



Tools Towards the Sustainability and Circularity of Data Centers

Mohamed Sameer Hoosain¹ · Babu Sena Paul¹ · Susanna Kass² · Seeram Ramakrishna³

Received: 24 November 2021 / Accepted: 22 June 2022 / Published online: 1 July 2022
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2022

Abstract

We are living in an age when data centers are expanding, require abundant spaces, and are an integral part in the urban communities, using massive amounts of environmental resources, and remains in the foreseeable future as the primary driver of the global energy consumption. This demand is disruptive and at times of both peril and opportunity due to impacts such as the COVID-19 pandemic, which is altering the demand of digital infrastructure around the world. With the global call for zero carbon emissions, there needs to be solutions put in place for the de-carbonization of data centers. New innovations are made available, which will have an economic, social, and environmental impact on data centers. Concepts such as circular economy and fourth industrial revolution technologies are useful procedural tools that can be used to systematically analyze data centers, control their mining and critical raw materials, can be utilized in the transition towards a sustainable and circular data center, by objectively assessing the environmental and economic impacts, and evaluating alternative options. In this paper, we will look at the current research and practice, the impact on the United Nations Sustainable Development goals, and look at future strides being taken towards more sustainable and circular data centers. We had discovered that decreasing the environmental effect and energy consumption of data centers is not sufficient. When it comes to data center architecture, both embodied and operational emissions are critical. Data centers also have a vital societal role in our daily lives, enabling us to share data and freely communicate via social media, transacting on the blockchain with cryptocurrencies, free online education, and job creation. As a result, sustainability and efficiency measures have expanded in a variety of ways, including circularity and its associated tools, as well as newer technologies.

Keywords Data centers · Sustainability · Circular economy (CE) · Fourth industrial revolution (4IR) · United Nations Sustainable Development Goals (UN-SDGs)

✉ Mohamed Sameer Hoosain
sameer.hoosain@gmail.com

Extended author information available on the last page of the article

Introduction

The increasing demand for data center sustainability and efficiency is directly proportional to the cost-effectiveness and daily demand of the environmental resources with regard to the manufacturing of data center products, construction, operation of the data centers, and reduction in the environmental impacts such as the carbon emissions and waste. They must also keep up with external factors, including driving forces of the likes of Industry 4.0 or also known as the fourth industrial revolution (4IR).

We have seen a growth in technical developments since the commencement of the industrial revolution. Factories were first powered by water and steam engines in the nineteenth century, then by electricity in the twentieth century, and ultimately by automation in the 1970s. We are presently on the verge of a revolutionary digital industrial technology. Cyber physical systems can communicate with one another in this fourth technology wave in business by employing artificial intelligence (AI), machine learning (ML), Big Data, and the Internet of Things (IoT), among other technologies. Japan proposed the intelligent manufacturing system (IMS) in the 1980s, and the US followed suit with the cyber physical system (CPS). Germany recently offered Industry 4.0, while China advocated China Manufacturing 2025. Productivity and growth will surely improve as a result of Industry 4.0.

If we are to succeed with circular economics in the data center industry, we must deliberately depart from the linear practices, transition to circular thinking, utilize newer digital technologies, measure our progress throughout the lifecycle for a data center, and facilitate these changes for those who design, build, manage, and maintain them. Therefore, the entire life cycle needs to be considered. Circular economy tools can assist in the transition from a linear economy to a circular economy in a data center, which in turn can lead to sustainability, efficiency, and optimization [1].

Like industrial systems, data centers require significant amounts of natural resources with a growing demand for energy and materials. It has a certain significance, and it is regarded as the dedicated space used for inventory management of computer hardware, require sufficient space, environmental control (air conditioned cooling, fire suppression, water usage), data connectivity, and power supply. Therefore, the large-scale data center industry is responsible for substantial environmental degradation and is now on the radar of growing environmental concern due to huge amounts of annual carbon dioxide emission. We need to rethink how *not* to, dig up materials, turn them into data center products, generate large volumes of carbon emissions, waste heat in the data center operation, and discard the electronic waste (e-waste) in the environment. We need to adopt circular thinking to create new sustainable products, as the circular economy synchronizes with each phase of the data center life cycle keeping materials in circulation. Several solutions and research outputs have been put in place for data centers to create sustainability and circularity.

Think of data centers as ever-evolving to support the surge of 2.7 billion online meeting minutes per day in the month of March 2020, the on-demand data analytics in zettabytes caused by tele-medicine and tele-diagnostic applications, and the sensors in the 40 billion IoT constantly gathering and correlating data. The Google Sustainability post reports 54% of the world's population lives in the urban areas which account for 75% of natural resource consumption, 50% of the global waste production, and 60–80% of greenhouse gas emissions (GHGE). According to the United Nations Migration report, 68% of the global population is expected to migrate and reside in urban communities, giving rise to 10 more megacities each with over 10 million residents. More data centers will be built in these urban communities; there is an opportunity now to develop “circular data center cities”

to adapt to the digital transformation changes. The data center life span depends on use, design, build, and operation. Just as you would care for a human being, the same is needed for data centers in the form of new technology adoption, maintenance, and upgrade of the physical and digital infrastructure [2].

Circular thinking is not just for data centers; they range from general construction to any electrical, mechanical, manufacturing, safety, and other systems. By using circular economy tools, stakeholders gain better insight into their buildings and businesses, while at the same time achieving sustainability and circularity [3].

While the data center sector continues to expand and its efficiency is being scrutinized more closely, it is important to raise awareness about where its highest economic, social, and environmental effects are. Examining the factors that affect this impact can help guide policy makers and decision makers, as well as promote the development of sustainable and circular data centers. It is time to adopt sustainability practices within data centers and simultaneously maximize their life cycle [4].

Background

Data Centers and Information and Communication Technology

Since the late 1950s, when American Airlines and IBM collaborated to create a passenger reservation system provided by Sabre, the idea of data centers has existed, automating one of its main business areas.

Data centers are information-based repositories which include server farms and networking equipment that store, process, and transmit enormous amounts of data. They offer digital services like cloud computing, virtualization, high availability, and unlimited compute, storage of data processing, data analytics, and data storage. A conventional data center comprises software digital application and physical infrastructure of:

- Information technology (IT) systems (server units, storage units, network, and communication equipment);
- Mechanical systems (compressors, heat rejection fans, pumps, cooling technologies);
- Electrical systems (transformers, uninterrupted power supply (UPS), generators, power distribution units (PDU), switches, rack mounted UPS, lighting);
- Physical infrastructure (building, physical facility, modular IT container).

Similar to two computers linked in a local network, internet servers transmit information through network connections to any internet addressable devices. The data center is the physical repository of the cloud, providing instantaneous access to digital services and cloud applications with unlimited compute, network and data scalability, and storage. Internet, cloud computing, and data centers make the internet possible. All the machines on the internet either provide the cloud and digital services to other machines (servers) or are used to access data of social media, digital services, and cloud applications (clients) using Internet protocol (IP) addresses. IP addresses are uniquely allocated to a computer or server that links to the internet. They assist in command mediation, addressing, and processing of data. The conversion of IP addresses into domain names (e.g.,.com,.co,.za,.org,.or.gov) radically altered the essence of the internet to deliver equal and ubiquitous access.

Tiers are used by Uptime Institute to identify the redundancy representation of the data center components at the infrastructure level to compare the uptime of different data centers, namely:

- Tier 1 — a single path for power and cooling and few, if any, redundant and backup components.
- Tier 2 — same as tier 1, but with less down time annually.
- Tier 3 — has multiple paths for power and cooling and systems in place to update and maintain it without taking it offline.
- Tier 4 — built to be completely fault tolerant with redundancy for every component.

Most large communications companies have dedicated backbones of their own which link different regions. In each area, the company has a point of presence (POP), a location where local customers can reach the company's network either through a local telephone number or a dedicated line.

