

Bharat 6G Alliance Whitepaper

# Powering the Next-Gen Telecom

Towards energy efficiency in 6G Macro and Small cell deployments



OCTOBER 2025  
VERSION 2.0



## Executive Summary

The advent of 6G promises to revolutionize connectivity, ushering in an era of hyper-connected devices and seamless experiences. However, this transformative technology comes with a significant energy-efficiency challenge. As 6G networks grow in complexity and scale, enhancing energy efficiency will be critical to achieving sustainable and cost-effective deployments. This whitepaper examines key energy efficiency issues and considerations for 6G macro and small-cell deployments, and explores innovative techniques and technologies to reduce power consumption while maintaining network performance, reliability and scalability.

## Audience

This whitepaper is intended for:

- Telecom Project Managers and Solution Architects
- 5G/6G Research Teams
- Telecom Network Planning and Optimization Teams
- Network Operations Centre and Field Engineers
- Other professionals and organizations involved in the Telecom Industry

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# 1 Introduction

The dawn of the sixth generation (6G) of wireless communication heralds an era of unprecedented connectivity, promising transformative advancements across sectors. From autonomous vehicles and remote surgery to the Internet of Things (IoT) and augmented reality, 6G technologies will underpin a hyper-connected society. However, the realization of this vision hinges critically on achieving significant gains in energy efficiency.

The escalating energy consumption of telecommunication networks poses a significant environmental challenge. As 6G networks evolve to support a multitude of demanding applications, their overall energy footprint is poised to grow substantially. This necessitates a paradigm shift towards sustainable and energy-efficient network design and operation.

This whitepaper examines the key aspects of energy efficiency in 6G macro and small-cell deployments. It explores a range of innovative techniques aimed at minimizing energy consumption while maximizing network performance and user experience.

Allied topics such as sustainability, energy harvesting, renewable energy sources, and a possible methodology for measuring radio-network efficiency are provided in the respective appendices.

## 2 Global Energy Consumption Trends in Telecom Industry

### 2.1 Introduction

The telecom industry<sup>1</sup>, as a backbone of global digital infrastructure, is experiencing a sharp rise in energy demand driven by data-intensive applications, 5G rollouts, and network densification. Yet, this surge comes at a time of heightened environmental scrutiny and climate commitments. Leading communication service providers (CSPs) such as Airtel, Jio, Deutsche Telekom, NTT Docomo, Telefónica, and Verizon are increasingly embedding Environmental, Social, and Governance (ESG) strategies into their operations to mitigate energy consumption and reduce carbon emissions. ESG disclosures reveal a growing emphasis on energy-efficient network technologies, AI-driven optimization, renewable energy procurement, and phasing out legacy systems. For instance, Deutsche Telekom now powers its entire network with renewable electricity, while Airtel and Jio are advancing solarization and dynamic power management across mobile sites to curb operational emissions.

Industry bodies like GSMA and Omidia provide critical benchmarking and highlight sector-wide progress and gaps. GSMA's latest *Mobile Net Zero* report (2025) shows that while total electricity consumption by mobile operators reached approximately 290 TWh in 2023, energy efficiency per unit of data has improved, demonstrating progress toward decoupling emissions from network growth. However, Scope 3 emissions and energy use from user devices and supply chains remain significant and under-addressed. Omidia further notes that the shift toward software-defined networks and edge computing may increase short-term energy needs, even as they promise long-term sustainability gains. As regulatory and investor pressure mounts, CSPs must balance performance, connectivity expansion, and environmental impact—making energy strategy a defining element of telecom transformation in the years ahead.

### 2.2 Analysis on Communication Service Providers ESG

#### 2.2.1 Reliance Jio

Jio's ESG and energy efficiency commitments [1]

- **76 % reduction in absolute Scope 1 & 2** GHG emissions by FY 2028-29 (baseline FY 2020-21) in alignment with Science Based Targets initiative (SBTi)
- **66.5 % reduction in Scope 3** emissions over the same period.
- Scale **renewable electricity procurement** from 1.2 % in FY 2020-21 to **100 % by FY 2029-30**, and thereafter maintain 100 % renewable power usage.
- Installed over **174 MWp of solar capacity across more than 20,000 sites** nationwide and is **exploring wind power and methanol fuel cells** to further reduce its carbon footprint.

