6G

Next G Alliance Report:

Evolution of Sustainability Indicators for Next-Generation Radio Network Technologies

FOREWORD

As a leading technology and solutions development organization, the Alliance for Telecommunications Industry Solutions (ATIS) brings together the top global Information Communications Technology (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.

EXECUTIVE SUMMARY

Climate change is the defining issue of our time and one the greatest challenges for humanity to address. As the world starts to experience the negative impacts of climate change — including record-breaking heatwaves, floods, and storms [1] — climate science is clear: To avoid the worst impacts of climate change, humanity needs to reduce global emissions by 45 percent by 2030 and reach net zero emissions by 2050 or earlier if possible [2]. Net zero is a future state achieved by cutting greenhouse gas (GHG) emissions to as close to zero as possible, with any residual emissions re-absorbed from the atmosphere by technological or natural processes. According to the U.N. Intergovernmental Panel on Climate Change (IPCC), global temperatures have already risen by 1.2 degrees Celsius above pre-industrial levels in some areas of the world [3], which is very close to the Paris Climate Agreement of limiting global temperature rise below 1.5 C. Humanity has a narrow window of opportunity to act and create a sustainable future.

The Information Communication Technology (ICT) ecosystem has developed a collaborative pathway to reach net zero emissions by 2050 at the latest. This net zero pathway encompasses the entire ICT value chain, including emissions within direct operational control (Scope 1) and indirect emissions (Scope 2) from the generation of purchased electricity, as well as emissions from products, during manufacturing, and transportation (Scope 3) [4, 5]. As the ICT industry collaborates on the research, development, standardization, and introduction of next-generation radio access technologies, environmental sustainability must be at the forefront of all decisions throughout this lifecycle. The objective of this white paper is to provide recommendations for operational key performance indicators (KPIs) that the ICT industry can use to benchmark progress toward achieving environmental sustainability and climate action goals.

This white paper discusses current and future environmental sustainability KPIs, as well as technological enablers critical for the transition from Sustainability-Aware to Sustainability-Native next-generation wireless technologies. It also introduces three crucial dimensions — Observability, Choice, and Circular Economy — that provide an enhanced approach for implementing KPIs that ensure integration of environmental sustainability principles in design and operation of next-generation wireless technologies.

TABLE OF CONTENTS

1 INTRODUCTION

This paper focuses on the Radio Access Network (RAN) domain and shares recommendations that allow the ICT industry to benchmark carbon footprint and other RAN-specific sustainability Key Performance Indicators (KPI) to achieve climate goals, such as halving emissions from the 2015 level by 2030 and reaching net zero by 2050 [6]. The key perspective of this paper is to focus on the near term and longer term to evaluate the current KPIs, discuss trade-offs, and provide recommendations to advance the KPIs from where they are now to 6G.

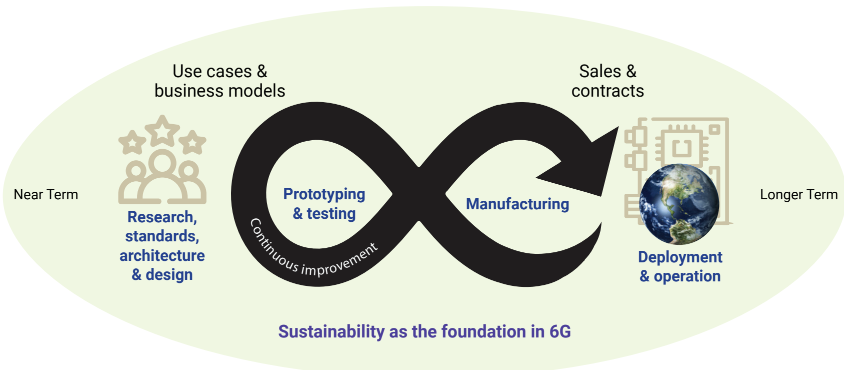


Figure 1: Depiction of the near term and longer term 6G technology lifecycle with sustainability as a foundational aspect

In the lifecycle of an end-to-end network, near term refers to the research, standards development, architecture, and design phases that feed the commercial deployments. To incorporate sustainability as the foundational element of the 6G design, it is crucial to define the sustainability KPIs in terms of its use cases and business models. Longer term, systems in the deployment and operation phase will be tested against these defined KPIs to validate the system design as a whole.

From a Sustainability-Aware 5G Toward a Sustainability-Native 6G

As we transition from one wireless generation to the next, sustainability is gaining heightened exposure and significance in the way it is incorporated into the design, analysis, and optimization of wireless networks. Indeed, a "sustainability-aware" ecosystem has become deeply intertwined with 5G, encompassing the deployed architectures and site infrastructure and the advancements implemented in the network's core. Looking ahead to 6G, the principle of sustainability will be inherently pervasive throughout the entire framework. In other words, every 6G use case and facet must take the lifecycle analysis (LCA) of energy expenditure and efficiency into play, from the very first step of the design process all the way to the final commercialization and assessment step [7]. As such, this perspective necessitates establishing both short-term and long-term objectives and principles. Serving as a compass and guiding us toward a wireless generation that is intrinsically attuned to sustainability.

Figure 2 illustrates how 6G will be both an evolution and a revolution compared to 5G. From an evolution standpoint, 6G will be a continued improvement of enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC) services. Moreover, 6G will also expand the scope of the existing "5G triangle" to include new capabilities such as integrated AI and sensing.

Environmental sustainability, security, privacy, and resiliency become integrated capabilities of 6G, enabling both the network and devices to minimize GHG emissions and other environmental impacts throughout their lifecycle. Important factors include improving energy efficiency and minimizing energy consumption and the use of resources. Examples include optimizing equipment longevity, repair, reuse, and recycling, and incorporating recycled and renewable content into the materials that make up the ecosystem.

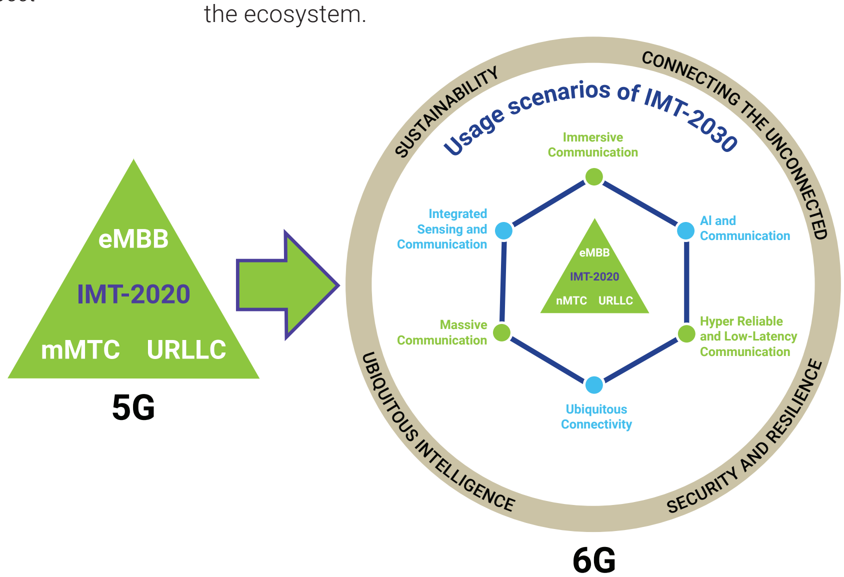


Figure 2: Growing network capabilities from 5G to 6G (Source: ITU) [7]

This holistic approach addresses the growing need for communication networking in the cyber-physical world. This progressive journey, as indicated in Figure 1, is driven by the interplay of network demand and monetization opportunities, closely following the path of previous mobile generations. This aligns with the ITU-R [8] Framework and underscores the vision of the Next G Alliance.

If we delve into these new 6G capabilities, it becomes imperative to scrutinize a range of considerations that hold significant importance to 6G being sustainable by design:

Enhanced Approach to Environmental Sustainability Indicators for 6G

The existing 5G network KPIs primarily emphasize observability to gauge performance and results with very coarse granularity. However, the advent of 6G necessitates a comprehensive paradigm shift. As Figure 3 illustrates, it encompasses three crucial dimensions in terms of implementing environmental sustainability KPI metrics: Observability, Choice, and Circular Economy (OCC).

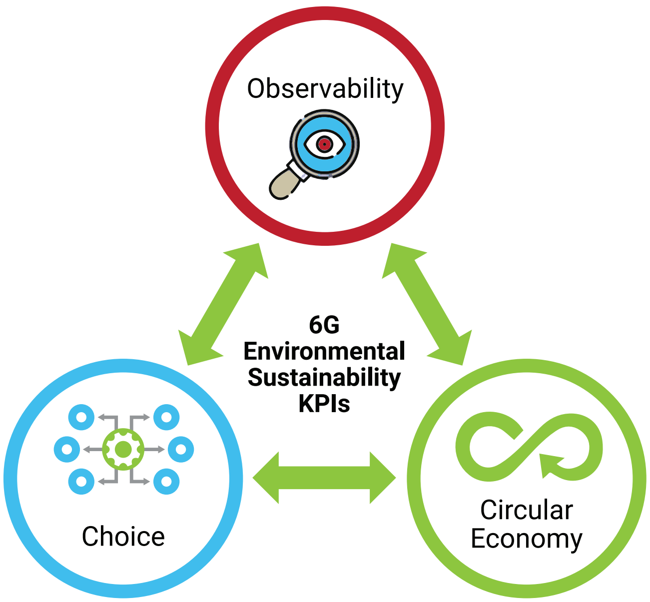


Figure 3: 6G Enhance Environmental Sustainability KPIs

Observability

Enhanced observability allows for the recording and reporting of environmental sustainability KPI metrics both during the design process and the operation of the 6G system. This may necessitate advanced models like energy consumption of its network elements and functions, as well as the end-to-end system.