It is estimated that data centers use 200 terawatt hours (TWh) each year, which surpasses that of some countries. Data centers contribute about 0.3% of total global carbon emissions, whereas information and communications technology (ICT) accounts for more than 2% of global emissions. This is predicted to increase to 20% by 2030, which in turn rises the carbon footprint of economies, according to the International Energy Agency in 2017. We look at the key estimates of digital evolution between 2018 and 2023 by Cisco which is re-modeled in Fig. 1 [5]. Contrary to common opinion, as the number of data centers increase every year, their energy consumption is constant and even slowly declining.

Standards and regulations need to be adhered to when planning, constructing, and running a data center. These codes are for basic security standards to guarantee protection of life and energy conservation. The major industry standards developed and are most often applied for the data center are shown below in Table 1 [6][7].

Data centers range in size from a single server room to clusters of buildings spread over many locations, but they are all common in regard to being business assets. We list some of the common types of data centers below:

- Enterprise — built and utilized by a single organization for its own internal objectives. These are frequent among technology giants.

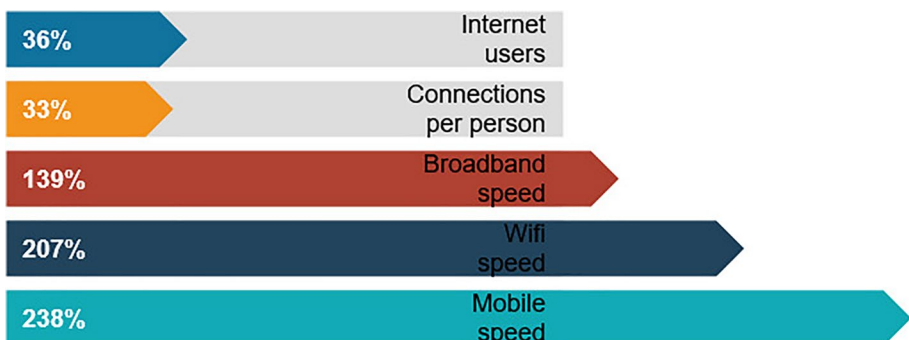


Fig. 1 Estimated digital evolution percentage increase from 2018 to 2023 elaborated from [5]

Table 1 The major industry standards developed for the data center

Standard	Description
Uptime Institute's tier standard	This standard develops a performance-based data center methodology during the design, construction, and commissioning phases to determine the facility's resilience with respect to four tiers or redundancy/reliability levels
Telecommunication Infrastructure Standard for Data Centers (ANSI/TIA 942-A 2014)	This standard is more IT cable and network oriented with various infrastructure redundancy and reliability concepts based on the Uptime Institute's tier standard
European standard (EN 50,600)	This standard consists of general concepts, building construction, power distribution, environmental control, telecommunications cabling infrastructure, security systems, management, and operational information systems
Regulatory standards	The legislation regulating data centers may depend on the complexity of the company, potentially including HIPPA (Health Insurance Portability and Accountability Act), SOX (Sarbanes Oxley) 2002, SAS 70 Type I or II, GLBA (Gramm-Leach Bliley Act) as well as new regulations
Operational standards	These standards guide the daily processes and procedures once the data center is constructed: Uptime Institute: Operational Sustainability, International Organization for Standardization (ISO) 9000 — Quality System, ISO 14000 — Environmental Management System, ISO 27001 — Information Security, PCI — Payment Card Industry Security Standard, SOC, SAS70 & ISAE 3402 or SSAE16, FFIEC (USA) — Assurance Controls, AMS-IX — Amsterdam Internet Exchange — Data Center Business Continuity Standard, EN50600-2–6 Management and Operational Information
Power purchase agreement (PPA)	An important contract that governs the sale and purchase of power, thereby reaping the benefits of renewable energy

- Colocation — functions as a type of rental property in which the space and resources of a data center are made available to those who wish to rent them.
- Hyper Scale — Cloud Computing has proven to optimize energy resources that private data center as a viable option by providers like Amazon Web Services, Google, and Microsoft Azure, and others, that are constructing new data centers in the form of Hyper Scale Data Centers. They offer scalable apps and storage portfolio services for businesses and developers.
- Edge — these are newer types of data centers and are smaller facilities that supply cloud computing resources and cached information to end users and are placed near to the populations they serve. They are often linked to a bigger central data center or a network of data centers.

Circular Economy

Circular economy ideas gained popularity in the late 1970s. Through literature, there is often a connection between sustainability and circular economy, and it has gained popularity among researchers and practitioners. Internationally, organizations such as the Ellen Macarthur Foundation have been promoting the term in a variety of fields. Critics claim that it can be defined differently to different people. According to research, the circular

economy is most commonly described as a combination of reducing, reusing, and recycling activities, whereas it is frequently overlooked that circular thinking necessitates systemic reform [8].

Establishing a circular economy is essential for overcoming growing waste obstacles, which are vital for both resource management and environmental protection, and will lead to a prosperous and competitive digital economy. It can lead to a reduction in waste such as e-waste, socio impacts such as water, supply chains, and maximize the re-use of recycled and second-hand products. Not forgetting the reduction in GHGE and job creation [9]. We depict a typical data center circular economy approach example of our own in Fig. 2. The diagram represents the steady movement of technical materials through the value chain.

Using current evaluation methodologies and methods is part of the Circular Economy toolbox. There are a variety of resources available, and the use of new technologies has made them more accessible. Online libraries and databases, software templates, online calculators, and algorithms are examples of emerging technologies. We look at some tools in Table 2 that can be used for the transition to a circular economy [10] [11].

Life cycle assessment (LCA) monitors environmental effect, life cycle costing (LCC) measures economic impact, and social life cycle assessment (S-LCA), which is a relatively young and expanding subject, assesses social impact. To measure sustainability, all the three techniques are currently being merged into a new statistic called life cycle sustainability assessment (LCSA).