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<sup>1</sup> The following subsections may contain information in reasonably short snippets that paraphrase or quote publicly available reports, which are referenced. All data are given as samples to understand industry trends. Bharat 6G Alliance does not prefer any specific operator/OEM/vendor/make/model.

- Optimizing diesel generator usage (DG run-hours), **shifting to battery backup** for low-utilization sites, and leveraging **energy saving techniques in network operations** (e.g. radio shut-off during non-traffic hours).
- Use of best-in-class technology, **AI / sensor systems, hot/cold air separation** in data centers (aisle containment), smart lighting and motion sensors, and infrastructure upgrades to minimize energy wastage
- **Transparency of energy balance:** Publicly available information of total energy consumption and the share of renewable sources.

### 2.2.2 Bharti Airtel

Airtel's ESG and energy efficiency commitments [2]

- Reducing **absolute Scope 1 & 2 emissions by 50.2 % by FY 2030-31**, using FY 2020-21 as the baseline in alignment with Science Based Targets initiative (SBTi).
- Reduce **absolute Scope 3 emissions by 42 %**.
- Achieve **net-zero carbon emissions by 2050**.
- Deploying **AI/ML techniques to reduce energy usage** in radio access (e.g. applying “zerotraffic, zerowatt” modes during idle periods) to cut emissions.
- Deploying **solar power** across its mobile network to reduce reliance on diesel generation and continues to expand the number of “**green sites**” (sites that are either energy efficient by design or powered by renewables), and aims to significantly reduce diesel consumption at tower sites (multiple million liters per month) despite expanding the network footprint.
- **ESG goals are integrated into its overall business strategy.**

### 2.2.3 Deutsche Telekom/T-Mobile

DT's ESG and energy efficiency commitments [3]

- **100% renewable electricity** for DT Group (From 2021 onwards)
- **Double energy efficiency** in DE&EU (2024 vs 2020)
- Net-zero for direct and indirect CO2 emissions (Scope 1 & 2) (until 2025)
- **Reduction in energy consumption** ex US (2020-24)
- Reduce Scope 1-3 CO2 emissions by 55% against 2020 by 2030 (2030 vs 2020)
- Net-zero CO2 emissions (Scope 1-3) with at least 90% reduction (Latest 2040)

### 2.2.4 NTT DOCOMO

NTTDCM's ESG and energy efficiency commitments [4]

- Improved network **energy efficiency**, Implementation of **renewal energy**
- 5G will be designated as Green 5G, **ultra-energy-saving** data center service
- Rolling out **green smartphones, Visualization of energy use in daily life & building Green Base Stations**

### 2.2.5 Telefonica

Telefonica's ESG and energy efficiency commitments [5]

- **Environment -Green networks**
- On track to be net zero by 2040, SBTi aligned
- Reduced emissions by 52% (Scope 1, 2 & 3) vs. 2015

- 100% **renewable energy** in 5 markets, 89% overall
- 5M reused equipment from operations, offices, and customers

### 2.2.6 Verizon

Verizon's ESG and energy efficiency commitments [6]

- **Scope 2 strategy**
- **Energy efficiency management** è Powering down radios when they are not in active use, Auditing sites to understand where improvements are needed to meet our high standards of energy efficiency, etc.
- **AI innovation** è algorithm to enable solar panel battery storage systems to discharge energy during peak periods when energy prices are highest, model to identify cell sites with anomalous energy consumption,
- **Transition to renewable energy**

### 2.2.7 Summary

Key highlights from the sample CSP's ESG reports are

- Energy Efficiency a key relevant metrics apart from data volume & revenue
- Renewable energy technology to enhance energy efficiency
- Energy efficiency beyond ESG reporting e.g. improvements, anomalous energy consumption
- Energy efficiency for B2C, B2B consumers w.r.t. plethora of network services, in terms of maximizing handprint for enterprise consumers

## 2.3 Analysis by Industry Fora<sup>2</sup>

### 2.3.1 Omdia Energy Efficiency Insights

A short summary of the findings from Omdia reports [7], [8] is:

