NEXT G ALLIANCE
An ATIS Initiative

6G

Next G Alliance Report:
6G Sustainability KPI Assessment
Introduction and Gap Analysis

FOREWORD

As a leading technology and solutions development organization, the Alliance for Telecommunications Industry Solutions (ATIS) brings together the top global ICT companies to advance the industry's business priorities. ATIS' 150 member companies are currently working to address network reliability, 5G, robocall mitigation, smart cities, artificial intelligence (AI)-enabled networks, distributed ledger/blockchain technology, cybersecurity, IoT, emergency services, quality of service, billing support, operations and much more. These priorities follow a fast-track development lifecycle from design and innovation through standards, specifications, requirements, business use cases, software toolkits, open-source solutions, and interoperability testing.

ATIS is accredited by the American National Standards Institute (ANSI). ATIS is the North American Organizational Partner for the 3rd Generation Partnership Project (3GPP), a founding Partner of the oneM2M global initiative, a member of the International Telecommunication Union (ITU), as well as a member of the Inter-American Telecommunication Commission (CITEL).

For more information, visit www.atis.org. Follow ATIS on Twitter and on LinkedIn.

The ATIS 'Next G Alliance' is an initiative to advance North American wireless technology leadership over the next decade through private-sector-led efforts. With a strong emphasis on technology commercialization, the work will encompass the full lifecycle of research and development, manufacturing, standardization, and market readiness.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Executive Summary and Objective

This paper's objective is to provide an overview of available sustainability Key Performance Indicators (KPIs) for the Information and Communications Technology (ICT) industry and their applicability to 6G ecosystem components such as the Radio Access Network (RAN), Core Network (CN), cloud and edge data centers, end user communications devices, and supply chain and manufacturing. Furthermore, this paper identifies areas of potential research to develop a harmonized set of sustainability KPIs for benchmarking of the 6G ecosystem components.

The latest findings outlined in the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) indicate that the world is on a pathway to global warming of more than double the 1.5° Celsius (C) limit that was agreed upon in Paris in 2015 [1]. To limit global warming to 1.5° C, the world needs to halve emissions by 2030 (compared to 2015 levels) and reach Net-Zero emissions by no later than 2050. Net-Zero is defined as a point globally where anthropogenic emissions of Greenhouse Gases (GHG) to the atmosphere are balanced by anthropogenic removals over a specified period [2]. The ICT sector has aligned on a science-based pathway to reach Net-Zero emission by no later than 2050, with 2040 as a recommended goal. ICT organizations, across the full value chain, start to employ strategies to reach net-zero, which include reduction of Scope 1, 2, and 3 emissions. However, those emissions are unfeasible for the ICT to abate if emission removals are permanent. Lastly ICT sector organizations need to enable decarbonization of other sectors through provision on ICT solutions and services. While the Net-Zero standards developed for the ICT organizations provide emission reduction goals and timelines, ICT organizations will also need KPIs to keep track of their progress toward increased energy efficiency, lower carbon emissions, and other environmental indicators. Considering the time horizon for deployment of 6G networks is 2030 and beyond, it is important for 6G networks and the ICT sector to establish KPIs that will guide the sector's Net- Zero journey.

To embark on a sustainability journey, organizations need to be able to effectively measure, benchmark, and evaluate sustainability efforts and their efficacy.

There are five key tenets relevant to the 6G ecosystem: energy efficiency, GHG and other emissions, water usage, recycle and waste, and land and biodiversity.

There are multiple environmental impact categories that apply to the entire 6G ecosystem. However, it's important to note that not all parts of the 6G network will have the same environmental impacts. To evaluate sustainability efforts, a Life Cycle Assessment (LCA) study of an organization is performed to quantify the environmental impact across the build and operation of a product, network, or service. KPIs provide a direct measure to quantify the environmental aspects and potential environmental impacts throughout the whole lifecycle. This paper introduces those environmental impacts categories, which can be used as indicators for overall sustainability assessment of the 6G ecosystem, investigate the possibility of KPIs for individual building blocks, and analyze the gap for improvement most relevant to each section of the 6G network.

1.2 Scope and Environmental Impact of 6G

The scope of the KPIs introduced in this document will cover the key building blocks of the 6G ecosystem including end user communication devices, RAN, CN, and cloud and edge (data center). Furthermore, this paper addresses the direct operation of the 6G ecosystem and considers the KPIs that can measure the environmental impact of the supply chain and manufacturing for the physical infrastructure, equipment, and software used. Within each of these areas, the document will cover key environmental sustainability indicators (Figure 1.2) essential to that 6G ecosystem building block, why they are relevant, and what should be specifically measured and reported for each aspect of the 6G ecosystem.

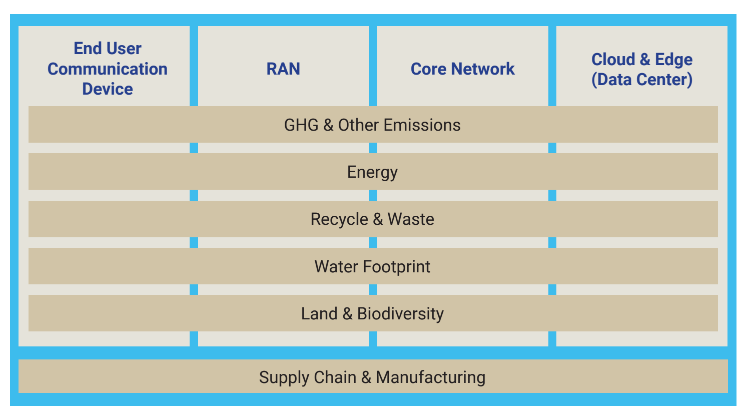


Figure 1.2: Scope of 6G Ecosystem KPIs

The 6G ecosystem building blocks are:

> **End User Communication Devices** that include smartphones and IoT devices. They can be a standalone device or an embedded communication component of other equipment (e.g., a connected vehicle).

> The **RAN** is part of the mobile network system. It controls and manages device access to the air interface, including front, mid, and backhaul transport network connectivity.

> The **CN** enables connectivity and controls security, sessions, mobility, manages policy and user subscriptions, and provides L1/L2/L3 connectivity between RAN, cloud, and edge.

> The **Cloud and Edge (Data Center)** are physical infrastructures that provide computational, storage, and network capabilities.

> **Supply Chain and Manufacturing** are processes that follow raw material to finished products and delivery to end customers. They include the manufacturing of hardware (HW) and software (SW) used in RAN, CN, cloud and edge data centers, and end user communications devices.

It is worth noting that the 6G system building blocks cannot always be as clearly delineated as postulated by the above, particularly with respect to the RAN, CN, and cloud and edge. Aspects of the RAN and CN building blocks can be provided as software components that are deployed and operated on cloud and edge hardware. 5G infrastructure deployed today operates in this way. It is expected that 6G systems will be cloud native, with a trend to move from purpose-built hardware and specifically from Application Specific Integrated Circuits (ASICs) to general-purpose processors that state-of-the-art 5G networks already use. An increased degree of agility and flexibility (e.g., with respect to capacity), as well as improved overall efficiency, are among the benefits of this transition, as is the promise of disaggregation of hardware and software, vendor-neutral supply chains, and open interfaces. These trends will thus establish software itself as a key building block of 6G systems and therewith render software a key consideration in the quest for environmental sustainability.

2 INTRODUCTION TO ENVIRONMENTAL SUSTAINABILITY KPI DEFINITIONS

Companies are expected to report their sustainability achievements and sustainability impacts annually, as well as measure the effectiveness of their environmental performance to meet their objectives. Using KPIs, organizations are able to measure business targets to determine the success of their sustainability strategy implementation.