Choice

Observability improvements through advanced modelling and monitoring allow choices in 6G system design, processes, and operations. Additionally, these choices can be made available to end users to select 6G services that best fit their sustainability needs. The implementation of choice will allow for the tradeoff between the various 6G system KPIs. Specifically, the 6G system should systematically enable trading off traditional KPIs with environmental sustainability KPI metrics, potentially in real time (e.g., through enhanced session and operational control protocols) to convey sustainability metrics for systematic management and choice. These enhanced KPIs could also be dynamically controlled through advanced Artificial Intelligence (AI)/Machine Learning (ML) techniques to improve 6G network environmental sustainability.

Circular Economy

The 6G economic model should encompass design or acquisition of products and components that are durable, upgradable, repairable, reusable, refurbishable, and at least recyclable or recoverable at their end of life. Metrics that can capture these circular economy aspects will quantify the eco credentials across the lifecycle from the products and components of 6G infrastructure and the connected devices to support choice in the design, operation, and end user selection.

Through the integration of environmental sustainability features at the core of 6G's design, there arises a need for new metrics to be measured and reported and for existing ones to be enhanced, (e.g., to enable real-time reporting and optimization). These metrics will encompass the environmental sustainability criteria of components or products during both design and operation phases. Additionally, implementing novel mechanisms and controls will be essential to communicate these metrics through the 6G infrastructure, sometimes in real-time session and control protocols. This empowers carriers, organizations, and end users to make informed choices, enabling the 6G infrastructure to dynamically adjust and meet predefined sustainability objectives and maintain its goals.

2 CURRENT RAN SUSTAINABILITY KPIS AND THEIR IMPACTS

Energy consumption is a major consideration in the RAN, so improving energy savings and efficiency are pivotal for the 6G RAN. Energy consumption is the total amount of energy consumed by the RAN during operations whereas energy efficiency is the data volume transmitted per unit of energy consumption, in GB/kWh, during a fixed time frame [8].

The RAN's overall energy performance comprises two main areas: climate control and base station equipment. The RAN's energy efficiency is also impacted by operational configurations such as network density, spectrum bands, and bandwidths, and the number of radio access technologies (4G, 5G, 6G, etc.).

Existing mobile network energy efficiency KPIs are documented in the European Telecommunications Standards Institute (ETSI) standard ES 203 228 '*Assessment of mobile network energy efficiency*' [9], related to metrics and methods to assess network energy efficiency up to 5G, which are continuously being improved by ITU [10]. RAN energy efficiency is usually evaluated by the ratio between the total energy consumed by active equipment (baseband, radio, and control) and the total energy consumed by passive equipment, including power supply and cooling/air conditioning. The Energy Re-use Effectiveness (ERE) as expressed in the ETSI '*Energy management; Operational infrastructures; Global KPIs*' [11] is an important KPI to quantify the ratio of re-used energy (e.g., the waste heat from cooling the RAN) to the RAN's total energy consumption. Spectral efficiency is an existing and well-known KPI for International Mobile Telecommunications IMT-2020 systems. But the evaluation of the efficiency and flexibility of the RAN to adapt its energy consumption to traffic loads and/or the services required is rather novel and further discussed in this paper. Table 1 provides an overview of RAN sustainability KPIs.

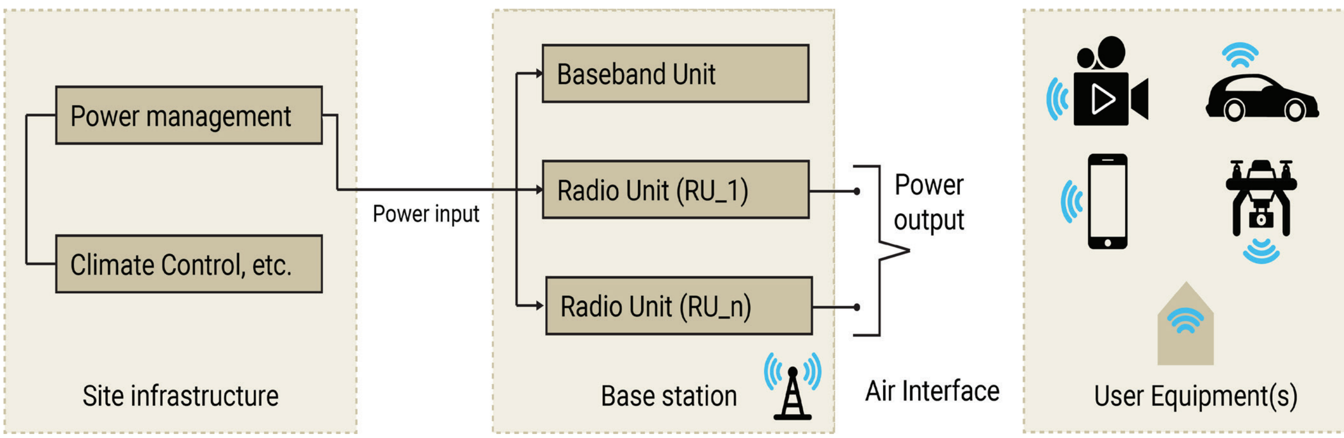


Figure 4: Typical RAN site depicting energy flow from the site infrastructure to the base station and to the UEs

Table 1: Overview of RAN-Specific KPIs

KPI	Explanation	Notes
DV_T/EC_T [9]	Ratio of the total data volume (DVT) of the user plane data and the total RAN energy consumed (ECT) in kilowatt hours (kWh) when accessed during the same time frame.	Provide an indicator of overall RAN energy efficiency in delivering services.
SEE or PUE_R	The Site Energy Efficiency (SEE) or Power Usage Efficiency of RAN (PUER): The energy used by network equipment for communication/computing/sense in RAN versus total energy usage in the site.	Provide an indicator of what percentage of energy is used for RAN equipment. PUE [6] is a ratio that describes how efficiently a data center uses energy; specifically, how much energy is used by the computing equipment (in contrast to cooling and other overhead that supports the equipment).
ERE [11]	The Energy Re-use Effectiveness (ERE) ratio of re-used energy by facilities, external to the ICT/BTS site, to the total energy consumption of theICT/BTS site.	Thermal energy can be reused in different forms, liquid or gas (air). It shall be measurable and quantifiable. It is a dimensionless number. All energy input to an ICT/BTS site is converted into heat. Possible initiatives to re-use the heat produced by the ICT equipment in ICT sites include heating: • Water • Facilities within the ICT/BTS site • Other premises (commercial or residential)
EC_N/DV_T	Total RAN equipment energy consumed (ECN) in kWh in the reporting period divided by total data volume (DVT) of user plane data.	Provide an indicator of RAN equipment power efficiency in delivering services. It is the exact inverse of the ECT/DVT KPI mentioned above.
P_R [9]	Percentage of power from renewable sources (PR) over total energy used in RAN.	Provide an indicator of how much energy used in RAN is from renewable sources such as solar, wind, hydropower plants et al.
UE_{ACT}/EC_T	Average number of user equipment (UEACT) or connections during data collection period/ total energy used (ECT).	Provide an indicator of overall RAN power efficiency in serving users.
A/EC_T	Area (A) in square meter [m^2] which has a signal strength of -110 dBm or better/Total energy used (ECT).	Provide an indicator of overall power efficiency of RAN in serving area with certain quality of coverage.
PRB_O	Physical Resource Block occupancy percentage utilization (PRBO) can be measured on per carrier or per cell level. PRBO = PRB_USAGE/ PRB_TOTAL.	Provide an indicator of the potential upper limit of energy saving using dormancy features.
EC_T/N_S	Total energy consumption (ECT) in the reporting period divided by total subscribers (NS) served (Energy consumption per individual subscriber measured as ratio in kWh per customer).	Provide an indicator of energy efficiency in delivering services to end subscribers.
ECT	Total Energy Consumption (ECT) is sum of ECN and ECs, where ECN is EC of network nodes including X-haul for delivering services and ECs is other.	Energy consumed for running site (cooling, lighting, and general power usage) excluding running network equipment. ECT covers the total energy used, whether by an operator or multiple operators sharing the same RAN infrastructure.

3 POTENTIAL INNOVATION GUIDELINES FOR RAN DOMAIN SUSTAINABILITY

3.1 Architectures, Components, and Technologies

Current 5G systems are designed with a focus on peak performance and therefore there have insufficient scalability and flexibility to maintain high energy efficiency at low loads. On one hand, network traffic distribution is very uneven across geographic areas and across time. On the other hand, a dramatic increase in data traffic poses a big challenge in digital signal processing capacity in the digital radio front end and baseband. These challenges call for innovations in system architecture, component deign, and radio technology to achieve dramatic improvements in energy efficiency.

Spatial domain adaptation methods for network energy savings have been studied in current and past standardization efforts. These methods mostly target low resource utilization where network energy savings can be achieved without seriously degrading user throughput. For 6G systems, spatial domain adaptation methods should also address medium- to high-load scenarios to uncover their full energy saving potential. Turning off network transceiver ports or subarrays of antenna panels reduces beamforming gain, which is important for coverage-limited users irrespective of high or low load and negatively impacts User Equipment (UE) power consumption because UEs need to stay awake longer. 6G systems should thus support a flexible base station transceiver architecture that can adapt over various spatial domain network energy-saving schemes, enabling various assumptions on array gain.

To address network energy savings, especially in the high packet-arrival scenario, technologies with high spectral efficiency can lower the resource utilization and provide time gaps for applying various energy-saving methods. To unleash the potential of spatial domain adaptation for network energy savings, new Channel State Information (CSI) codebook structures must allow for adapting between precoders with different assumptions on network port number. This renders the CSI training phase power consumption as scalable as that of the data transmission phase. Hence the need for a new CSI framework that embraces the fact that an experienced channel is invariant to the port number at either transmitting or receiving side.

Reducing the carbon emissions in the first place rather than offsetting them later can speed up the achievement of carbon neutrality. Beyond energy efficiency, to reduce carbon emissions further, it is important to improve carbon awareness through enhanced observability of the 6G system and to increase the adoption of renewable energy in cellular networks. Due to the highly variable and unpredictable nature of renewable energy sources such as solar or wind energy, the carbon intensity (i.e., the average carbon emissions per unit of energy consumption) equally varies considerably by time and location. Future 6G systems will need to be aware of the status of energy sources and adapt their operation to the high variability of renewable energy.

