Designing and Building the Next Generation of Sustainable Data Centers

By Susanna Kass and Alberto Ravagni.
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Introduction

The latest Climate Change analysis shows that if we act now we can reduce carbon emissions enough in the next 12 years to keep the global average temperature increase within 2°C and even, as indicated by the latest science, to 1.5°C above pre-industrial levels [1]. Achieving this would mean better quality of life for all of us, with hundreds of millions fewer people suffering water scarcity, coast line erosion, heat related illness, poverty, and decreased food availability [2]. This white paper is a call to action to rethink the design, impact, and sustainability of the data center and ICT industry. I, Susanna Kass, am making a plea:

We are responsible beyond achieving our economic goals and beyond building data centers cheaply with no regard to environmental impact, human welfare, and societal consequences. Data centers have a global cost in impact to resources, to the environment, and to society: their Sustainable Cost of Ownership.
Rethink, act now, make a sustainable pledge.

Through this paradigm shift we can achieve a sustainable cost of ownership, make a positive impact, become a globally recognized sustainable infrastructure leader, and make invaluable contributions to the communities where our data centers are located; all while maintaining the 24x7x365 resilience our industry is known for. With this white paper the authors, Alberto and I, aim to start an industry wide dialogue, foster collaboration, increase awareness, educate, and share our ideas to prepare the data center industry to be a Sustainable Development Goals (UN SDG) leader on global energy and sustainability practices.

Authors

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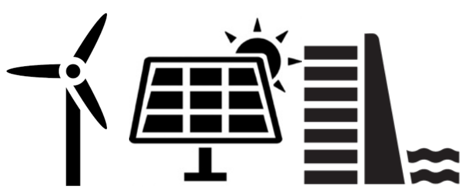
Alberto Ravagni brings over 20 years of energy experience and is a domain expert in fuel cell technologies. Previously, he was the founder and CEO of SolidPower, a board member of the Joint Technology Initiative for Hydrogen and Fuel Cells of the European Commission, and held executive management positions at New Energy World, Oerlikon Balzers AG, Unaxis Nimbus Ltd, and Delphi Automotive Systems.

Call to Action

We must rethink how we design, build, and operate next generation data centers and adopt using the sustainable cost of ownership which includes economics, resource impact, and society benefits.

Rethink social future.
The designing, building, and operating of data centers must improve long-term human welfare on both a local and a global scale.

Rethink cost of ownership.
Measure both direct and indirect costs for data centers in terms of Sustainable Cost of Ownership. This allows innovation to emerge and decisions to properly consider economic results, environmental impact and societal benefits.



Rethink clean energy.
Plan and transition to clean energy infrastructure. With these new designs, renewable energy is produced on or near site for consumption on a per kilowatt hour basis with zero carbon footprint, zero emission, and is able to grow to a global scale.

Rethink measurement.
Measure a data center's inputs (resources) and outputs (waste) end-to-end. With this measurement based approach we can think in a circular way to reduce resource usage by minimizing its resource-intensity, reduce waste by maximizing its re-use efficiency, and eliminate toxic materials in design.

Background

The data center industry needs to take action and develop an immediate plan to fix dirty cloud computing, pledge to achieve carbon neutrality, phase out coal along with other fossil fuels, and transition to carbon neutral infrastructure. The design of next generation data centers needs to use nature-based technological solutions to protect the earth's resources and the environment. Builders of data centers must take responsible steps in the extraction of natural resources, both direct and indirect. Designers of data centers can use a modular approach to handle megawatt scale growth and avoid overprovisioning. Data center construction and operation plans need to embody resource lifecycle optimization as the key to transitioning from single use designs to recycling, reusing, and remanufacturing. Through these changes, the industry can make progress towards eliminating landfill impact and achieving a perpetual life cycle for materials.