This section provides an overview of the five environmental sustainability impact categories that are then further broken down in specific KPIs relevant to each 6G infrastructure domain. The five impact categories include GHG and other emissions, energy, recycle and waste, water usage, and land and biodiversity.

> **GHG and Other Emissions**: A simple definition of carbon dioxide equivalent (CO_2e) is the gases that trap heat in the atmosphere. These are called GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3).

> **Energy**: Energy consumption, energy efficiency, renewable energy usage, and sources.

> **Recycle and Waste**: Aspects of the product circularity covering reuse, recycle, and refurbish leading to waste reduction.

> **Water Footprint**: Withdrawal from sources, consumption, water discharge, and efficiency of water reuse.

> **Land and Biodiversity**: Minimize the impact, and promote sustainable use, of terrestrial ecosystems.

KPIs are used to evaluate potential environmental impacts using the collected information with specific environmental impact category indicators. GHG emissions, for example, is the most important category regarding the ICT goods, network, and services (usually related to energy consumption). Yet one single impact category cannot represent the overall environmental impact of the product, network, or services, so multiple impact categories will be used.

The following sections provide an overview of the most common environmental impact categories (or KPIs) that are currently in use and could be used for future 6G infrastructure after deployment.

2.1 GHG and Other Emissions

GHG emissions are the most widely used KPI to measure environmental impact. It is an indicator of infrared forcing an increase in the average global temperature as a result of GHG emissions, generally associated with fossil fuel combustion. All GHGs are converted to the Global Warming Potential (GWP) in reference to GWP of CO_2.

Each GHG has its own GWP, which indicates the amount of warming caused by a gas over a given period of time (usually 100 years). The GWP potential for CO_2 is "1" and that of sulfur hexafluoride is "22,800." CO_2 including other GHG can lead to understating the total impact of global warming on an organization. To avoid this, GHG emissions are reported in "CO_2e." For a particular quantity and type of GHG, CO_2e signifies the amount of CO_2 that would have the same impact [3]. This allows GHG emissions to be expressed as a single number using "metric tons of carbon dioxide equivalent" ($MtCO_2eq$). It is important to note that the ICT sector accounts for approximately 1.4% of global GHG emissions and that the sector's carbon footprint could be reduced by 80% if powered by renewable electricity [4].

By measuring Scopes 1, 2, and 3 of CO_2 emissions, organizations can assess how the market presence of their products or services are impacting climate change.

There are three different types of GHG emissions that can be tracked, noted as Scope 1, Scope 2, and Scope 3.

> **Scope 1** are the direct emissions resulting from sources owned by the operation. This includes emissions created by burning fossil fuels, such as onsite power generation, transportation of goods and materials, and carbon emissions released by cooling solutions.

> **Scope 2** CO_2 emissions come from indirect use — think electricity, steam, heating, and cooling that's been purchased. Although Scope 2 emissions physically occur at the facility where they are generated, they are accounted for in an organization's GHG inventory because they are a result of the organization's energy use.

> **Scope 3** is by far the largest GHG impact of most organizations. These are indirect emissions related to the supply chain, both upstream and downstream.

Any products used in one's operation include a GHG profile that counts toward Scope 3. In order to assist in calculating Scope 3 emissions, it is important that vendors create transparency. One example is to publish Product Environmental

Profile (PEP) [5] documentation for products. Those documents are externally certified by internationally recognized organizations, such as eco Passport [6]. They include detailed information about materials used, the energy profile to source those materials, and its use of recycled materials.

By keeping track of one's carbon footprint in the aim to be Net-Zero, the following metrics should be considered to effectively find ways to make it smaller.

> **Carbon intensity (CI)** is the sum of Scope 1 and Scope 2 carbon emissions divided by the total energy consumption.

> **Carbon Usage Effectiveness (CUE)** is the ratio of the annual CO_2 emissions to IT equipment energy demand. It was originally created by "The Green Grid" and is currently a standard under International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 30134-8. The standard describes three categories of measurement: Basic, Intermediate and Advanced.

> **Total carbon offsets** are total reduced or avoided carbon emissions outside an organization's operation through purchased carbon offsets. Carbon offsets are also known as Verified Emission Reductions (VERs) or carbon credits.

> **Hour-by-hour supply and consumption matching** is a metric measuring the extent that the renewable energy generation matches the energy consumption within an organization.

There are different metrics proposed (Table 2.1) that allow operators to measure and evaluate their carbon footprint. Once adopted, it allows comparisons across all network components for planning and design phases, as well as operations to measure effectiveness of continuous improvement programs.

Metric Categories	Key Metrics	Units
GHG emissions	GHG emissions (SCOPE 1)	$mtCO_2e$
	Location-based GHG emissions (SCOPE 2)	$mtCO_2e$
	Market-based GHG emissions (SCOPE 2)	$mtCO_2e$
	GHG emissions (SCOPE 3)	$mtCO_2e$
	Location-based carbon intensity (SCOPE 1 + SCOPE 2)	$mtCO_2e$/kWh
	Market-based carbon intensity (SCOPE 1 + SCOPE 2)	$mtCO_2e$/kWh
	Carbon usage effectiveness (CUE)	$mtCO_2e$/kWh
	Total carbon offsets	$mtCO_2e$
	Hour-by-hour supply and consumption matching	TBD

Table 2.1: Data Center GHG Emission KPIs

2.2 Energy

Organizations need to measure how much energy operations consume and then determine where less can be used. This will result in cost savings for the company, fewer used resources, and a decrease in emissions expelled from energy across the production and operation of products and delivered services. Specifically, the focus on energy efficiency in building, operating, and maintaining telecom networks is to keep the energy consumption as low as possible. This covers the energy consumed in sourcing materials, the production of products, and the efficiency in the operation of a product. Digital tools are more than capable of measuring how much energy is used in different functional areas and network applications, such as in the Industrial Internet of Things (IIoT) to monitor and report energy consumption across large facilities. These measurements can provide valuable information on production energy consumption.

The ICT industry uses about 1.4% [5] of global electricity consumption. The digital sector is one of the largest corporate buyers of renewable power in the United States, enabling the installation of additional renewable power assets in the utility grid. In addition to consuming electricity from grid providers, many ICT organizations use fossil fuels like diesel in stationary generator engines that provide backup power to ensure network reliability.

To establish a holistic view of energy, the following metrics are examples of what should be considered.

> Total energy consumption measured in kilowatt-hour (kWh).

> Renewable Energy Factor (REF) expressed as a ratio, dividing the sum of renewable energy by the total energy consumption [7].

> Energy Reuse Factor (ERF), which is the ratio of reused energy compared to the total energy consumption [8]. As an example, if waste heat is being repurposed or reused, the ratio gets closer to factor 1.

2.3 Reuse, Recycle, and Refurbish, Leading to Waste Reduction

With customers becoming more conscious of the recyclability and sourcing of product materials, businesses are making changes in procurement and operations to remain competitive. To remain in line with market trends, companies will benefit from monitoring their recyclability and waste management to ensure that not only the production of products is sustainable, but also that the products themselves fit into a circular economy.

As businesses upgrade to higher-performing, more energy-efficient devices, or transition to an as-a-service delivery model, some of the products and technology become obsolete with time. Those obsolete products should be managed properly in a circular manner to avoid waste and pollution to the environment. Equally, new replacement products should be designed with reuse, recyclability, and minimal waste in mind. The purpose of the circular economy is to manage assets in an environmentally responsible way when they reach the End of Life (EoL). Before the recycling option is utilized, other techniques may be employed to make optimal use of a product's constituent materials through 1) product repair, reuse or refurbishing and 2) product repurposing, a process by which products or components of products are combined in order to create a new asset with its own lifecycle (second life). When a given product or product component is not a candidate for one of these techniques, recycling can help keep the materials in use. The ultimate aim of the circular economy is making a product or providing services without causing or incentivizing additional extraction of Earth's resources. Realization of the circular economy requires incorporating elements in product design that support the reduction of material use, repair, reuse, recycling, and recovery of products, product parts, components, and materials to circulate them in the value chain for as long as possible.