The IMT-2020 Minimum Performance Requirements [12] include energy efficiency only as a qualitative requirement. Despite this fact, 3GPP and other Standards Development Organizations (SDOs) have increasingly focused on energy-efficient solutions, especially in the RAN. Some energy-saving benefits, however, are more challenging to leverage without causing backward-compatibility issues, making energy efficiency a key milestone on the path towards sustainable 6G. Hence, it is recommended to have quantitative metrics for energy efficiency in the IMT-2030 Minimum Performance Requirements, leading to a foundational 6G design centered around energy efficiency.

Different methods and metrics can be employed to establish quantitative energy-efficiency design goals. One proposal could be based on expanding the qualitative evaluations performed for IMT-2020 energy-efficiency requirements. For 6G energy efficiency, requirements could be defined for eMBB in the following scenarios:

a) **Loaded Case:** Full buffer traffic scenario similar to prior evaluations where average downlink spectral efficiency will also be correlated with higher energy efficiency.

b) **Medium-Low Load Case:** The majority of the cells in a network are mostly experiencing low to medium load. Hence, optimizing energy efficiency in this scenario could yield high benefits to deployments. An average downlink spectral-efficiency target could be established for this scenario, along with a maximum energy-consumption target. The maximum energy-consumption target for this scenario could be derived as a percentage of the energy consumption of the loaded case using a base station power model with a dependency on the output power.

c) **No User Plane Load:** For 5G evaluations, ITU-R M-2412 proposed to evaluate potential sleep durations with a minimal control plane overhead. A similar approach could be established for 6G with a clear target sleep time and with established maximum transition times to ensure deeper sleep states can be efficiently leveraged.

d) **No User Plane Load and Further Reduction in Control Plane Overhead:** This new scenario would target to eventually achieve a zero-load, zero-power target. Establishing a KPI for sleep duration in this scenario would lead to designs enabling even deeper sleep states with further reductions in energy consumption. Similar to the previous load state, it is essential that transition times in and out of this state are not hindered by the designed frameworks.

Evaluation methodologies — including simulation assumptions, traffic models, and potential base station power models for these scenarios, along with the target values — will require further research, as outlined in 3GPP technical report (TR) 38.864 "*Study on network energy savings for new radio (NR)*" [13], as well as ETSI ES 202 706-1, "Metrics and measurement method for energy efficiency of wireless access network equipment; static measurement method" [14].

While the above is more focused on power models for one base station/cell, RAN energy efficiency also must consider the operational perspective of the overall RAN with many base stations/cells in a cluster, different spectrum bands, different RATs, and in case of network sharing/roaming, even different PLMNs.

Continuous Evolution of Hardware and 6G-Specific Needs

6G is gearing up to be a blend of evolution and revolution. It is important to note that that the enhanced processing demands in 6G mostly come from the digital front end (DFE). This is due to the need for larger bandwidth, larger antenna arrays, and shorter transmission time intervals (TTIs). This, in turn, has a cascading effect on the entire system architecture, influencing not only the radio unit and the operation of beamforming processes but also layer one, physical layer (PHY) processing, along with the processing needs for layer two Media Access Control (MAC). Advanced Application-Specific Integrated Circuits (ASICs) with specialized Digital Signal Processors (DSPs), accelerators, and other logic elements that provide advanced processing capabilities need to be available to support these [13]. Therefore, ASICs will become a key component for energy performance in future systems. Techniques such as ASIC clock gating — enabling radio ASICs to operate at slower clock speeds and save power consumption during low traffic hours — and bandwidth reduction enabling turning off parts of baseband ASICs will enable utilization of minimum resources for processing.

As discussed in the Next G Alliance report '*Green G: The Path Toward Sustainable 6G*' [15], component-level integration and use of highly efficient power amplifier (PA) designs are key enablers of improved radio energy efficiency, size, and weight while continuing to cater to growing network requirements. PA efficiency is optimized today by employing energy-efficient architectures (i.e., N-way Doherty architectures) and device technologies (i.e., GaN on SiC devices) in addition to implementing techniques such as activation of Dynamic VDD (drain voltage) to scale PA size, dynamically resulting in lower power consumption.

Another important component in increasing energy efficiency is to improve the PA's line-up power added efficiency (PAE), which dictates its power consumption. Note that PAE is near its optimum when the PA operates near its maximum output power, albeit at the cost of poor linearity. PA non-linearities are typically compensated in the transmitter by applying a power back-off, PAPR reduction, choice of modulation, and digital pre-distortion (DPD), which all require additional processing power at the transmitter. Flexibility to allow more relaxed adjacent channel leakage ratio (ACLR) requirements and out-of-band unwanted emissions will enable the PA to operate further in the non-linear region and facilitate higher energy efficiency and less processing power. Novel concepts need to be developed that can accompany such energy reduction techniques and limit the effects on spectral efficiency [13]. For example, UEs can assist the gNodeB (gNB) in reducing nonlinear impairments introduced by the PA by processing on training signals and reporting the information needed for gNB digital pre-distortion. Another example is that the UE can perform post-distortion processing to combat non-linear impairments from the transmitter.

PAE may also drop rapidly with increased backoff, driven by, for example, reducing transmisiont (Tx) power in low-load scenarios or improving linearity to support higher order modulations and control out-of-band emissions [16]. To further improve energy efficiency at mid to low loads, a modularized design at all levels — such as antenna array, transceiver chains, or System-on-a-Chip (SoC)/Application-specific integrated circuit (ASIC) — is needed to facilitate energy-saving operation features and a combination of them.

The possible introduction of sub-THz frequencies calls for a reassessment of current IC technology used for radio frequency (RF) front ends. Complimentary Metal-Oxide Semiconductor (CMOS) technology is the state-of-the-art for many RF circuits but starts to decline its utilization as it enters the sub-THz range. Although technologies such as Gallium Nitride (GaN) on silicon (Si) would enable operation at much higher frequencies and power levels compared to CMOS, regardless of the technology being used, the materials used limit the RF power capability. Power efficiency also drops significantly with frequency. Sub-THz frequencies also challenge the building practices, requiring higher geometric accuracy and lower loss in chip packaging and circuit boards. Thus the evolution of IC technologies will continue to be vital for 6G to accommodate the increased processing needs and other requirements.

Observability and the need for dynamic and configurable data collection for obtaining network data and insights are key to achieving low energy consumption in the RAN. 6G systems are thus expected to activate different energy-efficiency features depending on network traffic load. Optimizing energy performance involves minimizing the energy consumption for a set of performance requirements that could encompass user throughput, capacity, latency, and more. Energy savings can be facilitated only by energy-efficient specifications that create opportunities for deactivating hardware components over extended periods and specific time intervals. The concept of lean design was introduced in 5G NR, which enabled much larger energy savings due to micro sleep transmission than any previous generation. 6G products will need to be capable of fully utilizing further extended sleep opportunities in the time, space, and frequency domains. To capitalize on the sleep opportunities that the standards enable and to achieve energy savings for various network elements and functions while balancing performance requirements, proper data observability needs to be in place for products and services.

The 6G system needs to consider resources, processing, and transport capabilities, given the continuously expanding volume of data and events. Currently, modifying elements like the type of data collected or the granularity of data already being collected is complex and demands considerable effort. The challenge with current implementations is that applications consume network data from single, ad hoc pipelines, which is inefficient and wasteful of time and resources [17]. Hence, the system needs to have the ability to perform dynamic and configurable data collection that considers what data can be obtained and how to access it for a given product or a solution. A unified data infrastructure and standardized collection procedures are desirable to address issues related to redundancy, manual definition, multiple formats, and data aggregation issues that are prevalent in current systems.

Overall, consistent and timely availability of data, integrated into an AI-native architecture, is crucially needed for more comprehensive observability of user traffic KPIs, node states including devices, networks, cloud hosting, and network functions parameters, facilitating zero-touch orchestration and automation of solutions for end-to-end energy optimized networks.

3.2 Supply Chain, Manufacturing, and Operational Energy Efficiency

Modern Central Processing Units (CPUs) have various power saving features that take advantage of the time-varying demand for resources. Two major power saving features are deploying idling power states (C-states) and adjusting CPU frequency (P-states). C-states allow multicore CPUs to turn off unused components on a per-core or CPU package level to save power. When considering network load variation, AI/ML-enabled C-state management can minimize user experience impact while achieving power saving and has been applied to Open vRAN systems [20]. Processor performance states (P-states), on the other hand, control process power when work is being performed. CPU can operate in a range of frequencies (P-states), with lower frequencies consuming less power. P-states reduce the voltage and frequency of CPU cores or groups of cores to match the current workload on the CPU, achieving power saving without compromising workload completion time. When traffic is high, processors in RAN equipment can run at high frequency during busy traffic hours and dial down to low frequency when traffic is low to consume less energy while still supporting traffic.

Instruction set architecture (ISA) plays a crucial role in improving energy efficiency by enabling optimizations and techniques that reduce power consumption during instruction execution. ISAs can include specialized instructions that perform common operations more efficiently, thus reducing the number of instructions needed to complete a task. These instructions can include vector operations, encryption/decryption, multimedia processing, and more. Power consumption is reduced by executing tasks with fewer instructions.

Advanced Encryption Standard New Instructions (AES-NI), Advanced Vector Extensions (AVX), and Vector Neural Network Instructions (VNNI) are some examples that can be used for AI operation. Instructions such as MWAIT, MONITOR, PAUSE, UMWAIT, and TPAUSE can be used to save power.

Features such as clock gating might be leveraged to reduce power consumption of SoC/ASIC, but a linear scaling of power consumption for digital signal processing with traffic will not be sustainable given the dramatic increase in data traffic. Emerging disruptive computing frameworks such as compute-in-memory (CIM) will dramatically reduce the data read-write operations from memory. Thus they are ideal for operations such as matrix multiplication, which is most common in communication signal processing and ML inferences [21].

The evaluation methodology for an energy-efficiency application design should be based on its delivery mechanism: real-time, near-real-time, or non-real-time. For example, the Open RAN architecture introduces two new types of automation applications: extended applications (xApps) for real-time/near-real-time applications and rApps for non-real-time applications [22].