- The industry is not on track to meet carbon intensity goals: ITU target for ICT industry for carbon intensity (scopes 1 and 2) of 281g CO<sub>2</sub>e per kWh in 2025, 160g in 2030, and zero by 2050
- Energy consumption has gone up for most operators
- Energy primarily comes from electricity
- Electricity is increasingly coming from renewable sources
- While most CSPs cut operational emissions, some saw significant rises
- Scope 3 emission reporting is inconsistent
- Energy efficiency has become mobile operators' top priority for 5G evolution
- A holistic approach should be taken to improve RAN energy efficiency, from component-level enhancement and equipment-level design to network-level optimization.
  - Improving RAN energy efficiency is crucial for CSPs' energy-saving journey. However, the balance between network energy saving and user experiences should be carefully navigated to ensure network energy saving measures do not affect the competitiveness of network performance

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<sup>2</sup> The following subsections have a high-level, general summary of Omdia reports and GSMA. Further details can be obtained by the reader from Omdia directly or GSMA. Access to some reports may require paid subscription.

- Network energy efficiency will become a key performance indicator (KPI) of network operations and solutions.

The key highlights are:

- Energy usage per petabyte of traffic carried as a measure of energy intensity vs energy consumed per customer served is a more relevant metric for CSP
- Scope 3 emissions mostly relate to purchased goods and services and the use of telecom services by end customers: not reported/varies across if reported / consumers benefits need to be considered.
- The measurement, metering, and benchmarking of network energy consumption and relevant standardization are expected to be an essential part of the next steps to improve energy efficiency and move toward a carbon neutral network

### 2.3.2 GSMA EE Benchmarking

As per GSMA's analysis [9], [10] from 16 operator groups, 95 networks in 73 countries, 1.7 billion connections globally which constitutes 21% of total cellular connections, the goal of the Energy Efficiency Analysis and Benchmarking project is to help operators measure the relative efficiency of their networks.

Four KPIs combined can provide a comprehensive evaluation of network-level energy efficiency:

- Data traffic per unit of energy consumption
- Number of connections per unit of energy consumption
- Number of cell sites per unit of energy consumption
- Revenue per unit of energy consumption.

The visibility of energy-related data is surprisingly low and requires real-time data gathering, standardized metrics, full visibility and efficient data pipelines are essential to further increase energy efficiency

The following energy-related decisions are required:

- Which equipment should enter sleep mode and which depth of sleep mode?
- Where should the next solar panel be deployed?
- Which region should be prioritized for the next deployment?
- Which sites are overperforming or underperforming and why?
- When should an operators refill the diesel tank and run maintenance?

GSMA has developed the Green Network Index (GNI), which proposes a single figure that attempts to summarize overall environmental sustainability for networks and outline an evolutionary path to achieve the following:

- Tracking progress Energy efficiency, renewables, vertical enablement, costs and enablement solution revenue
- dynamic adjustment capabilities in place for network operations.
- Identifying and addressing shortfalls and gaps
- network strategy and investment decisions targeting sustainability improvements.
- Renewable energy & circularity

## 3 Energy Efficiency Challenges

### 3.1 Introduction

The challenge of energy efficiency (EE) in 6G networks is one of the most critical design constraints, with the goal being a 100-fold increase in energy efficiency (bits/J) compared to 5G. The key challenges are not just improving existing 5G technologies but overcoming the power demands introduced by the new 6G enablers and requirements. The following issues outline the energy efficiency challenges of sixth generation (6G) networks.

### 3.2 The Energy Impact of 6G Technologies

The architectural and technological advancements in 6G necessitate a significant rise in power consumption.

6G Technology	Energy Challenge
<b>Terahertz (THz) &amp; mmWave</b>	High frequency bands (above 100 GHz) suffer from severe path loss and atmospheric absorption. This necessitates extremely large antenna arrays and high-power radio frequency (RF) front-ends/Power Amplifiers (PAs) to compensate, leading to high power consumption at the Base Station (BS).
<b>Ultra-Massive MIMO (UM-MIMO)</b>	Requires complex signal processing and control circuitry for a massive number of antenna elements. Even during low traffic loads, digital signal processing (DSP) and analog components significant power is consumed.
<b>Integrated Sensing &amp; Communication (ISAC)</b>	Simultaneous operations of communication and high-resolution sensing (e.g. radar) functionality require continuous, high-power signal transmission and processing for both functions, increasing overall energy usage.
<b>Network Densification</b>	The transition to ultra-dense networks (UDNs) with more small cells and pico-cells means that the cumulative idle power consumption of a vastly increased number of network components becomes the dominant energy draw, even if individual cells are small.