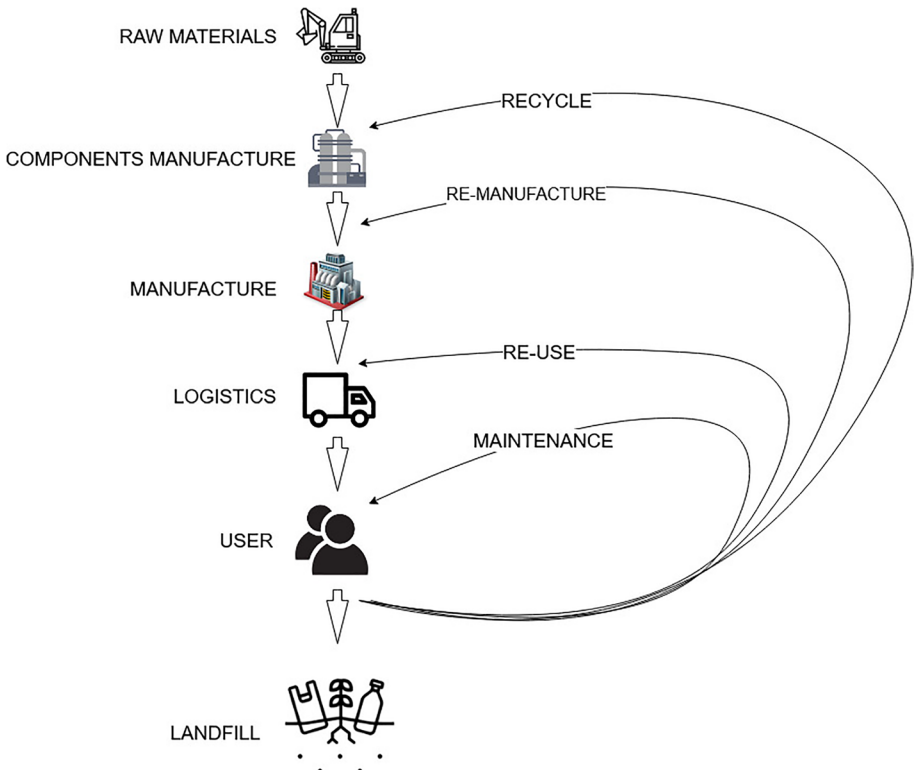


Fig. 2 A typical circular economy approach example

Table 2 Circular economy tools

Tools	Description
Materials passports	Materials passports is a value monitoring tool that can be used to bring back residual value to the market. Materials passports allow information about materials, substances, or processes available at any time, from manufacturing to ordering, use, and maintenance. The properties of the material are required; this information involves physical or chemical properties, material safety data sheets, bill of materials (BOM), logistics, disassembly, and recyclability. The process required to create one includes multiple stakeholders and organizations
Life cycle costing (LCC)	Derived from ISO 15686. LCC is an economic methodology that calculates the total cost of a commodity, resource, operation, or service over its life cycle. LCC is used for decision-making in a variety of ways and for a variety of reasons. It is classified into three types: conventional, environmental, and social
Life cycle assessment (LCA)	Derived from ISO 14040. LCA evaluates the net environmental impact of the production process, use, pollution, and activities associated with the construction and management of a building, service, or object. Economic or cultural issues, on the other hand, are ignored
Social life cycle assessment (S-LCA)	S-LCA adheres to the ISO 14040 framework; nevertheless, some features change, are more prevalent, or are intensified at each stage of the research. S-LCA does not provide information on whether or not a product should be created, but can provide information that is useful in making a choice. The United Nations Environment Programme (UNEP) is in charge of coordinating environmental responses across the United Nations system. They have also suggested recommendations and procedures for creating life cycle inventories
Material circularity indicator (MCI)	MCI is a decision-making process designed to evaluate how well an organization or product does as it transitions from a linear to a circular economy. The MCI value of the component or components is between 0 and 1 (or 0% – 100% of the recirculated parts), with a value greater than 1 indicating greater circularity

Methods

To investigate similarities and gather useful evidence, a literature review was conducted. This article's analysis process was accompanied by a snowballing technique for an in-depth evaluation. We looked for and uncovered a variety of literature based on circular economy and sustainability of data centers from around the world. The research centered on scientific papers (e.g., journal articles, conference papers, and dissertations) as well as non-academic papers (e.g., government publications, surveys, reports, newspaper articles, white papers by data center organizations) [12].

In this section, we will look at circular economy in the context of data centers, as well as the current applications and research being done towards circularity and sustainability. We will further assess 4IR digital technologies being used to assist towards circularity. Finally, we look at the impact on the UN-SDGs.

Circular Economy in the Context of Data Centers

Circular data centers redefine the longevity of data center infrastructure by incorporating primary and secondary business applications research into a common system, with transformative results. We can further assess how well data centers are performing in the transition from a linear to a circular economy by measuring MCI; these can be done by using the online platforms and calculators provided in Table 5. The calculation for MCI is quite complex; therefore, there are online digital calculators such as; Circular economy toolkit (CET), Circularity calculator, Ellen MacArthur's Material circular indicator (MCI) tool, Flex 4.0 by Delft University, and RELi 2.0 by USGBC, to name a few.

Tracking materials using materials passports is another solution towards circularity, with the result of bringing back residual value back to the data center market. Currently there are online databases for materials passports such as MADASTER and Buildings as Material Banks (BAMB) [10] [11].

There are a number of short-term and long-term goals and benefits for a transition towards a circular economy in data centers. Some of these are summarized below [13]:

- Stakeholders become knowledgeable about all the costs and environmental impact.
- Efficiency is increased.
- Energy efficiency and greater sustainability.
- A reduction in the carbon footprint.
- Investors are able to compare designs based on short-term and long-term yields.
- Compliance and regulation requirements are met.
- Public safety.
- Maximizes the life cycle of a data center.

Barriers and Solutions

There are still a number of barriers for the data center transition towards a circular economy. These are in the form of uncertain global markets, efficiency and sustainability, and competitiveness within the market, to name a few. We look at some barriers in Table 3 [14].

Despite the list of barriers above, we list some suggested solutions to help curb this:

Table 3 Barriers towards a circular data center

Barriers	Description of barriers
The lack of valuable data	The accuracy and quality of the data is a crucial concern. This is because of the lack of sufficient, applicable, and reliable historical data
Government policies and interventions	There are not efficient development strategies and enforcements in place towards circular thinking
Global economic instability	Unprecedented economic instability, increasing inflation with weak economic patterns, reduced buying power and restricted budgets
Others	<ul style="list-style-type: none"> • Stakeholders are not willing to pay the extra costs • Education is limited or slow

- Government interventions in the form of funding. Government should leverage its resources to change existing practices.
- Education to show the usefulness and worthiness, to improve the efficiency and sustainability.
- Finally, there needs to be an adoption of newer digital technologies. Some examples are described below:
- Smart Apps, sensors, and robots may be used to do sophisticated collection, sorting, and recycling of electronic waste.
- Machine learning and artificial intelligence can be used to process materials more efficiently.
- Additive manufacturing 3-dimensional (3D) printing may be used to help design better for circularity.
- Interactive platforms can be developed using online databases and IoT.
- Blockchain technology may be utilized to enhance circular production procedures, corporate operations, and financial and environmental performance.

While operational energy and carbon assessment are important when it comes to data centers, embodied energy and carbon play a pivotal role with regard to sustainability and circularity of data centers. This includes emissions from resource extraction, production, and transportation, as well as emissions from the installation of materials and components needed to construct the built environment. It also covers lifetime emissions from continued usage, such as maintenance, repair, and replacement, as well as end-of-life activities such as deconstruction, transportation, trash processing, and disposal. These lifecycle emissions must be taken into account in order to calculate the overall embedded carbon cost. However, because embodied carbon is largely paid up front as the facility is built, there is a strong rationale to incorporate it in all assessments and data center design decisions. A whole life carbon strategy that incorporates embodied and operational emissions gives the possibility to positively contribute to SDG's goal to decrease greenhouse gas emissions, while saving money. More information on embodied carbon in data centers can be found in i3 Solutions white paper [15], as well as the use of life cycle assessment when examining the effect and utility of design decisions on a cradle-to-cradle basis, taking the circularity of the facility and its components into consideration.

The control of hazardous and unethical mining and materials processing for data centers are of utmost importance, particularly the effect this has on the SDGs. Mining, whether large-scale industrial mining or small-scale artisanal mining, is a hazardous industry. The majority of data center equipment is made up of ordinary metals, polymers, and key critical raw materials (CRM). Many of these and other commodities are extracted using hazardous chemicals, and because much of their mining is uncontrolled and/or illegal, the accompanying negative environmental and social repercussions are severe. Many of the components' functionality is dependent on CRM. Twenty-three of the 30 CRMs are found in server, storage, and networking equipment. This implies that the resources we rely on for the world's data centers are in low supply or are politically unpredictable. CRMs are finite materials provided by the European Commission that are in short supply globally; examples of some of these materials are titanium, lithium, germanium, etc. Because these raw materials are in low supply globally, there are no viable substitutes; hence, the answer to the CRM problem is a circular approach. This can be done by minimizing mining of these raw materials from the earth and re-use our existing resources. Choosing used equipment has several environmental, financial, and performance advantages. Selling obsolete IT equipment from data centers is another excellent approach to keep technology alive. We

can get a return on undesired equipment while assuring that all data is unrecoverable. As a result, by implementing circular economy waste reduction measures, such as product life extension through recycling, reuse, and remanufacture, could prove fruitful for the mining sector. Furthermore, facilities can be designed for these circular processes while at the same time develop ethical, well-paying opportunities that allow workers to work in ecologically safe, non-hazardous settings. Not forgetting, to have a positive social impact, mining projects should be controlled globally, and they must find better methods to connect with local populations, such as via active engagement in social development, increased respect for human rights, reduction in pollution, and assistance in overcoming poverty.