- Real-time xApps should focus on working with the scheduler to enable the fastest sleep-wake-up time.
- Near-real-time xApps should focus on implementation of changes based on traffic patterns and congestion prediction.
- Non-real-time rApps should focus on cognitive classification at the cell, slice, and Quality of Service (QoS) levels.

In addition, applications should be AI/ML-based and optimize the performance of applications such as traffic steering to achieve energy-efficiency target KPIs.

While ensuring that every mobile user is served without service experience degradation, one key approach is to dynamically switch network nodes to use renewables as much as possible by turning on the nodes that have plentiful renewables and shutting down the nodes that mostly utilize non-renewable energy at that moment. This idea can be illustrated via Figure 5. When base station (BS) 1 has the limited renewable energy on site while its adjacent BS 2 and BS 3 have higher re-generable energy sources, it needs to consume more non-renewables to serve all the UEs within its coverage. To reduce the carbon footprint due to the consumption of non-renewables, BS 1 can be turned off and its adjacent BSs (BS 2 and BS 3) can serve the overlapped UEs (UE1 and UE2). Turning off BS1, however, should be graceful so that it will not impact user experience migrated to BS 2 and BS 3.

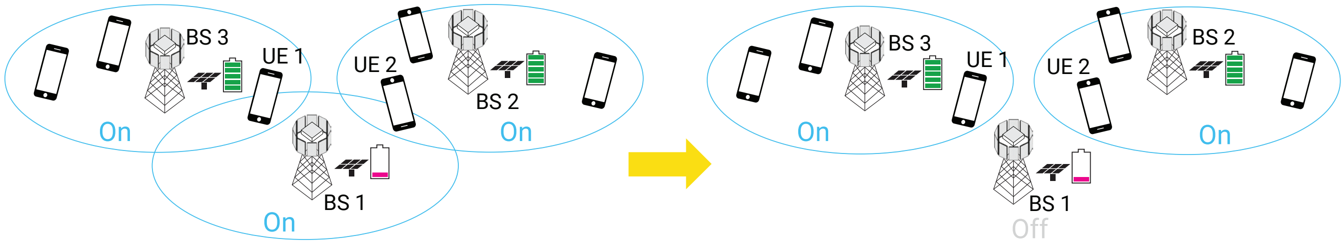


Figure 5: Carbon-Aware Base Station (BS) On/Off Switching

As more and more data are being processed and stored, heat generation has equally risen due to the increasingly high core counts and higher CPU/Graphics Processing Unit (GPU) frequencies, as well as accelerators and storage devices. Immersion cooling technology is one of several liquid cooling methods, which use less energy than traditional air. As mobile networks continue to evolve, edge data centers with RAN functions allow latency-sensitive tasks to be processed locally or as close as possible to the end users. Cooling technologies used in traditional data centers are increasingly applied to edge data centers, as well.

In a RAN site, cooling accounts for about 40 percent of the power usage [23]. Efficiently removing heat will help improve RAN power use efficiency (PUE).

There are alternative liquid cooling technologies that can also improve data center cooling efficiency. For example, direct contact liquid cooling (DCLC) delivers efficient cooling through a more effective heat removal than traditional air cooling and without requiring many changes to the existing infrastructure.

4 END COMMUNICATION DEVICE CONSIDERATIONS

4.1 Overview

In addition to RAN and data center power consumption, the end communication devices play a very significant role in the power and resource consumption of wireless systems. These devices are the endpoints for initiation or termination of a communication process and include smartphones and Internet of Things (IoT) devices such as sensors-actuators and displays. Smartphones have played an important role in people's lives. In fact, the U.S. smartphone market is one of the world's largest, with over 310 million smartphone users as of 2023 [24]. In line with the overall growth of the smartphone market worldwide, the U.S. penetration rate has continuously risen over the past several years, reaching around 92 percent in 2023 [25]. Although smartphones are the most prevalent end communication devices today, IoT devices will likely outnumber them in the future. The power consumption of end communication devices such as smartphones and IoT devices has thus been extensively studied, and many mechanisms that reduce energy consumption during communication have been defined within several 3GPP 5G specifications [26, 27, 28].

4.2 Operational Energy Efficiency

To further improve the energy efficiency of communication devices in the 6G era, various approaches could be explored, including:

1. Energy Optimization and Device Types
2. Low Power Wake Up Signal/Low Power Wake Up Radio
3. Energy Optimized Channel State Feedback
4. Joint Network and Device Energy optimization

Details about these approaches are presented below.

Energy Optimization and Device Types

To expedite the deployment process and reduce implementation efforts, it is beneficial if the design of an energy-efficient UE prioritized the optimization of specific operations rather than focusing solely on the UE type. As illustrated in Figure 6, the goal for designing a 6G system is twofold: to create a greener, more energy-efficient network, and to ensure scalability.

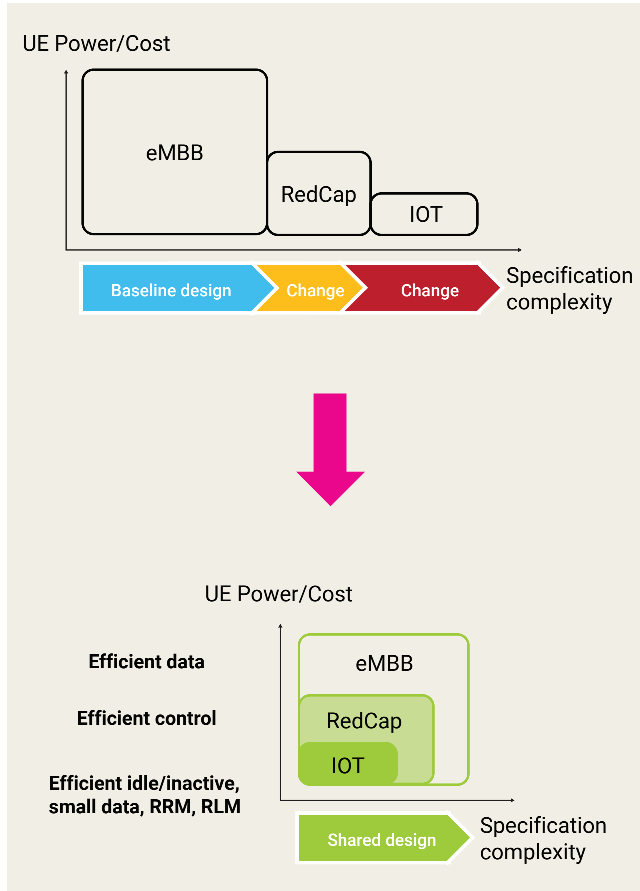


Figure 6: Scalable and Green Design for 6G Syste

This calls for targeted designs that ensure operations such as eMBB idle/inactive power consumption aligns with IoT power consumption. For instance, an eMBB UE monitoring paging in idle mode should ideally have power consumption similar to an IoT UE. Furthermore, it's critical to incorporate least-complexity features suitable for all UE types while maintaining consistent control and CSI overhead and complexity regardless of the number of carriers and antennas, respectively.

Low Power Wake Up Signal/Low Power Wake Up Radio

One way to enable device energy efficiency for specific operations and use cases is to use a low-power wake-up signal/low-power wake-up receiver. A low-power wake-up signal can allow a dedicated low-power radio to trigger the main radio so it can go into a deep-sleep mode or even be turned off entirely when there's no data activity [29]. The key to a low-power receiver thus lies in a hardware module with a relaxed noise figure, low-accuracy oscillator, and low-complexity digital baseband. Consequently, operations using the low-power receiver are limited and mainly focused on paging indication in RRC idle/inactive mode. Looking ahead to 6G, the goal is to design a system that is scalable, capable of accommodating all types of devices, and able to minimize power consumption for UE activities during periods without a large amount of user-plane data. To fully optimize the energy consumption, the use cases for the low-power receiver should be expanded to include more fundamental operations such as paging monitoring, Radio Resource Management (RRM) measurement, and small data transmission/reception. Given the constraints of current hardware capabilities, new signal/channel design and performance targets are necessary to ensure that the receiver can operate with exceptionally low power consumption while still providing satisfactory coverage.

An energy-efficient software design methodology for end communication devices requires procedures that minimize UE energy consumption while maintaining performance targets such as average data latency. During periods of high user-plane data activity, discontinuous reception (DRX) can be used for UE power savings. However, for latency-sensitive data services, it is challenging to optimize UE power consumption while maintaining acceptable latency. In such situations, hardware solutions such as using low-power receivers can be advantageous.

Energy-Optimized Channel State Feedback

In addition to the low-power receivers, power consumption could be further optimized during channel state processing either in low-power receivers or the main radio. Currently, the traditional CSI framework requires the UE to provide feedback about precoders based on its channel measurement. To improve energy consumption, it could be beneficial if the UE reported the channel directly to support adaptation between different port configurations for data transmission without requiring CSI for each port configuration.

Joint Network and Device Energy Optimization

A UE's low-power design should focus not only on reducing UE power consumption, but also consider energy savings on the network side. One potential research area for low-power 6G UEs could involve developing an ultra-low-power receiver. Capable of accumulating power during RF reception over a period without using much energy, this receiver could enable the 6G network to reduce transmission power or beamforming for common synchronization signals. In this way, both the UE and base station can contribute to energy savings, promoting a more energy-efficient network.

5 CIRCULAR ECONOMY

5.1 Overview

A circular economy is restorative and regenerative by design. It aims to keep products, components, and materials at their highest utility and value at all times while reducing waste streams. A concept that distinguishes between technical and biological cycles, the circular economy is a continuous, positive development cycle. It preserves and enhances natural capital, optimizes resource yields, and minimizes system risks by managing finite stocks and renewable flows while reducing waste streams [30]. Figure 7 shows the United Nations Environment Programme's (UNEP) circular economy approach guided by the *reduce-by-design* principle and value retention processes. The reduce-by-design concept, when applied during the early stage of the product and services design, helps to minimize usage of material and resources during raw and virgin material extraction, production, and/or use stage. The design approach during the early stage influences the entire product life cycle until the product's end of life and next life(s) in case of products with multiple lifecycles via reuse, refurbishment, repurposing, etc. Life extension and/or value retention processes like reuse (of products and materials), repair, refurbishment, remanufacturing, repurposing, and recycling help transitioning to a circular economy by eliminating waste and pollution and circulating product and materials back to the economy.