Data center operators must also plan for the coming changes from urban migration. Today their service and infrastructure portfolios are primarily supported by "Cloud Computing" data centers. These multi-hundred-megawatt consuming, multi-billion-dollar sites represent long-term investments by their owners. However, with the majority of the world's population expected to live in cities by 2050, these same companies must now adapt their strategy to support adding many thousands of distributed computing locations at new megacities caused by the mass urban migration [3]. This balancing act will be vital over the next 20 years as the industry must maintain a constant uptime and handle massive growth while also optimizing power, land, water, and network usage. Consequently, the data center industry will not only minimize its environmental impact but also serve as an important contributor to human welfare as we evolve into the Global Connected Era.

This white paper focuses on the next generation of sustainable data centers. In the following pages the authors present design ideas, illustrate best practices for data center sites, and provide thought leadership on sustainability measurements. The authors emphasize the need for data center leaders to rethink the status quo; to achieve sustainability for next generation data centers design, construction, and operation; to improve usage effectiveness beyond Power Usage Effectiveness (PUE); and to expand Total Cost of Ownership (TCO) beyond direct business cost per megawatt installed. The authors take a holistic view on the resource impact of data centers by using the lenses of resource usage per kilowatt consumed, its impact to the environment, and waste created by data center construction and operations. In addition, this white paper demonstrates how Sustainable Cost Ownership (SCO) is the primary driver for the next generation of sustainable data centers in combating climate change and in measuring the true cost of ownership to achieve zero carbon, zero emissions, and zero waste.

Rethink and Make a Sustainable Change

The need for improved sustainability within the data center industry is gaining awareness. This shift is likely due to the leadership of hyperscalers who have pledged and committed to clean energy and the growth of renewable energy procurements by the data center industry. In the last twenty years the data center industry has averaged a tremendous growth rate of 6% per year globally. Because of this, data centers are rapidly becoming a major consumer of global resources and future projections indicate continued rapid growth. Future action and planning must consider sustainability as a key priority if the industry is to have a positive future for our businesses, for our environment, for our society, and for our quality of life. Sustainable data centers are the new normal in cloud computing and urban megacity society and they are key for the coming Digital Transformation and Connected Everything Era.

Thus, the data center and ICT industry are presented with a profound opportunity to increase their responsibility in the digital age; to rethink "business as usual"; to re-envision site selection; to transition to clean energy infrastructure; to take responsibility in clean energy generation; to do hourly measurement of clean energy consumption; to eliminate waste; and to design for recycling, remanufacturing, disassembly, and reuse. In improving our global sustainability efforts, we need to be accountable with regards to measuring the true costs of our choices economically, environmentally, and socially.

We can no longer envision the total cost of ownership solely in terms of the design, construction, and operation of a data center per megawatt installed. We must incorporate environmental and social costs to the sustainable cost of ownership. Finally, we need to be transparent with the carbon footprint and emissions generated per kilowatt-hour of power used by a site – but not via a synthetic instrument, such as a clean power purchase agreement, whereby the data center still consumes fossil fuel generated power.

Building and operating sustainable data centers is perceived as unfeasible today. This white paper seeks not to pontificate about future solutions but to show an immediately actionable path forward. What does need to happen is a change in perception: the data center industry must rethink and re-examine itself if it is to achieve sustainability by design.

Sustainability Through Design and Measurement

Sustainability has often been viewed through the lens of choices. As a consumer, that is the primary power an individual or business has: *When making purchasing decisions, do I choose the sustainable or unsustainable options*? And, to the credit of many visionaries and determined individuals, the data center industry has pushed other sectors of the global economy to make sustainability a realistic choice. Google has been a pioneering force in using Power Purchase Agreements (PPAs) to bring about renewable energy development. As of writing, the company has signed PPAs or other energy procurement agreements for over 3.1 gigawatts of renewable energy in the U.S., Europe, and South America [4]. Microsoft has achieved the remarkable result of reaching carbon neutrality in 2012 and continues working to decrease its data center PUE, which is currently just 1.125 for new data centers [5]. Facebook has made a pledge towards carbon neutrality, with a reported 75% carbon neutrality achieved in 2018 [6]. To continue forward with the progress started by these and other industry leaders, we must stop thinking of ourselves as consumers and instead as responsible citizens who will pioneer a future of sustainability. Data Center providers must use new metrics for their systems, including measurements of environmental and network resources consumed and the extended perpetual lifecycle of data center components.