Current applications and research towards circular and sustainable data centers

Global business has a vital role to play in switching from a *take-make-dispose* model-based economy to a restorative and regenerative system-based one. This circular thinking allows for efficiency and sustainability and a reduction in the environmental footprint of data centers. Given this need, there are a number of countries and organizations that have made significant strides towards sustainable and circular data centers; these applications and initiatives are listed in Table 4.

Data Centers and 4IR Technologies

With the introduction of the 4IR, which makes up a variety of fields such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine learning (ML), Big Data, Block chain, 3D technologies, Quantum computing, and Robotics, we find further solutions to a circular and sustainable data center in the form of digital technologies [29]. These technologies are capable methods of accelerating circularity, dematerializing, and making us less dependent on primary materials. Research has been done to show the impact of 4IR digital technologies together with CE on the UN-SDGs [10] [11].

AI and ML can be used for automating and enhancing operational performance, including materials upgrade, and CFE use. This is done with the use of historical performance data, AI algorithms, day ahead weather conditions which in turn can predict renewable energy generation and calculate 7×24 match with the energy consumption usage in the data center. With the use of IoT-based sensor networks and AI, we can monitor and predict server utilization and operation performances of any data center, thus allowing early warning notifications of faulty hardware, excessive heat from servers, as well as preventive maintenance to alleviate system downtime. Sustainable data centers for the hyper scale cloud providers such as Google have utilized renewable energy for its annual global consumption of over 3 GW in 2018. On Earth Day in 2020, Google announced it would source clean energy at its operations for 24×7 match across 21 sites, 22 cloud regions, and 200 countries; that is always and anywhere. In addition to using carbon free energy, naturally cold temperature outside air and submersion liquid cooling with AI provide benefits, such as reducing energy use and eliminating the use of diesel generators and air conditioning machines [30].

Researchers in the United States (US) also created a new energy-based benchmark for the quantum advantage to prove that noisy intermediate-scale quantum (NISQ) computers consume less energy than the most efficient supercomputer in the world when conducting a single function. A test to prove this theory was carried out between a supercomputer and NISQ computers with amazing results. The researchers found that Electra supercomputer

Table 4 Current applications and initiatives

Application/initiative	Description
ITRENEW [16]	ITRENEW is based in Silicon Valley and has been optimizing the lifetime benefit of data center technologies for more than two decades through creative circular economic models and a robust range of resources for decommissioning and network protection, computing and storage solutions on a rack scale. They have collaborated with some of the largest hyper scale data centers in the world. They have also built a new circular data center model to open up ways to increase the efficiency of the infrastructure and boost sustainability. By seeing the true promise of the data center equipment lifecycle, from network architecture to the remanufacture of complete systems after decommissioning
Amazon [17]	Amazon's commitment to fighting climate change, with the goal of reducing carbon emissions to be carbon-neutral by 2040. The companies' plan is to be run solely on renewables by 2030. Amazon currently gets 40% of its energy from renewables, such as solar and wind farms. "Our research shows that delivering a typical order to an Amazon customer is more environmentally friendly than that customer driving to a store," an Amazon sustainability representative had written
Google data centers [18][19]	<p>The strategic collaboration between Google and the Ellen MacArthur Foundation assists Google in expanding on current strategies and integrating circular economic concepts into the architecture of Google's technology, operations, and community. Maintenance, renovation/remanufacturing, redistribution/secondary sector selling, and recycling. These activities combined with Google's circular approach to managing server end-of-life based on the concept of total cost of ownership (TCO) culminated in expense avoidance of hundreds of millions of dollars per annum</p> <ul style="list-style-type: none"> ●Google is the product manufacturer in Google's server supply chain. Google performs an excess and obsolescence (E&O) project that analyses the life cycle of products and their overall ownership costs compared to new equipment and compares demand and supply to assess E&O rates ●Google's data center maintenance process helps the servers to have a longer life expectancy. When servers malfunction and collapse into maintenance, the faulty parts are replaced with refurbished components ●When data center servers are decommissioned, they are transferred to the main repository. At the core servers, their functional components (central processing unit (CPU), motherboard, flash drives, hard disks, ram modules and other parts) are removed and de-kitted. Once all components are in Google's inventory, both refurbished and new equipment are considered equivalent ●Memory modules, hard drives, and original equipment manufacturer (OEM) networking equipment are examples off access equipment; therefore, they are sold in the secondary market ●Finally, all equipment that cannot be resold or reused is recycled. This is done by crushing the equipment and is then converted into reusable materials

Table 4 (continued)

Application/initiative	Description
Facebook [20]	Facebook's data centers are among the world's most modern and energy efficient facilities. Electricity supply has been replaced by clean and renewable sources. Their sustainable hardware design approach is done by looking at the entire life cycle (raw material extraction → manufacturing → transport → use → end of use → reuse or recycling) with the goal of reducing fossil fuel inputs and emissions. Natural fiber-filled polypropylene (NFFPP) is being used as replacement for many of their materials, thereby reducing the carbon footprint
Microsoft [21]	Microsoft's Carbon Negative Pledge — not only to become carbon free by 2030 but also to offset its past carbon emissions by 2050. One solution is to use 100% renewables by 2025, as well as to work with supply chains and partners to reduce carbon emissions
European Union (EU) Circular Economy Action Plan [22]	Makes Europe less dependent on primary materials. A “Circular Electronics Initiative” to encourage longer life cycles on a variety of equipment for the data center. Acts include server and storage regulatory initiatives under the eco-design mandate to ensure systems are designed for energy consumption and reliability, reparability, upgradability, repair, reuse, and recycling
Infrastructure masons (IM) [23]	<p>Infrastructure Masons' Sustainability Committee have come up with several approaches on how data center designers and managers can reduce the industry's detrimental impact</p> <ul style="list-style-type: none"> • Using “waste” heat in district heating systems, comfort heating, heating swimming pools, spas, greenhouses, or industrial processes • Power sharing is being integrated into the power grid to provide back-up power to the community when it is not needed by the data center • Turning waste such as biofuel into power • The use of other materials to construct data centers; one example is wood • Managing equipment life cycles; this is done using LCA, LCIA, and LCC
Circular Economy for the Data Center Industry (CEDaCI) [24]	The data center industry has evolved fast and creates a significant amount of e-waste. The present infrastructure for dealing with this waste is inadequate, and as a result, there is a clear and pressing need to solve this issue right away. CEDaCI will create a Circular Economy for the Data Center Industry by bringing stakeholders from all stages of the equipment life cycle together to transform waste into a usable resource and support the industry's continuous fast expansion. CEDaCI will create a Circular Economy for the Data Center Industry by increasing the sector's reclamation and reuse of critical raw materials, extending product life through equipment reuse and remanufacture, reducing the use of virgin materials, waste, and environmental impact caused by the increase in redundant equipment, and developing a secure and economically viable supply chain. At the moment, only 10% from the sector is recycled and recovered, but this will climb to 19% and 24% 5 and 10 years after the project finishes; reuse of equipment will also increase to 65% and 75%, respectively, and overall product “waste” will be reduced to 35% and 25% at end-of-life

Table 4 (continued)