The RAN and the rest of the network infrastructure consist of equipment such as baseband unit, radio unit, and antenna module. With the transition of businesses and services towards high performing and more energy-efficient equipment, equipment lifetime extension becomes crucial. Circular economy is about considering these and other lifecycle factors even during the design phase. Circular economy encourages the design or acquisition of products and components that are durable, upgradable, repairable, reusable, refurbishable, and at least recyclable or recoverable at their end of life. It is important to consider that the production process itself needs to be sustainable, with minimal impact to the environment, underlined with renewable materials and energy.

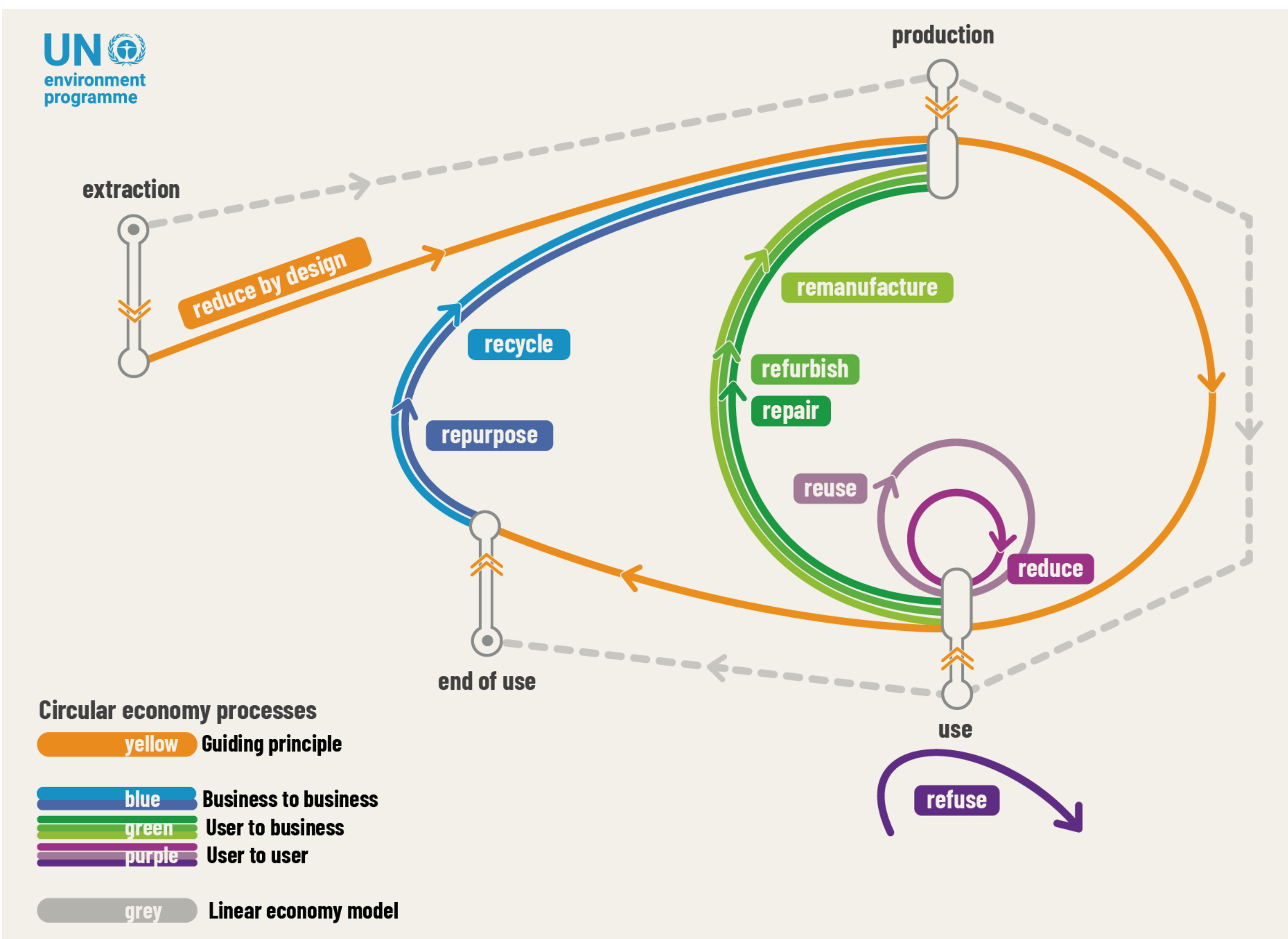


Figure 7: Circular Economy Processes [31]

5.2
Product Circularity Assessment

One example of a product circularity assessment is the three-step assessment methodology consisting of (1) estimation of *relevance* (R) of each criterion, (2) determining *margin of improvement* (MI) and (3) calculating the *circularity score* of a product based on the values from previous two steps. Table 2 presents the predefined three groups and 21 criteria to be used as guidance to assess a product's circularity score. Other examples include the Ellen MacArthur Material Circularity Indicator (MCI) [32] and the World Business Council for Sustainable Development (WBCSD) Circular Transition Indicator (CTI) [22].

Table 2: Criteria and Groups for Evaluating a Product's Circularity Score [34]

Circularity Aspect	Code	Circularity Indicator
Product durability (PD)	PD1	Software and data support
	PD2	Scratch resistance
	PD3	Maintenance support
	PD4	Robustness
	PD5	Battery for portable ICT goods
	PD6	Data security
Ability to recycle, repair, reuse, upgrade – equipment level	3Rue1	Fasteners and connectors
	3Rue2	Diagnostic support
	3Rue3	Material recycling compatibility - Plastic parts
	3Rue4	Material recycling compatibility - Metal parts
	3Rue5	Recycled/renewable plastics
	3Rue6	Recycled metals
	3Rue7	Material identification
	3Rue8	Hazardous substances
	3Rue9	Critical raw materials
	3Rue10	Packaging recycling
	3Rue11	Technical performance product mass-based material efficiency
Ability to recycle, repair, reuse, upgrade – manufacturer level	3Rum1	Service offered by manufacturer
	3Rum2	Spare parts distribution
	3Rum3	Spare parts availability
	3Rum4	Disassembly information
	3Rum5	Collection and recycling programmes
	3Rum6	Environmental footprint assessment knowledge available to improve the equipment material efficiency

The aim is to assess the product's durability, its capability to be repaired, recycled, and refurbished, as well as the manufacturers' support for circularity (for instance, take back, software upgrade, warranty, spare parts availability, etc.).

It is important to note that circularity-related aspects are relevant on a product level in the RAN infrastructure. In order to assess circularity, the full methodology needs to be followed, considering all aspects and steps included in the methodology.

There are other circularity-related indexes and KPIs either under development, in the standardization process, or focused on only limited aspects of circularity like material efficiency, repairability, and durability. However, most of those circularity aspects are reflected in Product Circularity Assessment methodology as shown in Table 2. Some examples of those alternative indexes/KPI are:

Repairability and Upgradability Scores

Products and components could be rated based on their ease of repair and upgradability. Metrics can include the availability of spare parts, ease of disassembly, and compatibility with future technologies.

Example KPI: Repairability Index

Definition: A score that rates products and components based on how easy they are to repair, including factors like availability of spare parts, disassembly simplicity, and repairability documentation.

Real-World Application: Encourage the adoption of products with high repairability scores to extend their lifespan and reduce waste.

Recycling and Reuse Rates

This KPI measures the percentage of materials from decommissioned 6G infrastructure that are recycled or reused in the production of new components. It encourages the adoption of sustainable materials and practices.

Example KPI: Recycling Rate of Decommissioned Components

Definition: This metric quantifies the percentage of materials from decommissioned 6G infrastructure that are recycled or reused in the production of new components.

Real-World Application: Set targets for recycling rates to incentivize the adoption of circular economy practices in the design and operation of 6G infrastructure.

6 ENVIRONMENTAL SUSTAINABILITY INDICATORS FOR 6G RADIO ACCESS TECHNOLOGIES

In the pursuit of this unprecedented connectivity and technological advancement, the evolution from 5G to 6G represents a pivotal juncture in the telecommunications landscape. However, as the world looks toward the integration of 6G, a critical paradigm shift must accompany this transition. Beyond merely enhancing speed and capacity, 6G necessitates a transformative approach that places environmental sustainability at its core. Unlike its predecessors, which primarily focused on performance and outcome observability, the success of 6G environmental sustainability lies in a holistic reevaluation of three key facets: **Observability, Choice, and Circular Economy**. This innovative framework underscores the imperative for sustainable design as the linchpin for 6G's capabilities.

Making 6G Environmentally Sustainable as a Design Foundation

For 6G to realize its full potential and effectively address the challenges of the 21st century, it must be sustainable by design. This entails an intricate interplay of enhanced observability, empowering choice, and embracing circular economy principles. By incorporating advanced models and monitoring mechanisms, the network's environmental impact can be meticulously observed and recorded, not only during operation but also in the very design process. This foundational observability enables unprecedented insights into the energy consumption patterns of components, ultimately driving efficiency improvements.

Moreover, choice emerges as a cornerstone in this new paradigm. Users and operators alike must be afforded the capabilities to tailor their 6G experience in alignment with their unique sustainability objectives. Through real-time trade-offs and AI-driven recommendations, individuals and organizations can dynamically balance traditional performance metrics with environmental sustainability considerations. This empowering flexibility ensures that 6G services are not only cutting edge but also consciously attuned to the sustainability imperatives of the present and future.

Furthermore, the transition from a linear economic model to a circular one is imperative. Products and components within 6G infrastructure must be engineered with circular aspects like durability, modularity, resiliency, upgradability, reusability, repairability, and recyclability at their core. Metrics assessing the eco-credentials of these elements will be instrumental in quantifying the environmental footprint across their lifecycle. By prioritizing circular economy principles, 6G sets the stage for a network infrastructure that meets the demands of tomorrow and does so in an environmentally responsible manner.