By tracking the product with KPIs at every stage from cradle to grave, one can see how products are being produced, used, and how one can improve these reuses in the future. Promoting responsible end-of-life management through use of programs to reuse/refurbish products or to responsibly recycle helps to minimize the environmental impact.

Different ideas already exist today to measure and to reduce waste. Tables 2.3.1 and 2.3.2 suggests KPIs to measure the recycle content and waste being produced during the entire life cycle of equipment and buildings.

	Key Metrics	Units
Refurbish & Recycling	1. Assets (products) taken back by producer at EoL	Metric tons/per unit and time cycle
	2. Assets taken back that are repaired or refurbished for remarketing	% of 1
	3. Recyclability of constituent materials in equipment produced	% of the mass of the product(s)
	4. Use of post-consumer recycled materials in equipment produced	% of the mass of the product(s)

Table 2.3.1: Reuse, Recycle, Refurbish Metrics

	Key Metrics	Units
Waste Diversion (KPIs measured separately for Regulated and Unregulated waste)	1. Total waste generated from direct operations	Metric tons/per unit and time cycle
	2. Total hazardous waste from direct operations	% of #1
	3. Total non-hazardous waste from operations	Metric tons/per unit and time cycle
	4. Non-hazardous waste diverted from landfill	% of #3

Table 2.3.2: Waste Metrics

2.4 Water Usage/Footprint

Mainstream news coverage of droughts, groundwater depletion, and municipal water shortages creates greater awareness of water being a scarce resource. By tracking different aspects of an organization's water use, one can get a true idea of an organization's sustainability impact in terms of water usage.

Although water is thought of as being one of the Earth's most plentiful resources, when it's polluted it takes massive amounts of energy to make it clean and usable again. Polluted water also has detrimental effects on the planet's natural systems — including waterways and the ocean. Besides, only 3% of the world water consists of freshwater, and from that portion, two-thirds are not accessible for human use (frozen in glaciers) [9].

Most operations consume water either directly or indirectly. Direct water usage is related to business operation, and indirect water usage is related to the organization's products and services. The direct water used during operations is usually reported in the company's annual environmental footprint reporting. By comparison, water use from the impact categories introduced earlier — indicating the withdrawal of water resources from the local region where the activities take place (expressed in volume of water, usually m^3) — is an estimation based on LCA databases. This method is based on lifecycle thinking and considers the entire lifecycle (or value chain) of the product, network, or services. Other impact categories — such as acidification, ecotoxicity, and eutrophication — also provide the impact of product, network, or services on the water resources and its ecosystems.

Context of water consumption is another important aspect. Water scarcity, the water source, and watershed characteristics must also be considered. There should be consideration of local water stress, such as the impact of consuming water for a data center located near a major body of water versus in a desert region.

2.5
Land and Biodiversity

As a category, biodiversity includes plant and animal species diversity. It is impacted by habitat loss and degradation caused by exploitation of biological resources, pollution, and introduction of invasive species or disease vectors.

The latest Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report, IPBES-8 [10]], issued by the UN [11] clearly warns that the rate of extinctions of species due to climate change is accelerating. More than one million animal and plant species are threatened with extinction. IPBES-8 [12] states that 75% of the land and 66% of the marine environment have been “severely altered” by human activities.

It is critical that the 6G ecosystem addresses the impact on land and biodiversity caused by data centers, cell sites, network equipment, and manufacturing facilities, as well as access and easements for backhaul and metro-area networks.

However, quantification of the impact on biodiversity is very challenging. Currently there is no standardized way for measuring and reporting the biodiversity footprint of a product, services, or businesses. There is ongoing research to model biodiversity impact, which must be considered in the future as it evolves. Besides, some aspects of biodiversity are already covered by other environmental impact categories that are presented in this paper (e.g., climate change, land use, and water resource use).

Land use is one of the major drivers of the biodiversity loss [13]. It reflects the damage to ecosystems due to the use or the transformation of land due to agricultural production, mineral extraction, and human settlement [14]]. The inventory data for land use originates mainly from public databases and global averages. The results are estimates based on that inventory data and only cover some aspect of land use effects in the environment or biodiversity.

There are possibilities for business to make a positive contribution to biodiversity and nature protection.

Some example solutions to consider are [15]:

> Green and living roofs for factories, buildings, and data centers.

> Permeability restoration of the soil being used.

> Altered natural habitat restoration by reuse of native plants and trees, avoiding lawns, adding bird habitats, and limiting fertilizer and pesticide use.

Figure 2.5 illustrates one example of biodiversity KPIs, the Mean Species Abundance (MSA) [16], described by the Global biodiversity model for policy support [17], which aims to model interactions between humans and nature. Currently, very few businesses are considering these types of environmental metrics, including data centers and hyperscale data center operations.

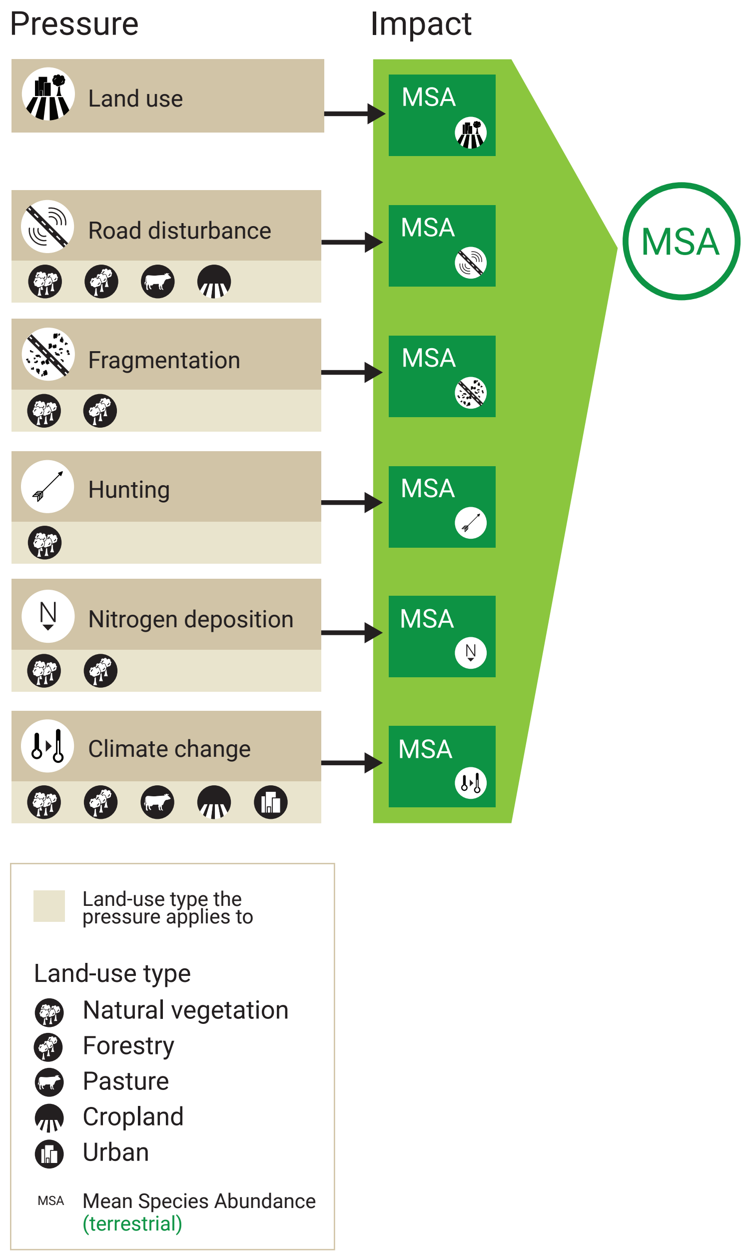


Figure 2.5: Mean Species Abundance (MSA) Model [17]

2.6
Environmental Sustainability KPI Metrics

Table 2.6 summarizes some environmental and sustainability KPI metrics which are in use today but not be extensively used by all companies. The table serves as a checklist to identify how vectors apply to all the 6G network domains.