Application/initiative	Description
EcoDataCenter [25]	Situated in Falun, North of Stockholm, which is made up of 8 MW 3600 m ² extension framework going up in a beautifully engineered “wood.” It is a product called “Glulam,” an engineered timber created by cross-laminating and gluing, under high pressure. Better fire resistance capability than steel frames due to the surface build-up of carbon limits the oxygen supply to the wood below and acts as an insulator. Glulam also has a much lower embodied energy than reinforced concrete or steel. And importantly a reduction in the carbon footprint
InfraPrime	A pure play start-up provides affordable 24 × 7 clean energy infrastructure for global data centers to align with the United Nations Sustainable Development Goals and enact Climate Action Plan. Arctic Prime data centers are located at the Arctic Circle, deliver net zero in carbon, emission, waste; each data center is resilient using the power duality architecture to utilize hydroelectric renewable energy grid supply, outside air cooling, waste heat reused for district heating to the Nordic communities, applications including green house for agriculture, and fish farming for salmons. EcoPrime Power Clean Energy module is a Carbon Free Energy (CFE) module which generates 24 × 7 carbon free energy on premise at any data center location. Its resilient design provides 99.999% uptime with a performance guaranteed to the data centers, uses renewable gas, fuel cells as the primary energy source using the fossil fuel grid as a backup without the need of a conventional diesel generator. The design has been selected by the European Union “Fuel Cell for prime power in data centers” ID-FCH-02–9-202 and is in operation at Microsoft Research Lab, Seattle, Washington achieving 99.999% uptime when the electric grid has a downtime failure
Santa Clara [26]	Silicon Valley is one of the largest data center markets in the US. Santa Clara has been the data center capital of Silicon Valley. The main reason for this location is due to the lower power pricing. Santa Clara boasts a number of well-known data centers. With this comes sustainable and efficiency requirements for the data centers The California Environmental Quality Act (CEQA) mandates that city and state officials weigh a project’s possible environmental impacts before determining if they approve it. The aim of the CEQA is to expose the possible impacts of a project, recommend strategies for mitigating such impacts and explore alternatives to the project so that decision-makers have complete knowledge on which to base the project One company, Vantage Data centers, had recently constructed another data center, designed to meet sustainability requirements. They have used new cooling systems which use less water than normal. This is done by using recycled water and modular chillers and dry-cooler technology
UNICA data centers	Use of access or wasted heat to heat 2 million households by 2030. As well as the use of LCC in their data center designs
Cloud data centers (CDC) [27]	Cloud computing has gained popularity in recent times. These facilities are hosted by CDCs. There is research being done for sustainable CDCs and reductions in emissions. Solutions such as renewable energy, reductions in heat waste, and modular data centers are used

Table 4 (continued)

Application/initiative	Description
CERN openlab2 and used by CERN [28]	Growing power prices and aging data centers are forcing many companies to rethink their computing infrastructure's energy efficiency. CERN has been grappling with this problem for many years, due to its huge processing demands and 35-year-old data center, and is taking a holistic path to achieving the best possible output per watt. CERN has replaced older servers with single-core processors with newer servers built on the newest 45 nm Intel Xeon processors, which have four cores per chip. This approach, according to the company, has added almost 2 years to the life of its data center, and potential multi-core Intel processors could extend it by another 6 months. CERN's tendering process, data center architecture, power and cooling methods, and software development techniques have also been changed. Both of these modifications are aimed at improving overall efficiency while using less total resources

at Ames required 97 MWh to solve a particular problem and 21 MWh on the Summit supercomputer (the world's most powerful supercomputer) at Oak Ridge, whereas the problem could be solved by a NISQ using only 4.2×10^{-4} MWh [31]. Research has been done recently with the use of two AI methods, namely, artificial neural networks (ANNs) and adaptive neuro-fuzzy inference system (ANFIS), for predicting life cycle environmental impacts and energy efficiency [32] [33].

While 4IR technologies have major benefits within data centers and their sustainability, they can function as a catalyst for a shift to a circular economy while also hastening the process of addressing some of humanity's most pressing issues, such as the UN-SDGs. Individuals' abilities are supplemented, and their capability is increased. It enables individuals to learn more quickly from reviews, cope with uncertainty more successfully, and gain a deeper understanding of large amounts of data [10]. E-waste is the world's fastest increasing waste source, particularly within data centers. It includes important resources, including those that are limited and critical. Mishandling of e-waste causes unnecessary pollution and greenhouse gas emissions. Newer digital technologies can help with the circular management of e-waste, including prevention, collection, and treatment, by improving information sharing, streamlining operations, and linking the key players across the value chain. AI can enhance information collecting and processing, allowing for the circular design of electronics. It can also help to enhance sorting and law enforcement. Digital product passports (DPPs), like materials passports, can allow producers and other value chain participants to track and trace electronics. Robots and IoT sensors can help with e-waste sorting and disposal. 3D printing may offer spare components for electronics, prolonging their lifespan [34].

Digital Tools

Many data center operators promote their energy efficiency, and some even publish their carbon footprint. However, there is a need for easy tools to assist operators in better understanding and quantifying the embedded impact, as well as informing green procurement. Focusing only on energy efficiency may result in a burden shift, for example, by replacing less efficient equipment with more efficient equipment while increasing the embodied

impact. The overall environmental effect may remain the same or rise, but with the perception of a “greener” data center [35].

Circular economy tools will surely provide for safety and reliability, efficiency, circularity, and sustainability in data centers. Together with these techniques, there are innovative software and prototype options available particularly for the purpose of circularity which are listed and explained in Table 5.

The Impact on the UN-SDGs

In 2015, the United Nations Member States created a shared blueprint for peace and prosperity for people and the planet. The 2030 agenda features 17 United Nations Sustainable Development Goals shown in Fig. 3, which are an urgent call for action by all countries in global partnership.

The following UN-SDGs are particularly relevant to the next-generation sustainable data centers:

- Goal #6: Clean water and sanitation
- Goal #7: Affordable and clean energy
- Goal #9: Industry, innovation, and infrastructure
- Goal #11: Sustainable cities and communities
- Goal #12: Responsible consumption and production.
- Goal #13: Climate action

While data centers’ energy efficiency has been widely examined, their water footprint has gotten little to no attention. Water consumption is an important factor in data centers, especially because it is tied to the SDGs. Data centers are predicted to need between 1047 and 151,061 m³/TJ of water. Data center outbound data traffic has a water factor of 1–205 l/gigabyte [36]. According to the Organization for Economic Cooperation and Development (OECD), worldwide water consumption for industrial industries would rise 400% between 2000 and 2050. As a result, in order to achieve Inclusive and Sustainable Industrial Development (ISID), water consumption efficiency must increase. United Nations Industrial Development Organization (UNIDO) describes water stewardship as, the use of water in a socially fair, environmentally sustainable, and economically profitable manner. This is accomplished through a multi-stakeholder process that includes site and catchment-based activities [37]. Water is used to cool servers in data centers, which have an influence on local water resources. As a result, water stewardship efforts in data centers should concentrate on lowering water demands. Water stewardship initiatives should include efforts targeted at replacing water consumed and enhancing overall watershed health, in addition to water consumption reduction. To get the most sustainable solution for data center cooling, power and water use must be balanced.

What we learned from previous economic dislocations, such as the dotcom bust and the 2008 financial crisis, is that data center providers adapt, emerge, and stay resilient. The acceleration of new business models, the data center hyper-scalers’ pledge to climate change and the leading sustainability leaders to rebuild the economy to a more sustainable future. The data center sector is the beneficiary of the shift to a socially distanced, contactless, work-anywhere new normal. Furthermore, some environmental, social, and

Table 5 Software and prototype options available for the purpose of LCC, LCIA, and circularity

Software and prototype	Brief description	Source
TOMRA Expert Line	TOMRA Expert Line in Canada has developed algorithms for material recycling and waste solutions <i>The software is a paid service</i>	https://www.tomra.com/en
OPTORO	Have also developed algorithms for material recycling and waste solutions <i>The software is a paid service</i>	https://www.optoro.com/
CEP-AMERICAS	This Circular Economy Platform (CEP) of the Americas is an initiative powered by the Americas Sustainable Development Foundation (ASDF). It fills the vacuum for an easy-access one-stop-shop portal where information about circular economy from and for the Americas is made available	https://www.cep-americas.com/
Eco invent	Database for the life cycle assessment on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services. The Eco invent life cycle inventory database, aids in environmental analyses of goods and processes globally <i>The software is a paid service</i>	https://www.ecoinvent.org/home.html
Simapro	Simapro enables you to successfully apply your sustainability expertise to enable informed decision-making and improve product life cycles The program enables you to acquire insights about the environmental performance of products and services, allowing you to become an informed change-maker who actually promotes long-term change. The program may be used for a variety of purposes, including sustainability reporting, carbon and water foot printing, product design, environmental product declaration generation, and identifying key performance indicators <i>The software is a paid service</i>	https://simapro.com/