In this transformative journey towards 6G, it is abundantly clear that sustainability must per-meate every facet of design and operation. It is through this intentional and concerted effort that the full potential of 6G can be harnessed, delivering a network that revolutionizes connectivity and in a manner that safeguards the planet.

The following sections delve into specific Environmental Sustainability Indicators, offering a comprehensive framework for realizing this vision.

6.1 Observability in Environmental Sustainability

Enhanced observability, within the context of 6G's sustainability objectives, entails the meticulous recording and reporting of environmental sustainability metrics. This encompasses a comprehensive understanding of the energy consumption patterns exhibited by individual network elements during their construction and in the course of operational deployment. Advanced modeling techniques become the vanguard, offering unparalleled insights into the energy profiles of diverse elements within the 6G infrastructure.

Starting with the design and standardization of 6G systems, observability is key to assess the development of 6G technologies environmental impact through each and every design choice. This is achieved through significantly enhanced models of components such that trade-offs in the design and standardization phase are quantifiable from the onset and before initial deployment of the technology. Long before the first product, the environmental impact of technology choices and their trade-offs can reliably be predicted and consequently be considered, so the 6G system becomes sustainable in a systematic and predictable manner before it's ever turned on for the first time.

During the build phase, this observability unveils a precise tapestry of the environmental impact associated with the manufacturing and assembly of network elements. It empowers manufacturers to opt for sustainable materials and processes and lays the foundation for products engineered with ecological responsibility as a guiding principle. By quantifying the emissions, resource consumption, and energy utilization inherent in production, the telecom industry can embark on a trajectory toward environmentally conscious innovation.

Yet observability's purview extends far beyond the confines of production facilities. It stretches into the operational realm, wherein real-time insights into the energy consumption of deployed network elements facilitate dynamic optimization and resource allocation. This iterative feedback loop empowers operators to fine-tune network configurations, ensuring that sustainability objectives are not relegated to a distant aspiration, but rather are woven into the very fabric of operational decision-making.

Powered by this illuminating journey, observability becomes the fulcrum upon which the entire 6G ecosystem pivots towards a more environmentally sustainable future. By exposing the eco-footprint of components and products from inception to operation, it ushers in an era where network evolution and environmental preservation are inexorably intertwined. The subsequent sections will delve into how specific Environmental Sustainability Indicators offer a comprehensive framework to assess and augment the sustainability indicators of 6G radio networks.

Renewable Energy Ratio (RER)

> Definition: RER quantifies the proportion of energy consumed by a specific network element or domain that is derived from renewable sources, such as solar, wind, or hy-droelectric power.

> Formula: *RER*=Renewable Energy Consumption/Total Energy Consumption×100%

Grid Dependency Ratio (GDR)

> Definition: GDR assesses the reliance of a network element on the external power grid versus its capacity to generate power itself from its own local site energy sources (e.g. batteries, solar/wind site installation). Diesel electricity generators would not count here because they need external action to be refilled.

> Formula: *GDR*=Total Energy Consumption by network element/Grid-Sourced Energy Consumption by network element×100%

Carbon Intensity of Energy (CIE)

> Definition: CIE measures the amount of carbon dioxide (CO2) emissions associated with the energy consumption of a network element, reflecting its environmental impact.

> Formula: *CIE*=Total Energy Consumption by network element CO2/Emissions from Energy Consumption by network element

Energy Efficiency Index (EEI)

> Definition: EEI evaluates the efficiency of a network element in converting energy input into useful energy output. It indicates how effectively the network element utilizes the energy it consumes.

> Formula: *EEI*=Useful Energy Output by the network element/Energy Input by the network element

Peak Load Efficiency (PLE)

> Definition: PLE measures the energy efficiency of a network element during periods of high demand, which is crucial for reducing strain on the energy grid.

> Formula: *PLE*=Energy Input during Peak Load/Useful Work Output during Peak Load

Dominant Energy Source (DES)

> Definition: DES evaluates the percentage of energy relying on the single highest energy source used by a component, promoting resilience and reducing reliance on specific types of energy.

> Formula: *DES*= Energy Consumption from a energy source with the highest input by the network element/Total Energy Consumption by the network element×100%

Energy Storage Efficiency (ESE)

> Definition: ESE measures the effectiveness of energy storage systems integrated with the network element, ensuring minimal energy loss during storage and retrieval.

> Formula: *ESE*=Energy Input for Storage/Useful Energy Output from Storage

6.2 Pioneering the Circular Economy Indicator Paradigm

Central to the ethos of Circular Economy is the departure from traditional linear economic models, characterized by the "take-make-dispose" philosophy. Instead, 6G envisions an eco-system where products and components are conceived and constructed with a profound commitment to longevity and resource efficiency. In this paradigm, the lifecycles of network elements extend far beyond their initial deployment, fostering a culture of refurbishment, reutilization, and ultimately responsible recycling.

During the design and acquisition phase, the Circular Economy framework compels stakeholders to prioritize products that embody durability, upgradability, and repairability. These principles ensure that network components are built to withstand the rigors of time and technological advancement. Furthermore, they provide a foundation for components to be easily maintained, upgraded, refurbished, and repurposed, thereby extending their operational lifespan.

However, the efficacy of this Circular Economy model hinges on the establishment of standardized sustainability indicators that serve as a universal language for the industry. These indicators act as the common thread that binds manufacturers, operators, and regulators in a collective commitment to environmental stewardship. By adhering to consistent metrics that assess the durability, reusability, and recyclability of components, the industry fosters transparency while paving the way for innovations that truly embody circularity.

In this epoch-defining shift toward a Circular Economy, standardization and consistency of sustainability indicators become paramount. They provide the bedrock upon which a sustainable and regenerative telecommunications ecosystem can flourish. The ensuing sections will delineate specific Environmental Sustainability Indicators, offering a comprehensive framework for evaluating and fostering the circularity of 6G network.

Lifecycle Assessment Metrics

These metrics evaluate the environmental impact of products and components throughout their entire lifecycle. This includes factors like the energy and resources used in manufacturing, transportation, operation, and end-of-life disposal.

Example KPI: Environmental Impact category/Indicator Score

Definition: Environmental impact of products and components throughout their entire lifecycle, considering factors like energy consumption, resource use, and emissions. There are various midpoint impact categories like climate change/GHG emissions, resource depletion, land use changes and endpoint indicators like extinction of species and resource cost, etc., which are based on the LCA results and could be selected as individual KPIs.

Real-World Application: Set a target for environmental impact reductions (e.g., GHG emission reduction) to guide the procurement of products and components, favoring those with lower environmental footprints.

6.3 Empowering Through Choice

The concept of 'Choice' in 6G represents a departure from the one-size-fits-all approach that has hitherto defined network services. It acknowledges that sustainability is a multi-dimensional endeavor, encompassing the traditional metrics of speed, latency, and reliability, as well as the intricate interplay of environmental impact. This new choice dimension empowers end users and 6G network operators and service providers to navigate a landscape where sustainability goals align seamlessly with performance objectives.

At its core, choice fosters an environment of dynamic trade-offs, allowing stakeholders to consciously balance traditional KPIs with a suite of environmental sustainability metrics. Through advanced models, real-time monitoring, and AI-driven recommendations, individuals and organizations can fine-tune their network configurations, or service requests, ensuring that performance enhancements are inextricably linked with ecological responsibility.

This paradigm is as transformative for end users as it is for operators and service providers. For the first time, these stakeholders will have the capability to select services that resonate with their unique sustainability preferences. Whether it be prioritizing lower energy consumption, minimizing carbon emissions, or maximizing the use of renewable energy sources, choice catalyzes a profound shift towards user-centric sustainability.

In this pioneering era of 6G, the concept of choice revolutionizes the way we interact with and derive value from our networks. It signifies a fundamental shift toward a more personalized and ecologically responsible approach, where end users and operators become active participants in shaping a sustainable telecommunications future. Creating awareness to support choice is expected to provide transparency and virtuous behaviors from service providers while creating opportunities for individuals or organizations to adjust their own expectations. Here are some examples of how the use of Environmental Sustainability Indicators can support a comprehensive framework for navigating this new dimension of choice within the 6G ecosystem.

Near-Real-Time Trade-off Dashboards

Advanced dashboards can provide near-real-time information (e.g., daily updates) about the environmental impact of different service configurations. Users (individuals or organizations, e.g., leveraging a private network) and operators can then make informed decisions based on their sustainability preferences.

Example KPI: Sustainability Impact Index

Definition: A composite index that dynamically quantifies the environmental impact of service configurations, allowing users to make informed decisions based on data gathered over a certain period of time (e.g., monthly traffic).

Real-World Application: Provide users with a dashboard showing the trade-offs between traditional performance metrics and sustainability metrics for various service configurations.

Example KPI: Green Service Performance Index

Definition: A composite index that factors in both traditional performance metrics (e.g., data speed, latency) and sustainability metrics to provide a holistic view of service quality.

Real-World Application: Display the Green Service Performance Index on user interfaces, enabling them to make informed choices based on both performance and sustainability considerations.

Example KPI: User Sustainability Profiles

Definition: A categorization of users within predefined profiles (or categories) related to sustainability goals and metrics.

Real-World Application: Show users their past and current sustainability profile/category, also with respect to other users and monitor user split rates amongst the various profiles, enabling them to get feedback about their choices.

Example KPI: Renewable Energy Usage Percentage

Definition: This KPI measures the proportion of energy used for providing services that comes from renewable sources, indicating the environmental impact of service delivery.

Real-World Application: Offer service packages to individuals or organizations (e.g., network slices, Non-Public Networks

(NPNs)) with different (minimum guaranteed) percentages of renewable energy usage to cater to diverse user preferences or objectives.

Example KPI: Energy-saving analytics when accepting QoS-Sustainability Balancing

Definition: This metric assesses the energy savings (e.g., in percentage over time) achieved by the network due to the user accepting to dynamically adjust (e.g., downgrade) QoS levels while primarily optimizing sustainability metrics in real time.

