dissipated energy amount is proportional to clock frequency. To resolve this problem, an architecture based on static two-level adiabatic logic (S2LAL) was proposed.[102] The S2LAL circuit uses the energy from the previous operation in the next operation. An implementation of a full microprocessor based on adiabatic principles has been reported in 2020.[103]

As long as circuits are reversible, adiabatic computing can operate near absolute zero Kelvin temperature as well as room temperature. While a commercial grade processor quantum dot cellular automaton (QCA) running at room temperature has not been constructed yet, an implementation based on QCA running at room temperature is considered possible. Although commercial grade ARL microprocessors have not come to the market yet, various computing elements with 10 times improvement in energy dissipation have been demonstrated.[104]

14. Quantum Computing Contributes to Achieving Sustainable IT

Quantum computing processes complex computations much more energy-efficiently than traditional computers. For example, Google's D-Wave computer uses just under 25 kW of energy to power the system. However, the sheer power amount is used for powering the refrigeration unit and cooling the quantum processor to the required temperatures. This has led to a question about the overall energy efficiency of quantum computing. However, experts in the development of quantum computing expect that as quantum processing power can exponentially increase, the energy consumed for powering the refrigeration unit will not grow at such a fast rate.[105]

There are estimates that quantum computers can reduce energy usage by more than 20 orders of magnitude compared to conventional computers.[106] In addition to significant energy efficiency, the superior computing power of quantum computing can enable development of more accurate models for climate change.

15. Conclusion

I hope readers will find my article helpful in understanding how their organizations can achieve sustainable IT. We have only one planet and we need to take care of it.

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