Vector	Description	Metrics	
GHG Emissions	Simple definition of CO_2e (Global Warming Potential) Gases that trap heat in the atmosphere are called greenhouse gases Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs),and Sulphur hexafluoride (SF_6)	> GHG emissions (scope1, 2, 3)	mtCO_2e/kWh
		> Location-based & Market based carbon intensity	mtCO_2e/kWh
		> Carbon usage effectiveness (CUE)	mtCO_2e/kWh
		> Carbon Intensity	Ratio kgCO_2e/ per unit and time cycle
Energy	Energy consumption, energy efficiency, renewable energy usage & sources	> Total energy consumption	kWh/per unit and time cycle
		> Power usage effectiveness (PUE)	Ratio/per unit and time cycle
		> Energy Reuse Factor (ERF)	Ratio/per unit and time cycle
		> Renewable energy factor (REF)	Ratio in kWh/ per unit and time cycle
		> Renewable energy consumption	Ratio in kWh/per using and time cycle
		> Energy consumption per customer (operator clients)	Ratio in KWh per customer
		> Energy Intensity	Ratio kWh/IP traffic in TB
Recycle & Waste	Life Cycle Assessment, energy requirement to recycle	> Total waste generated	Tons/per unit and time cycle
		> Waste landfilled & diverted	Tons/per unit and time cycle
		> Waste diversion rate	Ratio/per time cycle
		> Percentage recycled hardware	Ratio/per unit and time cycle
Water Footprint	Consumption, waste of water incl. recycle efficiency of water	> Total site water usage	m_3/per time cycle
		> Total source water usage	m_3/kWh
		> Water usage effectiveness (WUE)	m_3/kWh
Land & Biodiversity	Minimize the impact and promote sustainable use of terrestrial ecosystems	> Total Land occupation to support the product/system	M_2 – year %
		> Proportion of land degraded over total land area	Ratio
		> Mean species abundance (MSA)	MSA/km_2

Table 2.6: Environmental and Sustainability KPI Metrics [4, 18, 19]

3 6G ECOSYSTEM BUILDING BLOCK KEY KPI METRICS

3 6G Ecosystem Building Block Key KPI Metrics

This section identifies the key KPI metrics for the environmental and sustainability impact categories that apply across each of the 6G infrastructure building blocks. By indicating some of the past and current activities that cover these areas, identify potential gaps and make recommendations for research areas to improve 6G sustainability over current state of art for the specific building block.

3.1 RAN

The scope of RAN sustainability KPIs must consider every level of the RAN deployment and operation (e.g., antennas, 6G equivalent-RU/DU/CU, and any other 6G nodes supporting the RAN function). Among all the aspects introduced in Section 2, energy consumption is the major consideration in the RAN and the main source of GHG emissions. According to a Global System for Mobile Communications Association (GSMA) study [15], the RAN infrastructure consumes over 73% of the energy used by a Communications Service Provider (CSP). Most of this energy consumption is due to active RAN communication, but even in the absence of any data transmissions, the RAN still consumes energy.

KPIs most relevant to RAN component:

RAN energy consumption depends on many factors, and it may change significantly depending on geographical location, user distribution, and traffic patterns. At a given RAN site, the power consumption varies based on the load: at busy hour load during a day, the power consumption is much higher than that at low-load periods. Furthermore, according to a Next Generation Mobile Networks Alliance (NGMN) study [18], approximately 80% of RAN sites carry only approximately 20% of all traffic. Thereby, low-traffic and idle sites account for a disproportional and potentially significant higher energy consumption. Hence, 6G RAN energy consumption needs to be minimized at different load levels, especially for the low-load and idle sites.

RAN sustainability can be expressed with different metrics. There are some metrics for current RAN defined within ITU's Telecommunication Standardization Sector (ITU-T) standard ITU-T L.1350 [20], European Telecommunications Standards Institute (ETSI) standard ETSI ES 203228 [21], and 3rd Generation Partnership Project (3GPP) standard 3GPP TS 28.554 [22]. Manufacturers can report the energy consumption and energy efficiency per product measured at different load levels. In addition, operators can get site-level energy consumption and renewable electricity ratios from multiple data sources, including their energy billing services. Those numbers enable them to calculate energy consumption per customer or network CI (with known energy mix CO_2 emissions per data traffic). All these metrics are also usable for 6G RAN, depending on the case, and situation-suitable metrics can be selected. Some examples of RAN sustainability metrics that have been considered are:

> **Average power consumption**, in kW, as measured by a weighted sum of power consumption over different load conditions (e.g., ETSI average).

> **Energy consumption per cell site** over 12 months.

> **Energy consumption per customer or per subscription** over 12 months.

> **Energy intensity**, measured by network energy consumption per unit of data traffic, in kWh/TB or kWh/GB.

> **RAN energy efficiency**, measured by average data volume transmitted per unit of energy consumption, in bit/J or GB/kWh, when assessed during the same time frame.

> **Network CI**, measured by CO_2 emissions per unit of data traffic, in kg/TBs.

> **Power consumption at 100% traffic load (peak traffic) per site**, in kW.

6G RAN can be deployed on standard server commodity hardware using the aforementioned principles. Benefits largely depend on the ability to virtualize the RAN functions. The trend is to containerize network functions as microservices, especially in the RAN, an architecture often called virtualized RAN (vRAN). vRAN technologies will thus blur the border between the RAN and data centers, which basically run baseband functions as cloud services, virtualized, on off-the-shelf hardware.

Executing software requires electricity, most of which relies on fossil fuels today. Thus, making SW more efficient immediately translates to energy savings and a reduction in GHG emissions. Inefficient SW coding practices often lead to higher processing resources and are directly responsible for higher energy consumption. Environmental stewardship in coding means that as little hardware as possible is used, and when hardware is used, idle resources are minimized. It is important that the SW, which is meant to make a process more efficient, is itself efficient and does not consume more energy than the energy and the savings it is intended to achieve. All these techniques require improved KPIs, efficient SW coding practices, and tools to observe the software code itself is compliant with energy-efficient coding practices. Their importance will only grow as the share of software increases in the overall 6G system architecture.

A 6G RAN architecture distributed across different HW and SW functions will need to ensure that each component can measure and coordinate with one another in real time to minimize energy consumption across the RAN infrastructure.

The potential for 6G network intelligence — making use of Artificial Intelligence (AI) and Machine Learning (ML) — should be implemented to enable service-based energy saving configuration and to eliminate any need for manual intervention. Qualification criteria may include mobility, coverage and handover, traffic management, and cell site performance. Energy-saving mechanisms in both downlink and uplink directions need to be included. When designing and evaluating downlink and uplink energy-saving mechanisms, it is also important to consider user experience and complexity, such as user throughput, coverage, and data plane latency. Additional KPIs must be introduced to quantify and track energy efficiency at different traffic loads, and to benchmark the RAN's progress toward the goal of minimized energy consumption at various loads.

Further research is needed to develop potential operational, architectural, and technological innovations that could dramatically reduce RAN energy consumption at different loads and while not transiting data, (e.g., idle). Any mechanisms employed to improve RAN energy-efficiency measures need to be carefully considered because they could potentially increase User Equipment (UE) energy consumption as a result.