Usage Effectiveness Metrics.

Power Usage Effectiveness (PUE)
The widely used standard for data centers to measure their power efficiency. We should expand this to the other core resources: water, land, and connectivity.

Water Usage Effectiveness (WUE)
The amount of water used per kWh of electricity consumed.

Land Usage Effectiveness (LUE)
The amount of land used per kW for IT capacity.

Network Usage Effectiveness (NUE)
The average usage rate of network connectivity compared to the amount purchased.

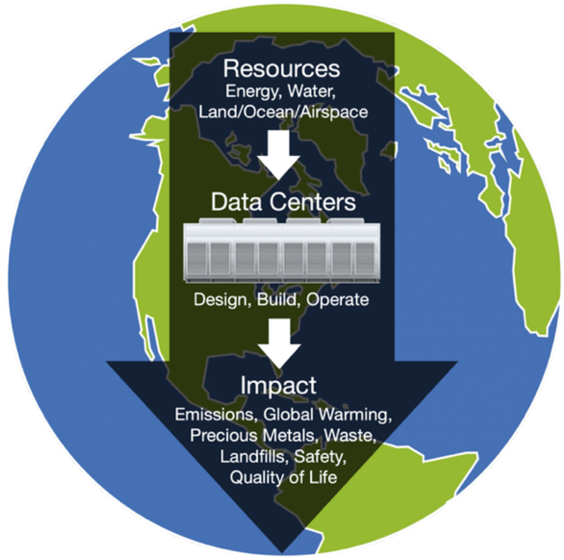
Life Cycle Analysis.

The standard and rigorous way of measuring the impact of a product over its entire lifespan is known as Life Cycle Analysis (LCA). LCA allows for a product's impact to be expanded from its use to include creation and end-of-life results. With this we can improve the long-term sustainability of data centers by understanding the pros and cons of material choices, byproducts of manu-facturing, repairability, part reuse, and landfill impact. LCA is also being expanded currently by the United Nations Environmental Program (UNEP) to create Social LCA (S-LCA) standards [7]. The data center industry should be one of the first industries to adopt and lead this effort.

From Status Quo to Sustainable

The Status Quo Data Center.
The conventional data center is designed around cheap extraction. It uses and then discards resources, often wasting value in the process.

The long-term results of status quo data centers are mass consumption of natural resources, regular idleness as standby capacity, an intense carbon footprint, and harmful emissions generated by the mass consumption of fossil fuels. Currently, most data centers worldwide are status quo data centers.



The Sustainable Data Center.
The next generation data center has sustainability at its core. It uses renewable energy 24x7x365 and achieves net zero results in carbon footprint, emissions, and waste. It does this while maintaining 99.999% uptime and achieving optimal resource (power, water, land, network) usage effectiveness, such as PUE near 1.000, and a WUE near 0.000. Sustainable data centers use renewable energy sources, reuse materials to perpetuate their life cycles, remanufacture by-products and reduce landfill impact. Overall, the sustainable data center benefits the environment, society, and human welfare 24x7x365, thus aligning with the UNSDG goals.

Sustainable Data Center Characteristics

The sustainable data center must be designed around the Sustainable Cost of Ownership (SCO) model this paper has introduced. The UN Sustainable Development Goals (UNSDG) provide the needed framework to pair with SCO to highlight the important characteristics for making a data center sustainable. For example, goal 12 of the UNSDG is "Responsible Consumption and Production" which is of the utmost importance for sustainable data centers. As mentioned in the prior section, sustainable data centers should achieve a PUE as close to 1.000 as possible and a WUE as close to 0.000 as possible. Part of this will require cooling that uses virtually no power and little to no water. Data centers must also transition to being powered by a renewable, emission free, and water neutral energy source. This can be done either through certain means of generating power at the site or selecting a site near an extremely reliable power grid that fits these criteria, both of which are explored as examples in the following sections of this white paper.