### 3.3 The AI/ML and Computing Overheads

The vision for 6G is a "smart" network natively integrated with Artificial Intelligence (AI), which presents its own paradox.

- **AI Training and Inference Energy:** Training and running complex Artificial intelligence (AI)/Machine Learning (ML) models in real-time across the network (AI-RAN) demands immense computational resources. Computational energy used for AI processing (data collection, model training, and real-time inference) can nullify the energy savings made by AI-driven optimizations.
- **Edge Computing Power:** Holographic communication and digital twins require ultra-low latency pushes computing from the core to the mobile edge, requiring significant local power and cooling making it decentralized and inefficient data centres.

### 3.4 Idle-State Consumption and Signalling Overheads

The energy efficiency of mobile networks is often determined by power consumption during low-traffic periods, which is where the current system is least efficient.

- **"Always-On" Signalling:** In previous generations, network devices (BSs and User Equipment - UEs) are prevented from entering deep sleep states because they must continuously monitor for essential "always-on" signals (like the Synchronization Signal Block - SSB) for network access and cell selection.
- **Limited Sleep Depth:** The necessary requirements for synchronization and immediate access severely limit the duration and depth of power-saving sleep modes for both the BS and the UE, making the "idle power" of the network too high.

### 3.5 Trade-off Complexity and Holistic Optimization

To achieve high energy efficiency is a non-trivial optimization problem that must be manageable system wide.

- **Trade-off between EE & Latency/Throughput:** To pursue aggressive power saving (e.g. deeper sleep) compromise on performance metrics like ultra-low latency and ultra-high throughput thereby increasing latency when a device needs to wake up and connect.
- **System-Wide Optimization:** A holistic, end-to-end EE framework is required as energy is consumed across the entire network (RAN, Core, Transport, and Devices). Optimizing one part (e.g. antenna) might increase overhead in another (e.g. fronthaul), making the energy optimization less effective.
- **Lack of Unified Metrics:** Challenge exists in establishing a standardized, measurable Key Value Indicators which reliably track both energy consumption and sustainability impact of 6G network.

## 3.6 Energy-related issues in Macro and Small Cell deployments

### 3.6.1 Introduction

Energy-related issues in macro and small cell deployments are a significant concern, impacting both operational costs and environmental sustainability.

### 3.6.2 Key Challenges

#### 3.6.2.1 High Energy Consumption

In Macrocells, these high-powered base stations consume substantial electricity, contributing significantly to the overall energy footprint of cellular networks.

In the Small Cells, while individually less power-hungry than macrocells, their dense deployment can lead to a collective energy consumption that is significant.

#### 3.6.2.2 Power Supply and Infrastructure

Use of Reliable Power Sources ensures continuous and reliable power supply for both macro and small cells. Power outages or fluctuations can disrupt service and damage equipment.

High-power electronics generate significant heat, requiring effective cooling solutions to prevent equipment failure. This often involves energy-intensive cooling systems, such as fans and air conditioners.

The cost of Deploying and maintaining power infrastructure, including power lines, transformers, and cooling systems, can be expensive and complex, especially in remote or challenging locations.

#### 3.6.2.3 Energy Efficiency Limitations

**Hardware Constraints:** Existing hardware components in many macro and small cells may have inherent limitations in terms of energy efficiency.

**Protocol Inefficiencies:** Certain aspects of existing communication protocols may not be optimized for energy efficiency, leading to unnecessary power consumption.

**Carbon Footprint:** The high energy consumption of cellular networks contributes significantly to greenhouse gas emissions, exacerbating climate change.

#### 3.6.2.4 Limited Grid Capacity

Existing power grids may not be able to handle the additional load, leading to potential infrastructure upgrades.