Table 5 (continued)

Software and prototype	Brief description	Source
Thinkstep GaBi	Life cycle assessments, product and organizational carbon footprints. This database spans over multiple sectors <i>The software is a paid service, whilst the database is free</i>	http://www.gabi-software.com/international/databases/gabi-databases/
Schneider Electric	Calculators based on data science. Tools are web-based that allow you to experiment with “what-if” scenarios using data and science to estimate outcomes during data center concept and design work <i>Free and paid services</i>	https://www.se.com/ww/en/work/solutions/for-business/data-centers-and-networks/trade-off-tools/
Circularise	An open, distributed and secure communications protocol for the circular economy. The platform allows information exchange between stakeholders throughout the value chain, creating transparency around product histories and material destinations	https://www.circularise.com/
Circular economy toolkit (CET)	An assessment tool, which identifies improvements in products’ circularity <i>Free</i>	http://circulareconomytoolkit.org/
Material circularity indicator (MCI)	Described by the Ellen MacArthur foundation as a tool used to assess European products in regard to a circular economy <i>Free</i>	https://www.ellenmacarthurfoundation.org/our-work/activities/ce100/co-projects/material-circularity-indicator
Circularity calculator	Supports manufacturers in product designs for a circular economy <i>Free</i>	http://www.circularitycalculator.com/
C-BUILD	Rates circularity developed by National University of Singapore (NUS). Supports zero-waste policy goals. The method is designed for rating future-proof construction of buildings. It operates on the requirements of architecture and listed metrics (design considerations), originating from CE definitions <i>Open source, free</i>	

Table 5 (continued)

Software and prototype	Brief description	Source
Embodied carbon in construction calculator (EC3)	A free and easy to use tool that allows benchmarking, assessment, and reductions in embodied carbon, focused on the upfront supply chain emissions of materials <i>Free</i>	https://www.buildingtransparency.org/en/
Documentation and record keeping for data centers	Software management tools such as DCIM (Data Centre Infrastructure Management), CMMS (Computerized Maintenance Management System), EPMS (Electrical Power Monitoring System), and DMS (Document Management System) for operations and maintenance can provide a “single pane of glass” to view all required procedures, infrastructure assets, maintenance activities, and operational issues	

1.No poverty	2.Zero hunger	3.Good health and well-being	4.Quality Education	5.Gender Equality	6.Clean water and sanitation
7.Affordable and clean energy	8.Decent work and economic growth	9.Industry, innovation and infrastructure	10.Reduced inequalities	11.Sustainable cities and communities	12.Responsible consumption and production
13.Climate action	14.Life below water	15.Life on land	16.Peace, justice and strong institutions	17.Partnerships for the goals	THE 17 UN-SDGs

Fig. 3 The 17 sustainable development goals, elaborated from (<https://sdgs.un.org/goals>)

governance (ESG) fund managers are outperforming the broader market during the pandemic, meaning new capitals invested in ICT and data center infrastructure have been more resilient. ESG, being the three main factors towards measuring sustainability and socio impacts of an investment in companies, is a data center in this case. ESG reporting towards sustainability has become compulsory in some organizations and countries around the world.

With the global call for zero carbon emissions, there needs to be solutions put in place for the de-carbonization of data centers; these include: *low carbon materials*; *embodied carbon*, which is the carbon emitted in the manufacture process and transport of building materials; and *operational carbon*, which is the carbon load generated by the heating and power consumption of the building.

The cleanest data centers are the ones that are not built at all. Digital transformation is a necessity to keep society running, especially in times of mass shutdowns to slow down the burden to our society of the transmission of COVID-19 pandemic. The goal is to promote digital services and sustainable cost of ownership throughout the data center life cycle to improve human, social, and environmental welfare. The data center materials must comprise a circular nature, not harmful to the environment, simultaneously prolong the longevity of nature and human progress, and zero carbon emissions and waste. A circular economy enabled sustainable data center is designed for disassembly, where each connection of the data center can be taken apart and each material component can be refurbished, reused, recycled with zero waste and remake into a new material to give rise to a circular economic growth.

In Fig. 4, we put theory to practice by mapping the circular economy for a data center lifecycle. Sustainable materials that are both friendly to the environment and people can have a perpetual life of use throughout the data center lifecycle. We align with the UN-SDGs in the data center design to protect the planet and ensure all people enjoy peace and prosperity. We select data center sites to locations with affordable renewable energy and utilize CFE generation for net-zero energy consumption. We build data center products and facilities with sustainable materials. We operate and maintain data center with a circular thinking to keep materials in circulation for multiple uses.

In the last decade, significant progress has been made in data center efficiency and sustainability. Access to clean, renewable energy is vitally necessary. It is mandatory to be

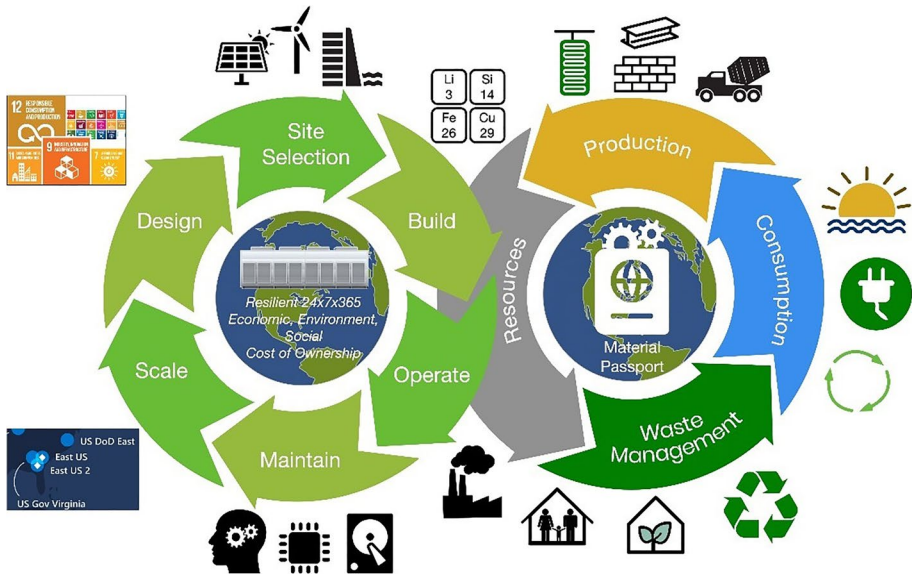


Fig. 4 The circular economy approach embraces end to end sustainability throughout the lifecycle for a data center and facilitates these changes for those who design, build, operate, and maintain them [38]

environmentally friendly when making decisions about using carbon free energy. Another critical component of an adaptive data center is advanced cooling technology that can result in 80% less energy and 85% less water. Global sustainability and data center leaders have made 100% clean energy pledge to reduce greenhouse gas emissions, promote carbon free energy, and adopt a de-carbonization pathway of fossil fuel for data centers. Sustain-Infra is the new infrastructure standard to use naturally clean energy generation for data center sites with 99.999% uptime, achieved naturally by location design of data centers at the source of renewable energy grids powered by hydroelectric, wind, or solar. Sustainable data centers are measured by zero carbon, zero emission, and zero waste. They use naturally generated renewable energy, increased resource-use efficiency, environmentally sound technologies such as outside air cooling and circular economy processes to reuse, recycle, and remanufacture waste. All countries will take action to adopt a clean energy infrastructure for the ICT sector.

CFE design enables a data center located anywhere to achieve the same net zero results; use of hydrogen, renewable gas with fuel cells — a technology to convert clean electric power generation on site — offers a good alternative. 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 server rack level. When paired with renewable natural gas (RNG) as a fuel source, fuel cells become a carbon negative power generation choice, therefore allowing a data center to be independent from the electric grid's cost, reliability, capacity, and carbon footprint.