3.2 Core Network

The RAN consumes 73% of the mobile network's energy [17]. An estimated 13% [17] is consumed by the CN's software execution in data centers. As to date, energy-related KPIs for the CN have yet to receive significant priority by the industry. The ETSI report "Measurement method for Energy efficiency of Core network equipment" [23] defines metrics for CN energy usage across various traffic load levels. However, data center energy efficiency will become a more prominent issue for the CSP as the emphasis on energy costs and sustainability is growing in general, and as gradually larger parts of the CN move into data centers.

The 6G CN is expected to be cloud native, with the CN SW deployed across commodity HW using containerized software network functions. It will be critical that CN SW is developed and managed to be carbon effective. It also will be critical to ensure that the 6G network is energy efficient not only the CN SW developed and managed, but also container management SW deploying the CN SW components. When developing carbon-efficient SW, the efficiency of protocols to transfer data must be considered, as well as memory usage. For instance, a piece of SW that runs in a more energy-efficient fashion may result in an overall increased energy consumption because of more frequent data transport or database queries. At the same time, being able to migrate data processing between geographically dispersed data centers using a lower CI can minimize the overall carbon footprint.

A principal factor is how efficiently the SW utilizes the infrastructure. A 5G CN requires less footprint in the data center compared to a legacy CN. This leads to the possibility to reduce energy consumption by similar numbers.

Some examples of CN sustainability metrics that should be considered are:

> **Average power consumption**, in kW, as measured by a weighted sum of power consumption over different load conditions.

> **Energy consumption per CN element function** (e.g., AMF, AUSF, SMF, UPF) over 12 months.

> **Energy consumption per customer or per subscription** over 12 months.

> **Average energy consumption per connection** in kW per connection.

> **Energy intensity**, measured by network energy consumption per unit of data traffic, in kWh/TB or kWh/GB.

> **CN energy efficiency**, measured by average data volume transmitted per unit of energy consumption, in J/bit and kWh/GB, when assessed during the same time frame.

> **Network CI**, measured by CO_2 emissions per unit of data traffic, in kg/TBs.

Potential for CN infrastructure energy savings:

Dual-mode and cloud-native SW design principles can enable CN energy savings compared to the current SW used in legacy CNs:

> **Dual mode:** SW can handle both legacy and new 5G access domains.

> **Service Based Architecture:** a key enabler for the overall network simplification, based on a strong simplification of the interworking between different Network Functions.

> **Software Probes:** network probing can be executed by software microservices instead of by hardware probes, reducing the need to manufacture, deploy, and power up external probes.

> **Flexible data storage:** distribution of data storage points in the network can be optimized and tailored to the specific business need (e.g., enterprise) instead of putting in common for all.

> **Gi-LAN** (segment of the network for which service providers deploy IP functions between the packet gateway and the Internet) consolidation with service chaining: multiple service functions are consolidated in one flexible and granular service chain, leveraging on a shared packet processing pipeline.

As part of its efforts to reduce network energy consumption, a CSP may choose to upgrade to infrastructure that consumes less energy than the previous generation. It is also possible to cut energy consumption with the help of an advanced scale-in/scale-out mechanism that reduce the amount of hardware in use when traffic is low, such as during the night. In these conditions, some servers can be turned off, which results in energy savings. For example:

> Micro-sleeps are a HW offload technique that transfers the handling of selected traffic flows from the processor. This frees up the CPU core that can be opportunistically applied in all idle periods, thereby saving energy across a wide range of traffic conditions.

> Computing processors have been increasing in core count and thermal design power to meet demands from ever-increasing mobile network features and capabilities. There technologies can be used to improve energy efficiency when processing capability is not fully needed. A processor can also reduce its speed (core frequency) to reduce power consumption.

Regardless of the energy-saving mechanism, it is essential to ensure there is no negative impact on real-time characteristics such as jitter and packet latency. Potentially CSPs could save additional energy in their data centers by applying micro-sleep modes in packet processing nodes. This approach has both lower overhead and lower latency than existing methods and makes it possible to reduce power consumption even at high load, without degrading application performance. Because power management is implemented in communications libraries, it is easy to integrate into existing applications [15, 24].

3.3 Cloud and Edge (Data Center)

Recent advancements in cloud computing enable users to offload computation-intensive tasks to cloud infrastructures. Moreover, edge clouds allow latency-sensitive tasks to be processed locally or as close as possible to the end user communications device. As a result, service demands for computing and communication resources in data centers (including both cloud and edge) have dramatically risen since 2010 [25]. Thus, the carbon footprint due to the increasing energy consumption of data center operations has become a matter of concern.

Nonetheless, with significant electrical efficiency improvements over the past decade, more can and must be done. The use of sustainable energy, with the potential to reduce or even eliminate water consumption, can further reduce the overall environmental impact of data centers. Furthermore, as the demand for digitization continues to grow and more data center capacity is built, special considerations are necessary to reduce waste and the impact on land and biodiversity.

There are multiple organizations, institutions, and agencies with a common objective to make data centers more sustainable. One of those is the Climate Accord [26], founded in early 2022, to which a growing number of cloud data center operators and service providers subscribe to reduce carbon in digital infrastructure.

3.3.1 GHG Emissions

Scope 1 GHG emissions (measured in Mt CO_2e) from data centers refer to direct emissions resulting from the data center operations. These include carbon emissions created by burning fossil fuels (e.g., onsite power generation), emissions released by cooling solutions, and transportation of goods and materials.

Scope 2 GHG emissions (measured in Mt CO_2e) from data centers refer to the emissions that result from purchasing energy, mainly electricity, and are not owned and controlled by the owner of data centers.

In addition to the GHC emissions by scope (as described in Table 2.6), data center emissions could also be characterized and measured by type (e.g., Scope 1 being CO_2, CH_4).

3.3.2 Energy

Energy consumption in data centers frequently accounts for more than 50% of the operational expenditure. As a result, for the past decade, the industry has implemented various technologies that led to significantly improved energy efficiency, measured against compute storage capacity and network bandwidth. Had those efficiency improvements not been made, today's data centers would have consumed four times as much energy [27]. Generally speaking, the "greenest" electron is the one that is not being consumed, hence not generated, transported, stored, switched, and so on.

Metrics such as measuring total energy consumption and its Power Usage Effectiveness (PUE) are standard measures that have helped to improve data center energy efficiency. The global data center industry has been very successful over the past decade to increase facility efficiency through a focus on reducing PUE values. Now the focus of both industry and policy makers have started to shift toward how to use the servers and other data center hardware in ways that increase their energy efficiency.

Additionally, the use of renewable energy to power data centers, the ratio of renewable to non-renewable energy, and the energy reuse factor require new metrics to measure and improve the overall sustainability of data centers. Some hyperscale cloud providers aim to power their data center assets with 100% green energy on a 7x24 operation. To power match the data center energy consumption with green energy supply every day, down to the hour, is a complex endeavor, and would require new operational and control methodologies to achieve.

Data center energy efficiency KPIs are already specified in ISO/IEC 30134-3:2016, Information Technology - Data Centers - Key Performance Indicators - Part 3: REF [7]. This standard defines the REF of a data center, specifies a methodology to calculate and to present the REF, and provides information about the correct interpretation of the REF.

Other KPIs are being considered today in light of the energy crisis. The next paper will detail the gaps and the improvements that can be made to measure and accurately report the energy efficiency of the data center.

3.3.3 Recycle and Waste

KPI measurements within LCA and Circular Economy are critical to truly make data centers sustainable, the same way it is critical for any other network component.

3.3.4 Water Footprint

Water usage has recently become a key issue in data center operations. In the past, the use of water for cooling improved the overall energy efficiency measured in PUE. Some communities are placing moratoriums on building additional data center capacity in their communities as they are depleting groundwater resources. Most of a data center's water is used to cool the heat created by operating IT equipment. There is a lack of transparency in how much water is consumed by the data center industry today.