### 3.6.3 Energy-related issues in Small Cells

Small cells, while offering significant benefits in terms of coverage and capacity, present unique energy-related challenges like below:

- **Limited Battery Life (for battery-powered small cells):** Frequent transmissions and high-performance demands can quickly drain battery power, requiring frequent recharging or battery replacements.
- **Environmental factors:** Extreme temperatures, humidity, and other environmental conditions can accelerate battery degradation.
- **Power Supply and Infrastructure, Power availability:** Ensuring reliable power supply for small cells deployed in various locations (e.g., streetlights, buildings) can be challenging.
- **Infrastructure costs:** Installing and maintaining power lines and other infrastructure for each small cell can be expensive and time-consuming.
- **Power theft and vandalism:** Small cells are susceptible to power theft and vandalism, which can disrupt service and increase operational costs.
- **Cooling Requirements:** Compact size and limited ventilation can lead to overheating issues, requiring efficient cooling solutions. Cooling systems themselves consume power, adding to the overall energy consumption.
- **Frequent Maintenance:**
  - **Battery replacements:** Frequent battery replacements due to limited battery life increase maintenance costs and downtime.
  - **Power supply checks:** Regular inspections and maintenance of power supplies and connections are necessary to ensure reliable operation.
  - **Cooling system maintenance:** Regular cleaning and maintenance of cooling systems are essential to maintain optimal performance and prevent equipment failures.
  - **Protocol inefficiencies:** Certain aspects of existing communication protocols may not be optimized for energy efficiency in small cell deployments.

## 4 Energy Efficiency Goals and Approaches in 6G Networks

### 4.1 Introduction

Energy efficiency<sup>3</sup> will be an important metric for the next generation of networks, at least as important as the traditional performance metrics such as throughput, latency, reliability and scalability [11]. While 5G improved over 4G substantially in terms of the bits/joule metric at peak load, it is highly inefficient during lightly loaded conditions. An important requirement for the 6G design should be to ensure that energy consumption scales down gracefully with traffic, approaching zero energy at zero traffic. With more than a 10- to 20-fold capacity increase expected at peak loads, 6G should leverage various technology advances to reduce overall average energy consumption by 50% and to improve the bits/joule metric by five to ten times at peak load, as compared to 5G.

It is envisioned that 6G would have a broad range of potential solutions for minimizing energy consumption that will have a significant impact at different load levels and on different components of the end-to-end system.

To achieve dramatic reductions in energy consumption while achieving higher capacities when required, the industry should consider the following new approaches in its next-generation standards:

- Adaptive waveforms to reduce PAPR while avoiding complex digital pre-distortion
- Frequency domain shaping or coding techniques to reduce PAPR by exploiting unused bandwidth and considering database-driven dynamic emission masks for exploiting more spectrum
- Facilitate mMIMO muting by ensuring coverage solutions for different array sizes
- Mesh fronthaul to ensure resilience and increase pooling gains for centralized functions
- Capability to power down RAN acceleration in the cloud during reduced RAN workloads
- Exposure of energy use statistics to consumer apps to promote energy awareness.

### 4.2 6G Sustainability by Design

#### 4.2.1 Introduction

Sustainability is commonly described in three dimensions: environmental, social, and economic. Environmental sustainability carries the greatest importance as it encompasses all ‘natural capital’, meaning all living forms. Rising energy costs, climate change, and evolving ESG regulations aimed at achieving net zero and aligning with the 1.5°C trajectory of the Paris Climate Agreement [13] are presenting key strategic priorities for Communication Service Providers (CSPs), driving the need for innovation and transformation. At the same time, infrastructure resilience is under strain as climate change and socio-economic volatility threaten energy supplies and network stability.

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<sup>3</sup> The following subsections may contain information in reasonably short snippets that paraphrase or quote the publicly available reports, referenced in the same subsections.

Technology is central to this transition. By enabling decarbonization, decoupling energy demand from growth in data traffic and building resilience, it can help industries chart a sustainable path forward. 6G, designed from the ground up with sustainability in mind, has the potential to be a key enabler, supporting net zero and circular pathways across its entire lifecycle, from design and production to deployment, use, and end-of-life (EOL).

Sustainability by design (SbD) [14], [13] offers a way to weave key sustainability considerations directly into the design process of any system and its surrounding context. A system that embeds guiding principles and enabling features from the outset is far more likely to perform effectively and resiliently than one that relies on aftermarket add-ons to mimic those capabilities later.

At its core, the SbD framework builds on the concept of future-back design. It begins by systematically recognizing the characteristics of the future context and destination (e.g., the 2030s will be different from the 2010s or 2020s), and then defining the guiding principles needed today to ensure that designs can meet the challenges of tomorrow.

### 4.2.2 Design Principles

Five SbD principles are envisioned that embed environmental, social, and economic responsibility directly into the design and architecture of 6G networks, devices, and data centers, ensuring that sustainability is addressed across the entire lifecycle.