Sustainable data centers must also avoid the pattern of overprovisioning which occurs when an unnecessary availability or redundancy exists. Overprovisioning can be seen with the installation of diesel generators as an auxiliary power source for data centers which adds expense, increases land usage, creates emissions when used, and is only needed when the grid power is not resilient enough for data center needs. Highly modular data centers also help prevent overprovisioning for site buildout because they allow for incremental capacity to be added over time. This avoids the construction of massive data centers whose single-tenant cloud provider or multi-tenant colocation owner may require many years to work up to using more than 50% of the building's capacity.

Emphasis must also be placed on considering the overall impact of design choices over their lifecycle, as outlined by LCA. While reduction and optimization of a data center's impact and waste should be minimized over its lifecycle, some aspects of data centers will inevitably produce waste. An improved framework for properly handling waste is necessary. Waste "RE" Efficiency (WREE) is a framework presented by this white paper to measure the effectiveness of diverting and up-cycling waste which cannot be prevented. WREE strives for all waste that can't be reduced to be reused, recycled, or remanufactured. Thus, data centers must incorporate waste and landfill minimization from their creation to their eventual closing. This should be applied to the structure of the data center as well as all equipment and internals of a data center, which will likely be upgraded multiple times over the structure's life. Achieving this starts with designing for reuse and disassembly during planning and construction. For the operation of data centers this includes finding uses for by-products like heat from the in-rack computing which could provide value to neighboring businesses, as opposed to being wasted.

Modular design and structure.
By utilizing a modular system for data centers, the components of a data center can be designed to have their own sustainable lifecycles. This makes the long-term path of a data center much smoother. Making a site's structure sustainable simply means making each module sustainable. Scaling can be done in a more continuous way that also allows for faster time to market.

Responsible Power Generation and Consumption.
Currently data centers have entirely redundant, unclean auxiliary power systems to handle power outages because the electric grid for most of the world is not reliable enough to meet the 99.999% uptime they need. This is not a responsible nor cheap solution. The data center industry must move towards renewable, sustainable onsite power generation.

Direct Clean Power.
As data centers continue to grow, we must move from using offset techniques to directly powering them with sustainable power. This means placing data centers near sustainable power generation, such as hydroelectric generation locations, or doing on-site clean energy generation so data centers can use renewable power in a clear, measurable, and efficient way 24x7.

High efficiency cooling module.
Cooling is the major use of water and the second main use of power in status quo data centers around the world. We must look to dramatically decrease the resources that cooling uses if we are to improve sustainability. This can start with reducing water and power used for cooling, but ultimately should eliminate water usage all together.

Minimum Waste and Landfill Impact.
Currently, status quo data centers do not track the production of waste from construction and operation. A shift must take place, beginning with accurately tracking all waste generated by the site over its entire lifecycle. This should be minimized through re-use, recycling, and re-manufacturing efforts that both reduce waste and have economic benefits. Data center design must use materials that are recyclable and which can be dis-assembled for reuse.

High density and scalable IT module.
Data centers are rapidly growing and sustainable strategies must have this as a core consideration if they are to succeed. To smoothly handle this growth without significant over-provisioning, data center builders should leverage highly dense designs that function as building blocks for being composed into larger sites.

Example: Leading the Clean Energy Infrastructure Revolution

The core design of the next generation of sustainable data centers is being both highly resilient and directly powered by clean energy. In fact, this duality is the key to the future of energy infrastructure for our entire planet. If we can transition global power production to follow this design then we will dramatically improve our future economy, environment, and society. However, this presents a problem for much of the world and many thousands of data centers which, at present, do not have an option for resilient, available and affordable clean power directly from the electric grid. Fuel cells, a technology for electric power generation, offers a good solution. The use of fuel cells for powering data center racks is a reality today and can be a cornerstone of the data center industry establishing itself as a global energy leader.