Real-World Application: Provide transparent and quantified feedback when implementing algorithms that adjust QoS parameters based on user demands and sustainability goals.

AI-Driven Sustainability Recommendations

AI algorithms can analyze user behavior, network conditions, and environmental data to suggest service configurations that align with the user's sustainability preferences while maintaining a satisfactory QoS. Recommendations can be non-real-time (e.g., to suggest moving to another monthly service package) or real-time (e.g., to trigger a timely decision from the user)

Example KPI: Sustainability-Personalized Service Recommendations Effectiveness

Definition: Measure the effectiveness of AI-driven recommendations in aligning (e.g., suggesting or adapting) services with user based on the level (percentage) of acceptance of such recommendations by the user.

Real-World Application: Evaluate the success rate of AI-generated suggestions and refine algorithms to enhance user acceptance.

Example KPI: Energy Efficiency Improvement from AI Optimization

Definition: Measure the percentage improvement in energy efficiency achieved through AI-driven optimizations compared to baseline configurations while taking into consideration the energy cost/consumption of the training and running of the AI-driven optimization "engine."

Real-World Application: Track and report the energy savings attributed to AI-powered sustainability enhancements.

These expanded examples illustrate a wider range of KPIs within the three key areas of observability, choice, and AI-driven sustainability recommendations for 6G networks. By incorporating a diverse set of metrics, the telecom industry can take a comprehensive approach towards achieving environmental sustainability in the next generation of wireless technology.

6.4
Potential Sustainability Considerations for the Next Generation

The 6G RAN needs to have disaggregated and composable architectures, enabling dynamic provision and orchestration of virtualized network resources based on traffic demands to optimize power usage. Moreover, 6G systems should have power-aware workload auto-schedule and auto-scale features to transfer computing/network tasks to resources where carbon emission can be minimized (i.e., combination of lower energy consumption, using green energy, high efficiency, while meeting QoS requirements). KPIs of power usage in various RAN functions and nodes in disaggregated, composable, and cloud-based architectures should be defined or refined and reported with more granularity to enable provision and orchestrate network resources dynamically.

As the RAN continues to evolve to a disaggregated and virtualized architecture, network functional nodes may not be from the same physical resource. Mapping between a functional node and physical resources may become 1 to N or M to N. Current energy consumption of a virtual network function is estimated by summing up the energy usage of its constituent Virtualized Network Function Components (VNFC), where the estimated energy consumption of a VNFC is obtained by taking the estimated energy consumption of the virtual compute resource instance on which the VNFC runs. This estimation method is cumbersome, requiring obtaining synchronized energy usage data from all VNFCs and may not work if a mobile operator does not have a full access to all VNFC energy consumption data. A better solution for measuring energy consumption in a virtualized network will need to be developed to align with the evolving RAN network architecture.

7 CAPABILITIES AND CHALLENGES IN ENVIRONMENTAL SUSTAINABILITY INTEGRATION

In the transition to 6G, a transformative wave of capabilities emerges, revolutionizing how environmental sustainability metrics are incorporated into the network's fabric. This paradigm shift encompasses a spectrum of advancements and corresponding challenges in conveying information, design, acquisition, operation, user selection of sustainability qualifiers, session management, carrier selection of sustainability qualifiers, and operational controls.

Conveying Sustainability Indicator Information

Capabilities: The advent of 6G introduces advanced mechanisms for conveying environmental sustainability metrics through the network infrastructure. Enhanced data transmission protocols and communication technologies enable seamless dissemination of real-time sustainability information to carriers, organizations, and end users.

Challenges: However, ensuring the integrity and security of this data flow presents a critical challenge. Safeguarding against potential vulnerabilities and unauthorized access requires robust encryption protocols and secure communication channels.

Design and Acquisition

Capabilities: In the design and acquisition phase, 6G networks benefit from innovative tools that facilitate the integration of sustainability considerations. Advanced modelling techniques enable engineers to assess the environmental footprint of components and make informed decisions regarding their selection and configuration.

Challenges: Yet, harmonizing diverse data sources and ensuring the accuracy and completeness of sustainability metrics during the design process remains a formidable challenge. Standardizing data formats and calibration protocols is essential to mitigate potential discrepancies.

Sustainability Indicator Data Integrity and Trustworthiness

Capabilities: In 6G networks, ensuring the integrity and trustworthiness of sustainability indicator data becomes a critical capability. Advanced encryption and data verification techniques safeguard against potential data tampering or unauthorized access, ensuring the accuracy and trustworthiness of sustainability indicators.

Challenges: However, maintaining sustainability indicator data integrity and trustworthiness requires continuous vigilance and robust cybersecurity measures. Addressing potential vulnerabilities and adapting to evolving threats is essential to uphold the reliability and credibility of sustainability metrics.

Operation

Capabilities: During operation, 6G networks exhibit a heightened capacity for real-time monitoring and adaptation. Advanced sensors and monitoring systems provide granular insights into the energy consumption patterns and environmental impact of network elements and functions.

Challenges: However, effectively leveraging this wealth of data introduces the challenge of processing and analyzing it in real time. Implementing robust data analytics platforms and algorithms capable of handling the volume and velocity of sustainability metrics is crucial.

User Selection of Sustainability Qualifiers, Session Management

Capabilities: 6G empowers end users with the capability to select sustainability qualifiers that align with their unique environmental preferences. Session management protocols now incorporate sustainability considerations, enabling users to customize their network experience based on their ecological priorities.

Challenges: Balancing user choice with network optimization poses a challenge. Striking the right trade-offs between performance metrics and sustainability qualifiers requires sophisticated algorithms and dynamic session management strategies.

Carrier Selection of Sustainability Qualifiers, Session Management

Capabilities: Carriers, too, wield newfound capabilities in selecting sustainability qualifiers that resonate with their organizational objectives. Session management protocols now integrate sustainability considerations, enabling carriers to align network operations with their environmental goals.

Challenges: However, balancing network efficiency and sustainability objectives requires carriers to navigate complex trade-offs. Developing adaptive session management strategies that account for both performance and environmental impact remains a significant challenge.

Operational Controls, Adaptation of Sustainability Indicators

Capabilities: 6G networks introduce adaptive operational controls that respond dynamically to sustainability indicators. This allows for real-time adjustments to network configurations based on changing environmental conditions and user preferences.

Challenges: The challenge lies in developing adaptive algorithms and control protocols that effectively balance sustainability goals with the operational requirements of the network. Striking this equilibrium demands a deep understanding of both network dynamics and environmental impact assessments.

In the 6G era, the integration of environmental sustainability metrics ushers in a new frontier of capabilities and corresponding challenges. Addressing these complexities is pivotal in crafting a telecommunications landscape that excels in performance and stands as a beacon of environmental responsibility. Through concerted efforts and innovative solutions, we can chart a course toward a more sustainable future for telecommunications.

8 SUMMARY AND RECOMMENDATIONS

This paper recommends emphasizing the three pillars of sustainable next generation of technology: Observability, Choice, and Circular Economy (OCC). Observability is the path to achieving fine granularity where some indicators can be potentially observed in near real time. With improvements in potential observability, choice lets end users select from various sustainable options. Circular Economy is at the core of sustainability, where the nine Rs as stated by UNEP (reduce by design or rethink, refuse, reduce, reuse, repair, refurbish, remanufacture, repurpose, and recycle) are key factors in the circularity process.

With advancements of 6G, sustainability needs to be the foundational aspect of the 6G Research and Development (R&D) and standardization. 6G will be an evolution and a revolution of the 5G ecosystem, so it is important to understand the current RAN sustainability KPIs and their impacts. Most likely those will be the ones used for measurements in addition to the potential new KPIs in 6G. It is widely acknowledged that the majority of power consumption in the network is attributed to the RAN. Even so, it is helpful to consider sustainability indicators of end communication devices and other aspects of the network, as applicable.

Key potential 6G sustainability indicators discussed in this paper may introduce novel methods from an end user point of view to measure sustainability in near real time by providing choices, current already defined indicators, such as energy efficiency, will complement them to effectively measure those key metrics. This paradigm shift encompasses a spectrum of advancements and their corresponding challenges, where each facet contributes to a dynamic ecosystem that empowers stakeholders in their pursuit of a more sustainable telecommunications landscape.

9 ABBREVIATIONS AND ACRONYMS

3GPP	3rd Generation Partnership Project
ACLR	Adjacent Channel Leakage Ratio
AES-NI	Advanced Encryption Standard New Instructions
AI	Artificial Intelligence
ANSI	American National Standards Institute
ASIC	Application-Specific Integrated Circuits
AVX	Advanced Vector Extensions
BS	Base Station
CIE	Carbon Intensity of Energy
CIM	Compute-In-Memory
CITEL	Inter-American Telecommunication Commission
CMOS	Complementary Metal-Oxide Semiconductor
CO2	Carbon Dioxide
CPU	Central Processing Unit
CSI	Channel State Information
CTI	Circular Transition Indicator
DCLC	Direct Contact Liquid Cooling
DES	Dominant Energy Source
DFE	Digital Front End
DPD	Digital Pre-Distortion
DRX	Discontinuous Reception
DSP	Digital Signal Processors
DV	Data Volume
EC	Energy Consumption
EEI	Energy Efficiency Index
eMBB	Enhanced Mobile Broadband
ERE	Energy Re-use Effectiveness
ES	ETSI Standard
ESE	Energy Storage Efficiency
ETSI	European Telecommunications Standards Institute
GaN	Gallium Nitride
GDR	Grid Dependency Ratio
GHG	Greenhouse Gas
gNB	gNodeB
GPU	Graphics Processing Unit

IC .... Integrated Circuit
ICT .... Information Communication Technology
IMT .... International Mobile Telecommunications
IoT .... Internet of Things
IPCC .... Intergovernmental Panel on Climate Change
ISA .... Instruction Set Architecture
ITU .... International Telecommunication Union
KPI .... Key Performance Indicator
kWh .... Kilowatt Hours
LCA .... Lifecycle Analysis
MAC .... Media Access Control
MCI .... Material Circularity Indicator
MI .... Margin of Improvement
ML .... Machine Learning
mMTC .... Massive Machine Type Communications
NPN .... Non-Public Networks
NR .... New Radio
OCC .... Observability, Choice, and Circular Economy
PA .... Power Amplifier
PAE .... Power Added Efficiency
PD .... Product Durability
PHY .... Physical Layer
PLE .... Peak Load Efficiency
PRB .... Physical Resource Block
PUE .... Power Usage Efficiency
QoS .... Quality of Service
R&D .... Research and Development
RAN .... Radio Access Network
rApps .... Non-Real-Time Applications
RER .... Renewable Energy Ratio
RF .... Radio Frequency
RRM .... Radio Resource Management
SDO .... Standards Development Organization
SEE .... Site Energy Efficiency
Si .... Silicon
SoC .... System-on-a-Chip
TB .... Total Data Volume
TR .... Technical Report
TTI .... Transmission Time Interval

Tx .... Transmission Power
UE .... User Equipment
UNEP .... United Nations Environment Programme
URLLC .... Ultra-Reliable Low Latency Communications
VDD .... Drain Voltage
VNFC .... Virtualized Network Function Components
VNNI .... Vector Neural Network Instructions
vRAN .... Virtualized Radio Access Networks
WBCSD .... World Business Council for Sustainable Development
xApps .... Extended Applications

10 REFERENCES

1. NOAA National Centers for Environmental Information, Global Climate Reports, https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/.