These principles are:



Figure 1: Design principles for 6G sustainability

#### a. Energy efficiency and GHG reduction

At the core of these principles is energy efficiency and GHG reduction, aiming to lower energy consumption in both networks and user equipment (UE) while minimizing greenhouse gas emissions. This principle is especially critical for meeting net-zero targets in the coming decades. With many ICT industry stakeholders committing to achieve net zero by 2040 at the latest, 6G deployment in the 2030s must actively contribute to this goal.

#### b. AI sustainability

While AI will be part of 6G deployments, it is imperative that the environmental impacts of AI (e.g. energy, resource and water usage) are responsibly balanced with the sustainability and efficiency gains from AI's usage. This principle also includes the trustworthiness and compliance readiness of AI processes, resources and datasets.

**c. Hardware efficiency**

Approximately 80% of material impact and cost originate from design requirements. This third principle - hardware (material resource) efficiency - promotes modularity, scalability and resource sharing. To reduce material waste and sustain a longer system lifetime, this principle also emphasizes higher utilization, for example through shared hardware and common resources such as compute capacity.

**d. Resilience and climate change adaption**

Networks must be resilient to prolonged extreme weather events, such as heatwaves, flooding, storm-force winds, and wildfires, which can cause power fluctuations and outages. In addition to these increasingly frequent environmental impacts, volatile social, economic, and political conditions make adaptability essential for maintaining reliable communications infrastructure in an unpredictable world.

**e. Value-oriented design and operations**

The 6G technology design must be centred around value-driven user requirements and inclusive access, focusing on use cases that deliver benefits for industries, individuals, and the planet while advancing digital literacy and social equity. This vision includes 6G connectivity as a driver of industrial decarbonization through automation, as well as remote access solutions that enhance health and safety.

All these five principles need to be addressed to ensure that 6G embeds sustainability into its design.

### 4.2.3 Design Vectors for Telecom Networks

From the telecom networks perspective, the following design vectors aim to minimize energy waste and improve overall energy efficiency. Besides sourcing energy from renewables, these are the strategic areas, opportunities and considerations as part of overall design for reducing the carbon footprint of a telecom network.

- a. **Radio Access Network:** RAN contributes majorly to energy consumption in wireless networks, with radio units consuming a significant portion of the overall power. Focus on improving energy efficiency at low loads, such as enhancing Power Amplifier (PA) efficiency and reducing digital power consumption. Discontinuous transmission (DTX) and deep-sleep modes offer energy-saving opportunities. Optimize air interface waveform design to reduce energy consumption, such as using single carrier waveforms or adapting guard sub-carriers in OFDM. Spectrum sensing can help reduce out-of-band interference and improve PA efficiency.
- b. **Mobile Cloud Architecture and Data Centers:** Cloudification and centralization of mobile RAN and core functions reduce compute resource usage

via pooling, while edge cloud networking supports low latency and high-capacity services. Dynamic relocation of network and application functions between edge and centralized data centers can optimize energy consumption. Specialized hardware like System on Chip (SOC) and Application Specific Integrated Circuits (ASICs) can reduce power consumption significantly. Implement energy-efficient hardware, enable pooling and sharing of accelerators, and use smart algorithms to dynamically manage compute resources based on load and application requirements.

- c. **Transport Networks, Protocol and Technologies:** Transport networks must handle increasing traffic due to network densification and disaggregation, making energy efficiency per bit a critical KPI. Optimize transport protocols and technologies to reduce packet bloating and energy consumption. Benchmarking protocols for energy efficiency is essential. Simplify network architecture to reduce processing hops, converge RAN and core functions, and leverage network slicing for energy-efficient configurations. Use digital twins to simulate and optimize network designs.
- d. **Optical Networking Technology:** Optical networks are more energy-efficient than electronics-based transport, minimizing energy use in data transmission and electro-optical transitions. Maximize optical-layer transmission, reduce Optical-Electrical-Optical (OEO) conversions, and adopt Silicon Photonics (SiPho) for improved efficiency and cost reduction. Use SiPho to integrate optical subsystems, enhance power efficiency, and optimize data center and network designs for energy savings.
- e. **Network Architecture:** End-to-end architecture must balance energy efficiency with service demands, considering radio, core, transport, and protocols. Use network slicing to tailor configurations for energy efficiency and support diverse services. Digital twins can validate energy efficiency KPIs without costly physical deployments. Reduce network complexity by minimizing processing hops and enabling smart selection of network functions. Convergence of RAN and core functions can improve energy efficiency.
- f. **AI Systems:** AI is central to building smarter networks, enabling energy-efficient operations, resource allocation, and service assurance. Use AI to analyze traffic patterns, predict user mobility, and optimize network configurations for energy savings. Apply AI for radio densification and turning off small cells. Ensure responsible AI design with fairness, inclusiveness, transparency, and privacy. Use energy-efficient AI technologies like Analog Compute-in-Memory (CIM) to reduce power consumption during data read-write operations.