Powering data centers with fuel cells is a departure from the status quo model of purchasing power from a third-party utility provider who generates and delivers power. Instead, in a design technique called Rack Level Fuel Cells (RLFC), renewable power is generated onsite with fuel cells installed at the rack level. When paired with renewable natural gas (RNG) as a fuel source, fuel cells become a sustainable power generation choice which is carbon negative. This allows a data center to be completely independent from the electric grid's cost, reliability, capacity, and carbon footprint. RLFC can deliver 99.999% resiliency as a power source, thus removing the need for onsite backup power generators which are expensive, large, polluting, and loud. In addition, RLFC with RNG removes the need to pursue power purchase agreements, green certificates, or other clean energy offset mechanisms due to its direct production of clean power.

With RLFC data centers can take control of responsible power generation and consumption. Research has shown that for every kilowatt of power used by a data center's in-rack IT equipment the power plant providing that power consumes 5.7 kilowatts of fuel due to generation losses, transmission and distribution losses, and additional data center functions such as cooling. This is an end-to-end efficiency of only 17.5%. Furthermore, most data centers purchase grid capacity to handle their absolute peak power consumption while they operate at a substantially lower rate. However, with RLFC power can be generated directly at the IT rack resulting in a greater than 50% improvement in generation efficiency due to modern fuel cell technology and virtually no transmission loss due to the proximity to the data center racks. Microsoft found in their research that this alone resulted in a 69% improvement in end-to-end efficiency that could be improved further using high temperature fuel cells – which are even more efficient and produced high temperature heat that could be used for site cooling [8]. With this we can also change the way we think about measuring the power usage of data centers, since production and capacity are for direct consumption.

A highly important aspect of RLFC is its improved water usage efficiency. In the US, approximately 15 gallons of water is used to produce a kilowatt-hour of power. That means a kilowatt-hour of power used by in-rack IT equipment uses 30 gallons of water! With RLFC no water is consumed for power generation. In fact, because fuel cells output newly formed water, RLFC holds the promise of the first ever water positive data centers which actually generate instead of consume water. This makes RLFC, and the use of fuel cells in general, a transformational force in urban environments where resources tend to be the most expensive.

Finally, a critical benefit of RLFC is the separation of data center deployment and growth plans from electric grid capacity. Thus, a data center can be built with nothing but a highly reliable gas line which delivers RNG to the site. Data center growth can also be done in a much more gradual way with the ability to increase a site's capacity by tens of kilowatts or tens of megawatts solely by installing more fuel cells. For many data center builders and operators this is a huge benefit which could dramatically improve the time to market for new sites and capacity expansions.

The use of RLFC is key for data centers' global transition to increased sustainability. As with all content discussed in this white paper, RFLC is a proven technology, not a future hypothetical. Microsoft has already proven this with a real-world implementation at their Advanced Energy Lab, which they've termed the *Stark Architecture* [9]. RLFC offers a new avenue for sustainable data centers in the many locations where highly resilient, directly clean grid power is not an option. In the coming years, we expect RLFC to become a standard way for designing sustainable data centers, especially in urban areas.

Example: Triple Bottom Line Site Selection in Boden, Sweden

The authors spent time visiting numerous data centers and open land which is suitable for immediate deployment and greenfield site development. During these visits they measured the sustainability aspects via Sustainable Cost of Ownership through the triple bottom line components of economic, environment, and society. To achieve a triple bottom line through a Life Cycle Analysis approach we must design and build data centers which go beyond the status quo metrics to include the minimization of resource utilization of land and water, to eliminate harmful emissions and waste, and to promote synergic interaction with the local community. Boden, Sweden is the site chosen by the authors to illustrate this idea.

Boden has achieved a remarkable feat; over the last 40 years it has delivered renewable energy in the form of hydro and wind-generated power with less than 10 minutes of down time per year. The renewable energy source is highly reliable and affordable, at just USD$0.04 per kilowatt-hour. The community of Boden embraces its natural environment; the citizens measure their demand of natural resources in every detail. The cold climate eliminates the water demand for cooling, as direct air cooling is available all year long. Land usage is optimized through the reuse of existing mission critical ex-military infrastructure. The data centers are integrated in the Boden local community which welcomes power intensive industry such as data centers, gaming, content development, artificial intelligence, and computing industries of the ICT sector. The waste heat from such ITC sites can be used by other nearby businesses, including greenhouses and fish farms, which puts sustainability at the center of the community's lifestyle.