Although introduced by "The Green Grid" back in 2011, Water Usage Effectiveness (WUE) [28] has not found wide adoption yet. However, as water usage is becoming significantly more important, the usage of WUE deserves more serious consideration.

To establish a holistic view of water consumption and returned, the following metrics can paint a more comprehensive picture of water utilization by data centers [29]:

> Total site water usage/year

> Total source energy water usage/year

> WUE/kwh

> Amount of water used/year

> Source of water used (e.g., freshwater, reclaimed water, groundwater)

> Percentage of recycled/year

> Percentage of water wasted/year

> Percentage of water reused/year

> Percentage of water returned unpolluted to the ecosystem/year

As energy consumption is projected to increase 50% by 2050 [30], it is fair to assume that the amount of water to be used in energy generation will also increase.

Data center WUE is already defined in the ISO standard, ISO/IEC 30134-9:2022, Information technology — Data centers key performance indicators — Part 9: WUE. The standard defines the WUE of a data center, introduces WUE measurement categories, describes the relationship of this KPI to a data center's infrastructure, IT equipment, and IT operations, defines the measurement, the calculation and the reporting of the parameter. It also provides information about the correct interpretation of the WUE.

3.3.5 Land and Biodiversity

Land and biodiversity are also relevant to data centers.

Building higher density data centers, which would require less land to offer equal compute capacity, should be considered. Additionally, building vertically versus horizontally may also reduce the impact on land and biodiversity. The industry's push toward the use of renewable energy resources will have an impact on land and biodiversity. There are direct and indirect impacts that need to be studied further.

3.4 End User Communications Device

Each individual end user communications device used for calling, messaging, and/or sending data would contribute to a carbon footprint due the energy consumption. Forecasts from Statista [17] show that there are 15 billion mobile devices in operation globally. The number of Internet of Things (IoT) devices worldwide is forecast to almost double from 14.4 billion in 2020 to more than 27 billion in 2025 [31].

A brand-new smartphone generates an average of 85 kilograms in CO_2 emissions in its first year of use. Ninety-five percent of this comes from manufacturing processes [32], including the extraction of raw materials and shipping. Therefore, creating a huge amount of carbon emissions from these communications devices has a significant impact on the environment.

Device manufacturers include KPIs in their corporate and product environmental reporting. KPIs also are reflected by a growing list of ecolabels to which manufacturers subscribe. Multi-attribute ecolabels evaluate the environmental impact of the entire process of production, transportation, use, and disposal of mobile phones, in addition to measures regarding corporate level sustainability performance, as well as in the supply chain. Ecolabels can apply ratings to varying performance levels to effectively give a rating to the sustainability performance of the device and the device manufacturer. Manufacturer reporting and ecolabels enable consumers to be increasingly aware of how the device choices they make can contribute to minimizing climate impact and lead to a more environmentally sustainable industry.

Key metrics and aspects that are measured and reported for mobile phones include:

> **Durability/Reliability**: The life of the product is one of the most important drivers for environmental impact. A product designed for durability and reliability has a water resistant and robust design, a long battery life, and comes with a manufacturer guarantee period regarding warranty and service of the device and its components.

> **Repairability and Repair Services:** Indicators regarding the ease with which the device can be repaired include mobile phone design supporting services and repair models that increase the useful life of the product by improving its repairability, reusability, and upgradability potential.

> **Recyclability:** The ability to disposition product materials toward productive use (e.g., as recycled content) can be reflected in several ways. Factors to consider include offering a product takeback program or recycling solution, incentives for responsible recycling (such as buying end-of-life products back from users), and the ability to recover device components and materials (including ability to separate or disassemble).

> **Climate impact:** GHG emissions during the whole lifecycle are an indicator of environmental impact and, over time, can demonstrate contributions to climate protection. Measures that reflect the energy efficiency of the product or the facilities that manufacture the product are also central.

> **Resource efficiency:** Scarce raw materials are used in the device (e.g., gold in electronic components). Efficiently using those materials reduces resource depletion. Using recycled and renewable materials is another key aspect for maximizing resource efficiency and limiting the impact of using virgin materials.

> **Chemical hazards:** Determination of chemical hazard ratings for key materials and substances contained in the product, or in use during manufacture of the product, can enable responsible substitution to address instances of higher hazard materials and substances. The extent to which a manufacturer has achieved this for its products and manufacturing sites is a key indicator of success at mitigating exposures and negative impacts to workers who manufacture, repair, and recycle these products, as well as the environmental impacts at EoL.

Regarding metrics that are more unique to 6G, specific consideration may be needed for new technologies required or driven by 6G. For example, a need to access spectrum above 100 GHz may lead to an increased use of electronics (such as dedicated transceiver circuitry and other components) for this frequency range, and an increased use of certain cellular communication materials such as indium phosphide (InP).

There is a need for further research into how end user communications device environmental sustainability KPIs can be measured and reported. Specifically, this research should explore how efficiently the device is utilizing 6G infrastructure when not transmitting data and how it can optimize the use of RAN power when communicating.

3.5
Supply Chain and Manufacturing

Sustainability is key in many aspects for supply chain and manufacturing. Human rights and responsible sourcing (from both a human and nature perspective) should be ensured. Material supply also creates environmental impacts. Circularity is the process of reducing the environmental impact by reducing material usage and keeping the products and materials in use as long as possible.

Transparency and traceability of materials and energy used during the supply chain and manufacturing process is important for tracking the sustainability of any product. This has been recognized, and a significant amount of work has been done regarding this topic, with more in the future. Currently, there are initiatives about a Digital Product Passport (DPP) [33] and standards under development for setting up global and common sustainability-related product information for product groups. One example is ICT, as reflected in the European Union (EU) Ecodesign for Sustainable Products Regulation (ESPR) [34]. In terms of supply chain and manufacturing, the Global Digital Sustainable Product Passport (GDSPP) is planned to provide sustainability-related information for materials used in the product.

From a sustainability perspective, supply chain and manufacturing impacts are included in the company and product footprint. As stated earlier, it is difficult to separate the 6G sustainability impact in a company footprint because the transition to 6G is gradual. Supply chain and manufacturing-related sustainability improvements should continue for all systems, including 6G in the future. Environmental impact of the supply chain and manufacturing is distributed over all domains of 6G ecosystem (RAN, CN, cloud and edge data center, and end user communication devices) and covered by the product footprints.

4 RESEARCH AREAS TO IMPROVE 6G ENVIRONMENTAL SUSTAINABILITY KPIS

With regards to the environmental impacts from new or expanded wireless communications that will be possible thanks to 6G, proactive consideration of expected use cases can be considered to enable mitigation planning. These are reflected in the ***Next G Alliance Report: 6G Applications and Use Cases*** paper [35] (e.g., the impacts from travel versus achieving more effective results through a mixed reality telepresence or remote medical surveillance).

It is expected that AI will play a key role in 6G networks and systems to reduce radio interface or optimize network operation (e.g., ***Next G Alliance Report: 6G Technologies*** [36]) that could lead to improved energy efficiency of the operation of 6G systems and networks. However, the total impact should take into consideration the impact from the computational work involved in the AI training phase (depending on the purpose served by instances where AI is finally used), and how often AI models will be trained.

Further research is required in developing and defining environmental sustainability KPIs for the 6G ecosystem that will be used to measure and report the effectiveness of 6G to achieve the environmental sustainability goals as outlined in the ***Green G: The Path Toward Sustainable 6G*** paper [37].

4.1 Current State of Sustainability Efforts

Current standards such as those from ETSI, 3GPP, and ITU already define metrics to measure network energy efficiency. ETSI ES 203228 and 3GPP TS 28.554 specify the mobile network energy efficiency (EEMN, DV) as the ratio between the Data Volume (DVMN) and the Energy Consumption (ECMN) when assessed during the same time frame measured in bit/J [20]. Improvements in spectral efficiency and energy efficiency introduced with prior network generations have shown positive trends through implementing these KPIs (e.g., reduced energy consumption for higher processed data volumes).