## 4.3 Energy optimization for Macro and Small Cell deployments

### 4.3.1 Measuring Power Efficiency

#### 4.3.1.1 Introduction

When energy consumption is measurable, it can be made more efficient. Therefore, the current focus of 3GPP is on measuring energy efficiency and consumption. The following subsection lists some of the 5G specifications of 3GPP and summarizes their main RAN KPIs for measuring consumption.

#### 4.3.1.2 3GPP 5G Energy Efficiency

##### 4.3.1.2.1 3GPP 5G RAN specific Energy Efficiency KPIs

The following table summarizes the evolution of the RAN specific Energy Efficiency KPIs in 5G:

Sl no.	Release	Energy Efficiency KPI updates in 3GPP TS 28.554
1	Release 15	Energy Efficiency KPIs were not defined in TS 28.554 Release 15.
2	Release 16.7	Energy Efficiency (EE) KPIs were first introduced in TS 28.554, specifically in section 6.7. No. of KPIs added from previous release = 3
3	Release 17.7	Energy Efficiency KPIs continued to be defined and refined within TS 28.554. (Specific detailed additions or changes beyond Release 16 are present in the full specification for Release 17.) No. of KPIs added from previous release = 26
4	Release 18.7 and 19.3	Energy Efficiency KPIs continued to be defined and refined within TS 28.554. (Specific detailed additions or changes beyond Release 17 are present in the full specification for Release 18.) No. of KPIs added from previous release = 9
5	Release 19.4 and beyond	Release 19 (including 19.3 and later 19.4.0) introduced several significant updates and additions to Energy Efficiency KPIs. These updates are documented through various Change Requests (CRs) and include:-  CR 0232: Addition of a multi-dimensional energy efficiency use case. CR 0233: Addition of EE KPIs evaluated from the network availability performance dimension. CR 0234: Addition of EE KPIs evaluated from the network quality performance dimension. CR 0235: Addition of measurements for carbon emission-related KPIs for gNB.  Some other proposed updates, such as those related to NF energy consumption and energy efficiency per node type for Network Slice, were not pursued.

Recently, 3GPP has initiated the below study items towards the 6G and EE specifications:

1. **TR 38.864:** Reuse and update reference configurations and power model for evaluating for 6G BS power consumption.
2. Metric(s) for UE and BS energy efficiency.
3. **TR 38.840(UEPS), 865(eRedCap), 869(LP-WUS/WUR), and 875(RedCap):** Reference configurations and power consumption model for 6G UE but not restricted to.
4. Baseline BS setting(s) for evaluating 6G BS and UE, EE improvement/impact, considering NR features and 6G BS and UE reference configuration(s)

#### 4.3.1.2.2 Energy Efficiency Aspects in 3GPP 5G NR system

There are several 3GPP 5G NR specifications that address considerations for energy efficiency.

The 5G NR system architecture addresses energy savings by enabling mechanisms that reduce power consumption at both the network and user equipment (UE) levels without compromising performance. From an architectural perspective, it supports energy efficiency through features like **Discontinuous Reception (DRX)** and **Discontinuous Transmission (DTX)**, allowing UEs and gNodeBs to enter low-power states during inactivity. The specification also introduces **flexible functional split** between Central Units (CUs) and Distributed Units (DUs), enabling centralized control of power-saving strategies and dynamic resource management. Additionally, support for **carrier and cell activation/deactivation**, **beam management optimization**, and **dual connectivity** allows for selective use of radio resources, reducing unnecessary energy expenditure. While TS 38.300 does not define energy-saving algorithms in detail, it establishes the framework and signaling support necessary for implementing energy-efficient operations across the NG-RAN.