Social impact that is synergetic with industries has a strong history with the Boden municipality. New permits of data center zoning can be obtained in weeks and the presence of data center professionals attracts entrepreneurial and technological innovators whom are well-suited to the local workforce and culture.

Economics

The Lapland region of Sweden is known for its cold climate and large availability of natural resources. As highlighted above, Boden offers 24x7x365 reliable renewable energy and cold weather conditions for sustainable data center site selection. The hydro power stations on the Lulea river provide 4.3 gigawatts of renewable, clean energy capacity. The transmission grid is designed to be mission critical and has historically served energy intensive industries such as steel production and military applications. The grid has a standing record of 40 years with over 99.99% uptime for use in Boden. Sustainable data center sites can be supplied by more than two separate independent feeders that do not connect; as a norm the data center uptime is in excess of 99.999% with clean renewable energy which has an average spot price in 2019 at Boden of USD$0.038 to USD$0.042 per kilowatt-hour [10].

Cooling a data center in a sustainable way is also possible in Boden thanks to its relatively cold year-round temperature. This allows for direct air cooling throughout the year with the temperature normally varying from -27°C to 20°C [11]. Land for the construction of new data centers is affordable and abundant with prices in the range of USD$42,000 to USD$45,000 per acre. Land reuse is common practice from previous developments for heavy industries and military uses. This makes land use effectiveness high and suitable for hyperscale, web scale, and colocation builds. The authors project that sites at Boden are shovel ready and can be taken to production at megawatt scale in only 7 weeks.

Environment

The environmental impact is evaluated in terms of resources consumed and emissions produced. The fleet of next generation sustainable data centers will largely be powered by clean hydropower, which is produced without depleting resources or releasing harmful emissions. Power consumption should be in close proximity to the generation, thereby reducing the transmission and distribution losses. With data centers in Boden the primary demand for water consumption – the evaporative air cooling used in status quo data centers – is fully eliminated and substituted by year-long direct air cooling. The increase in land usage can be minimized by using existing buildings and reconverting infrastructure to data centers, even if attractive land is available for new builds. In Boden, the presence of data centers does not represent a negative impact on the natural resources; on the contrary, data centers offer the opportunity to develop new environmental businesses such as green houses and fish farming with utilization of the waste heat.

Due to the abundance of renewable energy, which is available 24x7x365, sustainable data centers in Boden fulfill an industry goal of 24/7 clean energy matching. With this, there is arguably no need for certifications such as Guarantees of Origin (GOs) due to the direct transparency based on local production and consumption. Similar solutions are already being enacted, such as the recent Vattenfall and Microsoft's pilot of hourly renewable power matching [12].

Social

The Boden community has been actively involved with sustainable, closed-loop style solutions for 20 years. Sustainable data centers in Boden benefit from and contribute to this community which places sustainability at the core of its lifestyle. The Boden municipality cooperates closely with research groups on energy and waste technology at the University of Technology located in Lulea. The "Urban Mining" waste management program in Boden, started in 1995, focuses on reducing landfill waste. The organic waste from water treatment is converted to biogas, which powers the public transportation buses. A by-product of the recycling process is a bio-fertilizer which can be used in agriculture. The waste from the community could soon be used in combination with the waste heat from data centers to create sustainable solutions for local use via district heating and agriculture. All of this cements Boden, Sweden as a prime choice for doing sustainable, triple bottom line data centers.

Looking Beyond

We thank the data center industry for continuing its journey towards sustainability. The SDG goals are a blueprint to chart its own course of actions and develop a concrete plan, especially:

Goal #7: Affordable and Clean Energy
Goal #9: Industry Innovation and Infrastructure
Goal #11: Sustainable Cities and Communities
Goal #12: Responsible Consumption and Production

Susanna firmly believes that "Your work is needed now more than ever to demonstrate our industry's own Sustainable Cost of Ownership scorecard to combat Climate Change. It is wrong to set sustainability goals for 2030 when you can work relentlessly to achieve them in 2025. A clean data center is not one powered by wind, solar, or hydro. It is one that does not need to be built." She extends an open invitation to join herself and become a member of Most Influential Climate Leaders in Data Centers and Cloud [13].