Keppel Corporation is a Singaporean conglomerate who has made sustainability an important part of their business. Keppel data centers partnered with NUS engineering

department to develop an energy-efficient and cost-effective cooling system for data centers. Floating data centers are one solution to save energy and water; the IT equipment is cooled using the natural temperature of the water that data center floats on, thereby reducing water consumption.

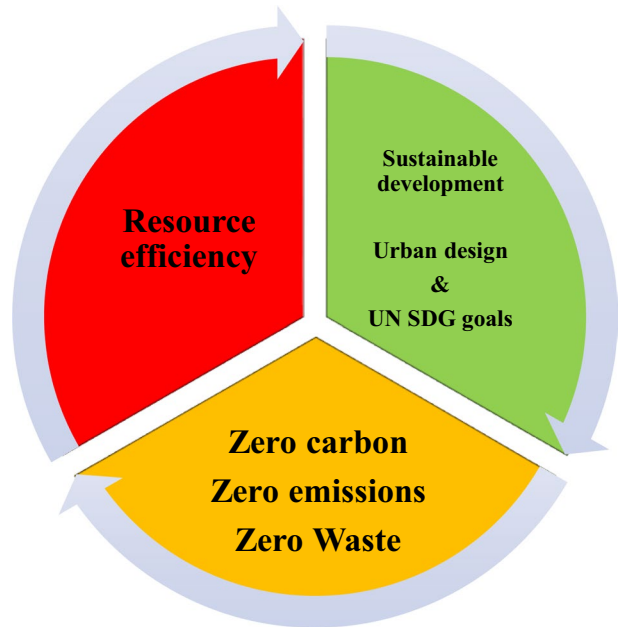
While environmental, energy, and carbon impacts are important with regard to sustainable data centers and the SDGs, social impacts play an important role as well. Data centers are hubs for major social media platforms globally; this allows for freedom of speech online, advertising, business opportunities, and social communication. The increase in sustainable data centers can lead to an increase to access to the internet to many more people around the world; this will in turn lead to more education opportunities for the less fortunate. Google, being a good example, allows people access to many forms of hyperlinks. They have enabled students to incorporate material for research projects, individuals to keep track of the stock market, and consumers to take advantage of unusual chances. With this increase in accessibility and sustainable data centers, more jobs are created. These are all important factors that are directly linked to the UN-SDGs.

Cryptocurrencies and crypto mining is presently disproportionately hurting the most vulnerable, worsening social, and environmental difficulties for people already suffering from numerous forms of deprivation. For the crypto blockchain to exist, the mining process necessitates enormous processing power and a great deal of energy, and has a significant impact on data centers. The social impact of some cryptocurrencies' unsustainable trajectory disproportionately affects poor people, and vulnerable communities, where miners and other actors profit from economic instabilities, weak regulations, and access to cheap energy, and other resources. Therefore, sustainable data centers need to implement stricter policies in order to curb these negative impacts left by crypto mining. One solution would be to decrease CO₂ emissions for blockchain and cryptofinance, by implementing low-carbon technologies and tools such as circular economy. Policies need to be also put in place by governments in order to support the sustainable data center, to limit the number of miners in a particular area. We need to also take note of the positive impacts crypto and the blockchain have on the UN-SDGs; (SDG 1) — cryptocurrencies and other blockchain-based tokens enable the world's 2 billion UN-banked people to trade and transact, (SDG 3, 12, 14, 15) —sharing of important data securely and efficiently, it has the ability to allow for a more circular economy by ensuring excellent provenance [39].

Discussion

We promote sustainability, circularity, combined with the UN-SDG goals in this paper for the data center. We came to understand the latest research and practice, as well as looked at future strides being taken with the use of 4IR digital technologies. What does this mean for the future data center? The circular economy is based on the concepts of waste and emission control, the conservation of goods and services in use, and the restoration of natural resources. We should shift towards sustainable and circular data centers by implementing circularity, 24 × 7 × 365 resiliency, triple zero (carbon, pollution, waste) measures, reduce water usage, refine e-waste strategies, social cost of ownership, capital usage, materials passports, lifecycle maintenance strategies, and 24 × 7 reporting per each kilowatt hour used; this future concept is shown in Fig. 5.

Fig. 5 Future concept of a data center



Conclusion

In order to achieve the efficient, sustainable, and circular data center of the future, we will need to incorporate the concepts such as SustainInfra and SustainTech, as well as companies such as Google and Microsoft. We need to reduce data center environment degradation by reducing carbon emissions. Resilience and 99.999% uptime are the primary goals of data center design and build. The next-generation data center should also include clean energy infrastructure, carbon free energy use, and net zero management; certain practices that were deemed groundbreaking a few years ago have now become common best practices. Every year, 50 million tons of e-waste composed of CRMs that may be reused, reconditioned, or repurposed are thrown to landfill. This quantity is expected to more than treble to 110 million tons by 2050. Therefore, by implementing circular approaches for future sustainable data centers would surely prove fruitful, particularly by controlling hazardous and unethical mining and materials processing. Finally, by following the ground rules set out by the UN-SDGs, we can manage engineering and innovations of data centers for a better environment and a better world for all.

Data centers are ever-growing and complex facilities; therefore, sustainability is challenging in an unpredictable world and unexpected circumstances such as the current COVID-19 pandemic, which will affect our choices. We can conclude that while reducing the impact on the environment and energy consumption of data centers is important, it is not enough. Embodied and the operational emissions are both important when it comes to the design of data centers. Data centers have an important social role in how our daily lives function. Social media allows individuals to freely interact and share data with those they trust. Similarly, data centers make education available to everybody through a variety of online platforms and smart apps, and the ability to complete business transactions and others, using the blockchain and cryptocurrencies through

responsible crypto mining. Most critically, there has been significant employment creation. Therefore, sustainability and efficiency measures have grown using a number of methods; these are in the form of circularity and its relevant tools as well as newer 4IR digital technologies.

Author Contribution M. S. H. had researched and compiled the article; S. K. had provided in-depth information and data with regard to data centers and their sustainability; B. S. P., and S. R. had provided feedback, supervision, and editing.

Data Availability Data for this study was extracted from scholarly publications, government reports, and statistical reports.

Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication The article may be published after review and acceptance, as a traditional publishing model.

Conflict of Interest The authors declare no competing interests.

References

1. Biolek V, Hanák T (2019) LCC estimation model: a construction material perspective. *Buildings* 9(8):182. <https://doi.org/10.3390/buildings9080182>
2. Shapiro S (2016) The life cycle of a data center. <https://www.datacenterknowledge.com/archives/2016/03/02/the-life-cycle-of-a-data-center>
3. Buyle M, Braet J, Audenaert A (2013) Life cycle assessment in the construction sector: a review. *Renew Sustain Energy Rev* 26:379–388. <https://doi.org/10.1016/j.rser.2013.05.001>
4. Flucker S, Tozer R, Whitehead B (2018) Data center sustainability – beyond energy efficiency. *Build Serv Eng Res Technol* 39(2):173–182. <https://doi.org/10.1177/0143624417753022>
5. Manganelli M, Soldati A, Martirano L, Ramakrishna S (2021) Strategies for improving the sustainability of data centers via energy mix, energy conservation, and circular energy. *Sustainability* 13(11):6114. <https://doi.org/10.3390/su13116114>
6. Matko V, Brezovec B, Milanović M (2019) Intelligent monitoring of data center physical infrastructure. *Appl Sci* 9(23):4998. <https://doi.org/10.3390/app9234998>
7. Chille V, Mund S, Möller A (2018) Harmonizing physical and IT security levels for critical infrastructures. In: Langweg H, Meier M, Witt BC Reinhardt D (Hrsg.), SICHERHEIT 2018. Bonn: Gesellschaft für Informatik e.V. (S. 133–143). https://doi.org/10.18420/sicherheit2018_10
8. Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. *Resour Conserv Recycl* 127:221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
9. Rezvani Ghomi E, Khosravi F, Tahavori M, Ramakrishna S (2021) Circular economy: a comparison between the case of Singapore and France. *Mater Circ Econ* 3(1). <https://doi.org/10.1007/s42824-020-00016-w>
10. Hoosain M, Paul B, Ramakrishna S (2020) The impact of 4IR digital technologies and circular thinking on the United Nations Sustainable Development Goals. *Sustainability* 12(23):10143. <https://doi.org/10.3390/su122310143>
11. Hoosain MS, Paul BS, Raza SM, Ramakrishna S (2021) Material passports and circular economy. In: Liu L, Ramakrishna S (eds) *An introduction to circular economy*. Springer, Singapore. https://doi.org/10.1007/978-981-15-8510-4_8