3GPP TR 28.813 "Study on new aspects of Energy Efficiency (EE) for 5G" explores the opportunities for defining new EE KPIs and new energy-saving solutions. It mentions the key issues and potential solutions for NG-RAN sharing and network slicing (e.g., enhanced Mobile Broadband (eMBB), ultra-reliable low latency communications (URLLC)) that previous studies missed. Network infrastructure may be leveraged for more than one type of slice or service. As a result, it becomes increasingly important to consider the "handprint" of networks when evaluating their energy consumption or efficiency. Handprint refers to a contribution that causes positive change in the world —including reductions to your or somebody else's footprint [38].

ITU L.1350 specifies the energy efficiency of the site (EEsite) as the ratio between the total energy consumption of telecommunication equipment (ECT) and the total energy consumption on site (ETS) [20]. Here, the metric is measuring actual energy consumption by the telecommunication equipment from the sum of total input energy sources.

The communications industry has set a target of net zero emission products. Modernizing a typical legacy base station site to single RAN (e.g., one base station with concurrent operation of 5G, 4G and older generations) can achieve an energy saving of up to 70%. 5G has shown to be more energy efficient in a live network compared to the previous generation when testing at different pre-defined traffic load scenarios that measure the energy consumed per transmitted bit [39]. AI- and ML-based tools and methodologies can reduce energy consumption in radio networks.

There is a plethora of environmental labels in the marketplace to provide ecolabels to manufactured products across different industries. Type 1 ecolabels follow the ISO 14024 standard and are recognized by the UN Environment Program as the most reliable because they deliver outcomes for people and planet at a product level across the whole lifecycle. As shown in the previous sections, the labels for data center products differ from those used for end user communications devices. The telecom industry needs to agree on a common set of ecolabels that can consistently provide information across the 6G ecosystem.

4.2 Research Areas and Recommendations

6G networks need to provide enhanced coverage, capacity, reliability, and lower latency, to name a few requirements, while at the same time finding ways to minimize energy consumption. Sustainability will need to be a foundational element of 6G research and design, implementing modern technologies and architectures with a sustainability mindset. At the same time, research is required into how to measure the sustainability of different solutions via use case specific and/or use case agnostic KPIs. Some examples of these research areas are:

- While 6G is used by other industries to run their operations, CSPs may be asked to provide consolidated KPIs that represent the measure of sustainability for the end-to-end communications service provided. 6G connectivity will be a sum of many parts (RAN and Core), so being able to coordinate KPIs across each of the 6G ecosystem domains to be able to provide the total sustainability impact/effectiveness (KPI measurement) to the end user communications device will be required.

- In the pursuit of minimizing energy consumption of a RAN that is not transmitting any data or at low load, research into RAN KPIs that evaluate the power consumption at minimum load is required. With those RAN KPIs in place, accurate measurement at the minimum load should help to quantify the path to reach Net-Zero emissions.

- Deployment of a CN in a public cloud is realized via virtual machines, which are provisioned as compute instances provided by Infrastructure as a Service (IaaS). Instances from different users/services may also share the same compute node. Due to difficulty in the separation of responsibility between application and IaaS in public cloud, it is challenging to identify energy consumption of a particular use/service in a public cloud. Standard software methods to measure power at the server level may not be exposed by the public cloud service provider in this environment. That is because isolation of each virtual machine (VM) environment is required for security, with limited capability to access to the underlying HW platform, thus providing only metrics enabled by the cloud service provider. How to partition energy consumption between core and cloud and data centers and across use/service will be an interesting research area.

- End user communications devices include both consumer smartphones and IoT devices. IoT devices could be in many formats to enable services such as smart traffic management, environmental monitoring, virtual reality, and telemedicine, as well as high-definition video transmission in drones and robots across a broad range of industrial sectors. These IoT devices could be self-contained equipment but could also be a module or chip-level component of another piece of equipment. In that case, there will be no clear delineation between the energy consumption of the equipment as a whole and that which relates to the communications component. An example of this could be a connected vehicle or an agricultural robot with one or more communications components embedded. Research is required to understand how sustainability KPI measures that pertain to the communications component of the equipment can be contained and reported, so that this can be extrapolated and quantified for the organization/user of the equipment.

5 ABBREVIATIONS

3rd Generation Partnership Project 3GPP
6th Generation 6G
Application Specific Integrated Circuits .... ASICs
Artificial Intelligence .... AI
Carbon Dioxide .... CO_2
Carbon Dioxide Equivalent .... CO_2e
Carbon Intensity CI
Carbon Usage Effectiveness .... CUE
Celsius C
Communications Service Provider .... CSP
Core Network .... CN
Data Volume .... DV_{MN}
Digital Product Passport .... DPP
Ecodesign for Sustainable Products Regulation .... ESPR
End of Life .... EoL
Energy Consumption .... EC_{MN}
Energy Efficiency .... EE
Energy Reuse Factor .... ERF
Enhanced Mobile Broadband .... eMBB
European Telecommunications Standards Institute .... ETSI
European Union .... EU
Global Digital Sustainable Product Passport .... GDSPP
Global System for Mobile Communications .... GSMA
Global Warming Potential .... GWP
Greenhouse Gas .... GHG
Hardware .... HW
Hydrofluorocarbons .... HFCs
Indium Phosphide .... InP
Industrial Internet of Things .... IIoT
Information and Communication Technology .... ICT
Infrastructure as a Service .... IaaS
Intergovernmental Panel on Climate Change .... IPCC
International Electrotechnical Commission .... IEC
International Organization for Standardization .... ISO
Internet of Things .... IoT

ITU's Telecommunication Standardization Sector .... ITU-T
Key Performance Indicator .... KPI
Kilowatt-hour .... kWH
Life Cycle Assessment .... LCA
Machine Learning .... ML
Mean Species Abundance .... MSA
Methane .... CH_4
Metric Tons of Carbon Dioxide Equivalent .... $MtCO_2eq$
Next Generation Mobile Networks Alliance .... NGMN
Nitrogen Trifluoride .... NF_3
Nitrous Oxide .... N_2O
Perfluorocarbon .... PFCs
Power Usage Effectiveness .... PUE
Product Environmental Profile .... PEP
Radio Access Network .... RAN
Renewable Energy Factor .... REF
Software .... SW
Sulfur Hexafluoride .... SF_6
Ultra-Reliable Low Latency Communication .... URLLC
United Nations .... UN
User Equipment .... UE
User Plane Function .... UPF
Verified Emission Reductions .... VERs
Virtual Machine .... VM
virtualized RAN .... vRAN
Water Usage Effectiveness .... WUE

6 REFERENCES

1. It's 'now or never' to limit global warming to 1.5 degrees | UN News, https://news.un.org/en/story/2022/04/1115452

2. The Intergovernmental Panel on Climate Change, https://www.ipcc.ch/

3. Greenhouse Gas Protocol, https://ghgprotocol.org/sites/default/files/Guidance_Handbook_2019_FINAL.pdf

4. A quick guide to your digital carbon footprint, Ericsson. https://www.ericsson.com/en/reports-and-papers/industrylab/reports/a-quick-guide-to-your-digital-carbon-footprint

5. http://www.pep-ecopassport.org/

6. http://www.pep-ecopassport.org/pep-association/

7. Information Technology - Data Centers - Key Performance Indicators - Part 3: Renewable Energy Factor (REF). ISO/IEC 30134-3

8. Information technology — Data Centers - Key Performance Indicators — Part 6: Energy Reuse Factor (ERF). ISO/IEC 30134-6