We wish to establish an industry wide dialogue, foster collaboration, increase awareness, educate, and accelerate the data center industry as a Sustainable Development Goal leader. Today, together, we can speak up, take a stance, measure our actions, clean up the dirty cloud, and only design, build and operate sustainable data centers.

Thank you for listening.

Very truly yours,

S Kass

Susanna Kass

Alberto Ravagni

SUSTAINABLE DEVELOPMENT GOALS

P.S. – Want to join the conversation. Let us know your thoughts by emailing Susanna at: susanna.kass@alumni.stanfordgsb.org

Glossary

Cloud Computing – A general term for software services which provide data center resources on-demand to users, such as compute, network, and storage. Cloud computing has become a highly mature technology since its productization in the mid 2000's. It provided a way for users to consume data center resources in a far more "elastic" manner than was possible traditionally because most cloud computing services provide "virtual" replicas of a historically physical asset. Thus, a compute machine or storage drive in a cloud system can be created, used, and destroyed in seconds with no human action required. This is in contrast to the prior need to do all these things with physical hardware which required human action and could take days or weeks. Because cloud computing allows infrastructure to be used in a highly elastic way, it is a benefit to both users and providers of data centers. For users, cloud computing is a competitive advantage because it eliminates concerns for physically owning and running infrastructure. For providers, cloud computing more efficiently uses data center resources because the systems which provide the resources as services can intelligently optimize usage. These results have led to the productization of cloud computing by some large data center operators such as Amazon, Google, and Microsoft who have mature global data center businesses.

Data Center – A facility for housing large scale computer systems which provides them with a highly reliable and controlled environment, including power, cooling, and internet connectivity. Data centers can range in size from tiny designs with hundreds of square feet (see "Edge Data Center" below) to massive designs with millions of square feet. With the rise of digital services and media, data centers have rapidly grown as the physical locations that house these services and content for individuals and companies alike. Generally speaking, a file or service is "in the cloud" when it is running on a cloud computing platform in a large data center.

Edge Data Center – Relatively small, generally urban located data centers which are designed to provide "last mile" benefits at a technical level, including latency and user bandwidth. As a result, edge data centers are well suited to providing high performance services to users which are relatively stationary within the geographic area a particular edge data center serves. This has made edge data centers appealing for businesses which do content delivery, such as video streaming, or large-scale data collection, such as for self-driving cars.

Global Connected Era – The new era of society brought on by global spanning of the ICT industry. This era is characterized by easy, convenient, and affordable access to communication and information systems that connect the significant majority of humanity.

Hyperscaler – A general term for referring to the largest data center operators in the world who must handle planning, building, and operating global data center footprints to support ever growing global services. While no de-facto criteria qualifies a company as a hyperscaler, they tend to experience tens or more megawatts of data center capacity growth per year on a global scale.

Kilowatt (kW) – A standard measurement denomination of power output equal to 1,000 watts. Please see "watts" for more information on the measurement's context as related to data centers.

Kilowatt Hour (kWh) – A standard measurement denomination of work equal to 1,000 watt-hours. Please see "watt hour" for more information on the measurement's context as related to data centers.

Land Usage Effectiveness – A new industry metric introduced by this paper to measure the amount of land consumed by a data center per kW of capacity offered by it. This includes all aspects of a data centers land footprint such as mechanical yards, parking, and office space.

Mass Urban Migration – The movement of the majority of the world's population from rural areas to urban areas. This is generally viewed over the 100-year span from 1950 to 2050 when the percent of people living in urban areas is predicted to increase from 30% to an estimated 68% of the world population [3].

Megacity – A City with a metropolitan area which has 10 million or more people. While the exact boundaries of metropolitan areas can be disputed, the UN expects 43 cities around the world to qualify as megacities by 2030 [3].

Megawatt (MW) – A standard measurement denomination of power output equal to 1,000,000 watts. Please see "watts" for more information on the measurement's context as related to data centers.