12. Carrière S, Weigend Rodríguez R, Pey P, Pomponi F, Ramakrishna S (2020) Circular cities: the case of Singapore. *Built Environ Project Asset Manag* 10(4):491–507. <https://doi.org/10.1108/BEPAM-12-2019-0137>
13. Biernacki M (2018) Benefits and inconveniences of the practical implementation of environmental life cycle costing. *Financial Sci* 23(3):9–16. <https://doi.org/10.15611/fin.2018.3.01>
14. Akinrata E (2016) Life cycle costing (LCC) in Nigerian construction industry: barrier and drivers facing its implementation. *World Sci News* 58:148–161
15. Reyher B (2022) Data centers must gain control over embodied carbon. Retrieved from <https://www.datacenterdynamics.com/en/opinions/data-centers-must-gain-control-over-embodied-carbon/>
16. ITRenew is powering the circular cloud - learn more. ITRenew. (2020). Retrieved 1 June 2020, from <https://www.itrenew.com/circular-cloud/>.
17. Amazon offers 1-day shipping on more items than ever. The environmental toll is huge. *Vox*. (2020). Retrieved 16 May 2020, from <https://www.vox.com/the-goods/2019/10/16/20917467/amazon-one-day-shipping-bad-for-environment>.
18. Circular economy at work in Google data centers. *Ellenmacarthurfoundation.org*. (2020) Retrieved 29 May 2020, from <https://www.ellenmacarthurfoundation.org/case-studies/circular-economy-at-work-in-google-data-centers>.
19. Circular economy of Google data centers | Google Sustainability. *Google Sustainability*. (2020). Retrieved 26 May 2020, from <https://sustainability.google/projects/circular-economy/>.
20. Tse J, Ehlen J (2020) Sustainable materials in the data center - Facebook engineering. *Facebook Engineering*. Retrieved 29 May 2020, from <https://engineering.fb.com/data-center-engineering/sustainable-materials-in-the-data-center/>.
21. Editorial H (2020) Data center management and the circular economy. *Horizon*. Retrieved 1 June 2020, from <https://www.horizontechnology.com/news/data-center-management-and-the-circular-economy-key-initiatives-to-watch/#microsofts-carbon-negative-pledge>.
22. European commission (2020) Circular economy action plan for a cleaner and more competitive Europe. *European Union*. <https://sdg.iisd.org/news/european-commission-adopts-circular-economy-action-plan/>
23. Infrastructure Masons (2020) Circular economy for datacenters. Version 1.4. [online] Available at: <<https://imasons.org/wp-content/uploads/2020/04/imasons-ce-1.4.pdf>> [Accessed 6 January 2021].
24. CEDaCI (circular economy for the data centre industry). *London South Bank University*. Retrieved 12 March 2022, from <https://www.lsbu.ac.uk/stories-finder/cedaci-circular-economy-for-the-data-centre-industry>.
25. (2015) 30 Sustainable Nordic buildings best practice examples based on the charter principles. *Norway: Nordic Innovation*. <https://www.nordicinnovation.org/2015/30-sustainable-nordic-buildings>
26. City of Santa Clara | Home. *Santaclaraca.gov*. Retrieved 12 May 2020, from <https://www.santaclaraca.gov/>.
27. Shuja J, Gani A, Shamshirband S, Ahmad R, Bilal K (2016) Sustainable cloud data centers: a survey of enabling techniques and technologies. *Renew Sustain Energy Rev* 62:195–214. <https://doi.org/10.1016/j.rser.2016.04.034>
28. Intel® Xeon® Processor (n.d.) White paper: reducing data center energy consumption. A summary of strategies used by CERN, the world’s largest physics laboratory. https://openlab-muinternal.web.cern.ch/03_Documents/3_Technical_Documents/Technical_Reports/2008/CERN_Intel_Whitepaper_r04.pdf
29. Sigwadi, Loshani (2020) Data Science and the Fourth Industrial Revolution (4IR). https://www.researchgate.net/publication/338646309_Data_Science_and_the_Fourth_Industrial_Revolution_4IR
30. Kawaguchi S, Azegami S, Suzuki Y, Yamate R (2017) Realization of energy-efficient, green data centers. *55 FUJITSU Sci. Tech J* 53:55–61
31. Villalonga B, Lyakh D, Boixo S, Neven H, Humble T, Biswas R, Rieffel E, Ho A, Mandrà S (2020) Establishing the quantum supremacy frontier with a 281 Pflop/s simulation. *Quantum Sci Technol* 5(3):034003. <https://doi.org/10.1088/2058-9565/ab7eeb>
32. Kaab A, Sharifi M, Mobli H, Nabavi-Pelesaraei A (2019) Combined life cycle assessment and artificial intelligence for prediction of output energy and environmental impacts of sugarcane production. *Sci Total Environ* 664:1105–1019. <https://doi.org/10.1016/j.scitotenv.2019.02.004>
33. Nabavi-Pelesaraei A, Rafiee S, Mohtasebi S, Hosseinzadeh-Bandbafha H, Chau K (2018) Integration of artificial intelligence methods and life cycle assessment to predict energy output and environmental impacts of paddy production. *Sci Total Environ* 631–632:1279–1294. <https://doi.org/10.1016/j.scitotenv.2018.03.088>

34. Šipka S (2021) Towards circular e-waste management: how can digitalisation help?. Retrieved from https://weee-forum.org/wp-content/uploads/2021/09/Towards-circular-ewaste-management_how-can-digitalisation-help_EPC.pdf
35. Flucker S, Tozer R, Whitehead B (2018) Data centre sustainability – beyond energy efficiency. *Build Services Eng Res Technol* 39(2):173–182. <https://doi.org/10.1177/0143624417753022>
36. Ristic B, Madani K, Makuch Z (2015) The water footprint of data centers. *Sustainability* 7(8):11260–11284. <https://doi.org/10.3390/su70811260>
37. Unido.org. n.d. Water stewardship | UNIDO. [online] Available at: <<https://www.unido.org/our-focus/safeguarding-environment/resource-efficient-and-low-carbon-industrial-production/industry-and-adaptation/water-stewardship>> [Accessed 10 March 2022].
38. Sustainable Development Goals for Data Centers (2020) Retrieved 5 June 2020, from <https://www.sdg-dc.com/>.
39. How blockchains can tackle the UN Sustainable Development Goals. PA Consulting. Retrieved 13 June 2022, from <https://www.paconsulting.com/insights/how-blockchains-tackle-UN-sustainable-development-goals/>.

Authors and Affiliations

Mohamed Sameer Hoosain¹ · Babu Sena Paul¹ · Susanna Kass² · Seeram Ramakrishna³

Babu Sena Paul
bspaul@uj.ac.za

Susanna Kass
susanna.kass@gmail.com

Seeram Ramakrishna
seeram@nus.edu.sg

¹ Institute for Intelligent Systems at the University of Johannesburg, Johannesburg, South Africa

² Stanford University, Stanford, CA, USA

³ National University of Singapore, Singapore, Singapore