9. World Wildlife Fund. (2022). https://www.worldwildlife.org/threats/water-scarcity

10. IPBES-8

11. UN Report: Nature's Dangerous Decline "Unprecedented"; Species Extinction Rates "Accelerating" - United Nations Sustainable Development. United Nations Sustainable Development; United Nations. (2019). https://www.un.org/sustainabledevelopment/blog/2019/05/nature-decline-unprecedented-report/

12. Nature's Dangerous Decline "Unprecedented"; Species Extinction Rates "Accelerating" | IPBES. https://ipbes.net/news/Media-Release-Global-Assessment

13. EUR 24586 EN https://publications.jrc.ec.europa.eu/repository/handle/JRC48211

14. https://www.un.org/sustainabledevelopment/blog/2019/05/nature-decline-unprecedented-report/

15. Going green: benchmarking the energy efficiency of mobile. (2021). https://data.gsmaintelligence.com/api-web/v2/research-file-download?id=60621137&file=300621-Going-Green-efficiency-mobile.pdf

16. Global biodiversity model for policy support. https://www.globio.info/

17. Number of mobile devices worldwide 2019-2023| Statista. https://www.statista.com/statistics/245501/multiple-mobile-device-ownership-worldwide/

18. A Deliverable by the NGMN Alliance Further Study on Critical C-Ran Technologies (2015). https://ngmn.org/wp-content/uploads/NGMN_RANEV_D2_Further_Study_on_Critical_C-RAN_Technologes_v1.0.pdf

19. Lin, P., & Bunger, R. (n.d.). Guide to Environmental Sustainability Metrics for Data Centers | Schneider Electric, https://download.schneider-electric.com/files?p_enDocType=White+Paper&p_Doc_Ref=WP67_SPD_EN

20. ITU-T L.1350, https://www.itu.int/rec/T-REC-L.1350-201610-I/en

21. ETSI ES 203228, https://www.etsi.org/deliver/etsi_es/203200_203299/203228/01.04.01_60/es_203228v010401p.pdf

22. 3GPP TS 28.554 https://www.etsi.org/deliver/etsi_ts/128500_128599/128554/16.07.00_60/ts_128554v160700p.pdf

23. ETSI ES 201 554 https://www.etsi.org/deliver/etsi_es/201500_201599/201554/01.01.01_60/es_201554v010101p.pdf

24. https://www.3gpp.org/specifications

25. Masanet, Eric, et al. "Recalibrating global data center energy-use estimates." Science 367.6481 (2020): 984-986.

26. Carbon neutrality in digital infrastructure, https://imasons.org/climateaccord/

27. OSTI United States Data Center Energy Usage Report https://www.osti.gov/biblio/1372902

28. WP#35 - Water Usage Effectiveness (WUE): A Green Grid Data Center Sustainability Metric | The Green Grid. https://www.thegreengrid.org/en/resources/library-and-tools/238-Water-Usage-Effectiveness-%28WUE%29%3A-A-Green-Grid-Data-Center-Sustainability-Metric-

29. Reig, P., Luo, T., Christensen, E., & Sinistore, J. (2020). Guidance for Calculating Water Use Embedded in Purchased Electricity. https://www.wri.org/research/guidance-calculating-water-use-embedded-purchased-electricity

30. U.S. Energy Information Administration. (2022). U.S. Energy Information Administration (EIA). https://www.eia.gov/

31. IoT Research Blog (2015), https://iot-analytics.com/research-blog/

32. Lee, P. (2021). Making smartphones sustainable: Live long and greener. Deloitte Insights. https://www2.deloitte.com/us/en/insights/industry/technology/technology-media-and-telecom-predictions/2022/environmental-impact-smartphones.html

33. Digital Product Passport, https://www.corporateleadersgroup.com/files/cisl_digital_products_passport_report_v6.pdf

34. Proposal for Ecodesign for Sustainable Products Regulation, https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en

35. Next G Alliance Report: 6G Applications and Use Cases https://www.nextgalliance.org/white_papers/6g-applications-and-use-cases/

36. Next G Alliance Report: 6G Technologies https://www.nextgalliance.org/white_papers/6g-technologies/

37. Next G Alliance Green G: The Path Toward Sustainable 6G https://www.nextgalliance.org/white_papers/green-g-the-path-towards-sustainable-6g/

38. Introducing Handprints: A Net-Positive Approach to Sustainability (2017), https://extension.harvard.edu/blog/introducing-handprints-a-net-positive-approach-to-sustainability/

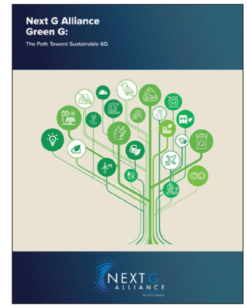
39. Nokia: Nokia 5G Energy Efficiency Revolution, https://onestore.nokia.com/asset/207360

NEXT G ALLIANCE REPORTS

6G Technologies

6G Applications and Use Cases

Roadmap to 6G



Green G: The Path Toward Sustainable 6G

6G Distributed Cloud and Communications System

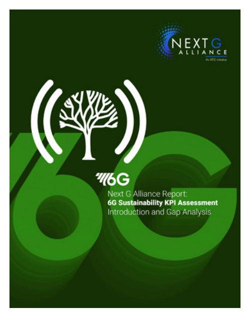
Trust, Security, and Resilience for 6G Systems

Digital World Experiences

Cost-Efficient Solutions

Sustainable 6G Connectivity — A Powerful Means of Doing Good

Next G Alliance Report: Terminology for Frequency Ranges



Next G Alliance Report: 6G Sustainability KPI Assessment Introduction and Gap Analysis

Next G Alliance Report: Multi-Sensory Extended Reality (XR) in 6G

6G Market Development: A North American Perspective

COPYRIGHT AND DISCLAIMER

Published March 2023

Alliance for Telecommunications Industry Solutions
1200 G Street, NW, Suite 500
Washington, DC 20005

The information provided in this document is directed solely to professionals who have the appropriate degree of experience to understand and interpret its contents in accordance with generally accepted engineering or other professional standards and applicable regulations. No recommendation as to products or vendors is made or should be implied.

NO REPRESENTATION OR WARRANTY IS MADE THAT THE INFORMATION IS TECHNICALLY ACCURATE OR SUFFICIENT OR CONFORMS TO ANY STATUTE, GOVERNMENTAL RULE OR REGULATION, AND FURTHER, NO REPRESENTATION OR WARRANTY IS MADE OF MERCHANTABILITY OR FITNESS FOR ANY PARTICULAR PURPOSE OR AGAINST INFRINGEMENT OF INTELLECTUAL PROPERTY RIGHTS. ATIS SHALL NOT BE LIABLE, BEYOND THE AMOUNT OF ANY SUM RECEIVED IN PAYMENT BY ATIS FOR THIS DOCUMENT, AND IN NO EVENT SHALL ATIS BE LIABLE FOR LOST PROFITS OR OTHER INCIDENTAL OR CONSEQUENTIAL DAMAGES. ATIS EXPRESSLY ADVISES THAT ANY AND ALL USE OF OR RELIANCE UPON THE INFORMATION PROVIDED IN THIS DOCUMENT IS AT THE RISK OF THE USER.

NOTE - The user's attention is called to the possibility that compliance with this document may require use of an invention covered by patent rights. By publication of this document, no position is taken with respect to whether use of an invention covered by patent rights will be required, and if any such use is required no position is taken regarding the validity of this claim or any patent rights in connection therewith. Please refer to www.atis.org/legal/patentinfo.asp to determine if any statement has been filed by a patent holder indicating a willingness to grant a license either without compensation or on reasonable and non-discriminatory terms and conditions to applicants desiring to obtain a license.

Building the foundation for
North American leadership in
6G and beyond.

nextgalliance.org

NEXT G ALLIANCE
An ATIS Initiative