Megawatt-Hour (MWh) – A standard measurement denomination of work equal to 1,000,000 watt-hours. Please see "watt hour" for more information on the measurement's context as related to data centers.

Network Usage Effectiveness – A new industry metric introduced by this paper to measure the amount of external connectivity consumed by a data center per unit available over a given time period. The standard usage of external network connectivity in data centers is for internet connectivity and thus the measurement is a ratio of the utilization.

Power Usage Effectiveness (PUE) – An industry standard metric for measuring the ratio of "overhead" power usage of a data center. The pioneering metric was created by The Green Grid in 2006 and has become the currently accepted industry standard for measuring overall data center power efficiency. It is computed by dividing the total power usage of a data center by the power delivered to and used by the IT equipment. For example, if over a given time period a data center consumes 1MWh of electricity and only 800kWh of it is used by IT equipment then the site's PUE for that time period is 1.25. A "perfect" score is 1, which would mean that the data center uses no power outside of the power used by the IT equipment over the given time of measurement.

Rack Level Fuel Cells (RLFC) – A new way for powering a data center by doing power generation for data centers directly at the rack level. For more information on the benefits of doing RLFC please refer to the "Example: Leading the Clean Energy Infrastructure Revolution" section.

Stark Architecture –An architecture created by Microsoft for doing RLFC [9]. This has been something Microsoft has been a significant pioneer for and thus shown the real-world feasibility of doing.

Sustainable Cost of Ownership (SCO) – The measurement of cost of ownership for doing a business activity in a sustainable way, generally as measured by the Triple Bottom Line framework. SCO is expected to become the standard way we measure business activity as sustainability becomes paramount to all aspects of society.

Triple Bottom Line (TBL) – A business and accounting framework which allows businesses and other entities to measure the outcomes of their efforts through three different aspects: financial, environmental, and social. Operating with a triple bottom line framework allows businesses and other entities to better understand the wholistic effects of their decisions and orient themselves towards a more sustainable path.

United Nations Sustainable Development Goals (UNSDGs or SDGs) – A system developed by the United Nations, the Sustainable Development Goals are described by the UN as: "[…] the blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace and justice. The 17 Goals are all interconnected, and in order to leave no one behind, it is important that we achieve them all by 2030" [14].

Usage Effectiveness System (UES) – A framework for measuring and incentivizing the efficient use of resources. This is an extension of the pioneering work of Power Usage Effectiveness (PUE) for data centers. This paper presents Water Usage Effectiveness (WRE), Land Usage Effectiveness (LUE), and Network Usage Effectiveness (NUE). Please refer to the "Sustainability Through Design and Measurement" section for more information.

Waste "RE" Effectiveness (WREE) – A new class of sustainability metrics introduced by this paper to measure the effectiveness of using all waste from a product or service. The "RE" in WREE refers to the group of actions that can be taken with waste: reduction, reuse, recycling, and remanufacturing. A perfect WREE means that no waste is generated because all potential waste has been prevented or captured and used for another purpose that is in line with a Triple Bottom Line mindset.

Water Usage Effectiveness (PUE) – A new industry metric introduced by this paper to measure the amount of water consumed by a data center per kWh of electricity used by a data center over a given time period. The standard usage of water in data centers is for cooling and thus the measurement is a ratio of water to electrical power usage because the electrical power usage is the source of heat which needs cooling.

Watt (W) – A standard unit of measurement for power output. In the context of data centers, watts generally refer to electric power. Watts can be used when talking about power capacity and power draw. In the context of power capacity, watts refer to the maximum amount of power which can be drawn at any given point. In the context of power draw, watts refer to the amount of power being used by something at a given moment.

Watt-Hour (Wh) – A standard unit of measurement for power consumption, in the context of electricity, or energy, in the more general context of physics. When used in the context of data centers, watt-hours refer to the amount of electrical energy consumed over a given time period. For example, if a computer draws an average of 10 watts over 24 hours then during that time period it consumes 240 watt-hours. Generally, a consumer is billed at a given rate per kilowatt-hour.

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