2. United Nations, Climate Action, https://www.un.org/en/climatechange/net-zero-coalition.

3. Goering, L. (2022). Explainer: How close are we to passing 1.5 degrees Celsius of global warming? Reuters. https://www.reuters.com/business/cop/how-close-are-we-passing-15-degrees-celsius-global-warming-2022-11-14/.

   COP27: Key outcomes agreed at the UN climate talks in Sharm el-Sheik, Nov 2022, https://www.carbonbrief.org/cop27-key-outcomes-agreed-at-the-un-climate-talks-in-sharm-el-sheikh/.

4. ITU, The collaborative path to a Net Zero ICT sector (2021). https://www.itu.int/en/ITU-T/Workshops-and-Seminars/gsw/202112/Documents/Pernilla_Bergmark.pdf.

5. ITU-T L.1471, https://www.itu.int/rec/T-REC-L.1471-202308-I/en.

6. Climate Champions. (2021). Mobile sector declares climate action breakthrough. Race to Zero. https://racetozero.unfccc.int/mobile-sector-breakthrough/.

7. IMT Towards 2030 and beyond. https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx.

8. Next G Alliance, Report: 6G Sustainability KPI Assessment Introduction and Gap Analysis, https://www.nextgalliance.org/white_papers/6g-sustainability-kpi-assessment-introduction-and-gap-analysis/.

9. ETSI ES 203 228, Environmental Engineering (EE); Assessment of mobile network energy efficiency, https://www.etsi.org/deliver/etsi_es/203200_203299/203228/01.03.01_60/es_203228v010301p.pdf.

10. ITU, Study of Multi-dimensional network energy efficiency metrics, https://www.itu.int/itu-t/workprog/wp_item.aspx?isn=18408.

11. ETSI, EN 205 200 series "Energy management; Operational infrastructures; Global KPIs", https://www.etsi.org/deliver/etsi_en/305200_305299/3052000202/01.02.01_60/en_3052000202v010201p.pdf.

12. ITU-R M.2410-0 Minimum requirements related to technical performance for IMT-2020 radio interface(s) https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2410-2017-PDF-E.pdf.

13. 3GPP TR 38.864, 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on network energy savings for NR (Release 18) https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3987.

14. ETSI ES 202 706-1, Environmental Engineering (EE); Metrics and measurement method for energy efficiency of wireless access network equipment: Part 1, https://www.etsi.org/deliver/etsi_es/205200_205299/2052000204/01.01.01_60/es_2052000204v010101p.pdf.

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

16. S. Wesemann, J. Du and H. Viswanathan, "Energy Efficient Extreme MIMO: Design Goals and Directions," IEEE Communications Magazine, vol. 61, no. 10, pp. 132-138, October 2023. https://arxiv.org/pdf/2301.01119.pdf

17. Data ingestion architecture for telecom applications (ericsson.com): https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/data-ingestion-architecture-for-telecom.

18. Improving energy performance in 5G networks and beyond - Ericsson https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/improving-energy-performance-in-5g-networks-and-beyond.

19. Sustainable 6G Connectivity A Powerful Means of Doing Good – Next G Alliance https://www.nextgalliance.org/white_papers/sustainable-6gconnectivity-a-powerful-means-ofdoing-good/#:~:text=This%20paper%20surveys%20the%20research,net%2Dzero%20greenhouse%20gas%20emissions.

20. A Holistic Study of Power Consumption and Energy Savings Strategies for Open vRAN Systems, https://networkbuilders.intel.com/docs/networkbuilders/a-holistic-study-of-power-consumption-and-energy-savings-strategies-for-open-vran-systems-1676628842.pdf, Accessed June 2023.

21. H. Viswanathan, S. Wesemann, J. Du and H. Holma, "Energy efficiency in next-generation mobile networks," Nokia white paper, (2022). https://onestore.nokia.com/asset/212810.

22. O-RAN Architecture Description 10.0, O-RAN Downloads, https://orandownloadsweb.azurewebsites.net/specifications.

23. NGMN Alliance, "Green Future Networks: Network Energy Efficiency,"(2021). https://www.ngmn.org/publications/green-future-networks-network-energy-efficiency.html.

24. Statistica, Smartphones in the U.S. - statistics & facts, https://www.statista.com/topics/2711/us-smartphone-market/#topicOverview.

25. Statistica, Penetration rate of smartphones in the United States from 2013 to 2028, https://www.statista.com/forecasts/1144749/smartphone-penetration-forecast-in-the-united-states.

26. 3GPP TR 38.840, Study on User Equipment (UE) power saving in NR, https://www.3gpp.org/DynaReport/38840.htm.

27. 3GPP TS 38.213, Physical layer procedures for control procedures, https://www.etsi.org/deliver/etsi_ts/138200_138299/138213/16.02.00_60/ts_138213v160200p.pdf

28. 3GPP TS 38.214, Physical layer procedures for data, https://www.etsi.org/deliver/etsi_ts/138200_138299/138214/16.02.00_60/ts_138214v160200p.pdf.

29. 3GPP 38.869, Study on low-power Wake-up Signal and Receiver for NR, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3989.

30. ITU-T L.1020, Circular economy: Guide for operators and suppliers on approaches to migrate towards circular ICT goods and network. https://www.itu.int/rec/T-REC-L.1020-201801-I/en.

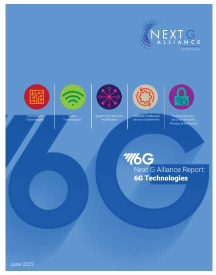
31. UNEP, Circularity, https://www.unep.org/circularity.

32. Ellen MacArthur Material Circularity Indicator (MCI), https://ellenmacarthurfoundation.org/material-circularity-indicator.

33. World Business Council for Sustainable Development (WBCSD) Circular Transition Indicator (CTI), https://www.wbcsd.org/Programs/Circular-Economy/Metrics-Measurement/Resources/Circular-Transition-Indicators-v4.0-Metrics-for-business-by-business.

34. L.1023: Assessment method for circularity performance scoring, https://www.itu.int/rec/T-REC-L.1023-202308-I.

NEXT G ALLIANCE REPORTS



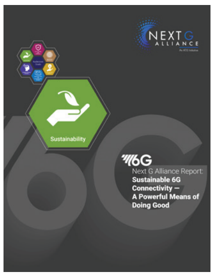
Next G Alliance Report: 6G Technologies

Next G Alliance Report: 6G Applications and Use Cases

Next G Alliance Report: Roadmap to 6G

Green G: The Path Toward Sustainable 6G

Next G Alliance Report: AI-Native Wireless Networks



Next G Alliance Report: Sustainable 6G Connectivity — A Powerful Means of Doing Good

Next G Alliance Report: 6G Distributed Cloud and Communications System

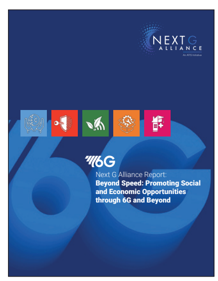
Next G Alliance Report: Trust, Security, and Resilience for 6G Systems

Next G Alliance Report: Digital World Experiences

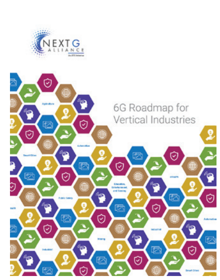
Next G Alliance Report: Cost-Efficient Solutions

Next G Alliance Report: 6G Radio Technology Part I: Basic Radio Technologies

Next G Alliance Report: 6G Technologies for Wide-Area Cloud Evolution

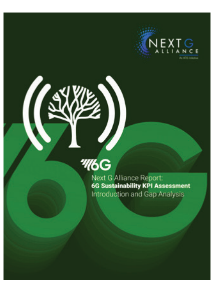


Next G Alliance Report: Beyond Speed: Promoting Social and Economic Opportunities through 6G and Beyond



Next G Alliance Report: 6G Roadmap for Vertical Industries

6G Market Development: A North American Perspective

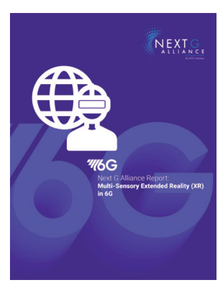


Next G Alliance Report: 6G Sustainability KPI Assessment Introduction and Gap Analysis

Next G Alliance Report: 6G Spectrum Considerations

Next G Alliance Report: Terminology for Frequency Ranges

Next G Alliance Report: Network-Enabled Robotic and Autonomous Systems



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

Next G Alliance Report: Shaping Tomorrow: The Evolution of Personalized Digital Experiences Through 6G Technologies

COPYRIGHT AND DISCLAIMER

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

nextgalliance.org

NEXT G ALLIANCE

An ATIS Initiative