Some of the 3GPP specifications addressing energy efficiency as describe above are: 3GPP TS 38.300, 3GPP TS 38.214, 3GPP TS 38.321, 3GPP TS 38.331.

#### 4.3.2 Energy-Efficient Hardware

Developing new energy-efficient base station hardware and components can significantly reduce overall energy consumption. But the available technology seems to have been saturated with all possible mechanisms to make the most efficient Hardware, and only marginal improvements can be foreseen with advancement in the chipsets and AI based software. However, in the long term, some OEMs are aiming to achieve a more “linear” power consumption characteristic as a function of radiated power by reducing the base power consumption when there is no signal.

#### 4.3.3 Improving Energy Efficiency via Software

For Efficiency improvement in the software, below are the options to explore using AI.

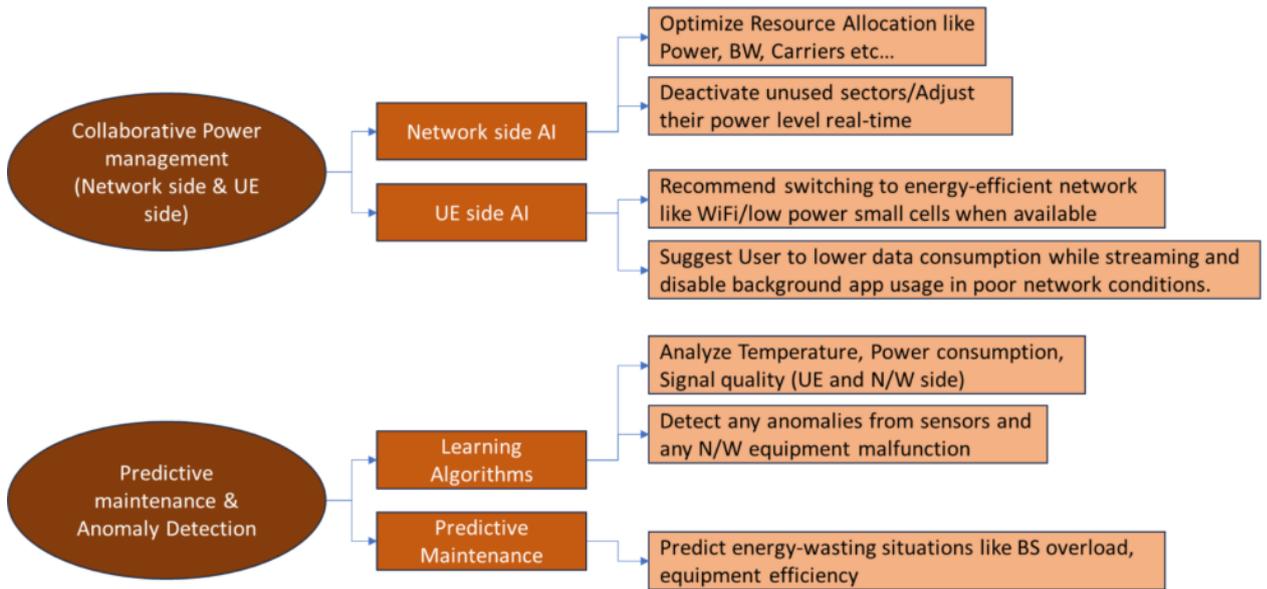


Figure 2 : Collaborative Power Management

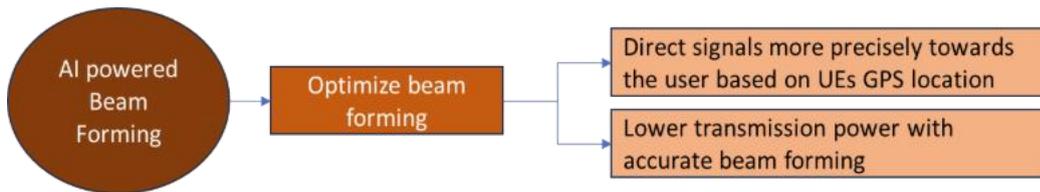


Figure 3: Collaborative Power Management

### 4.3.4 Collaborative Power Management

#### 4.3.4.1 Introduction

In 5G, 6G and beyond, the aim is to optimize energy consumption across the entire network ecosystem, encompassing both the network infrastructure and user equipment (UE).

#### 4.3.4.2 Network-Side Optimization

- Resource Allocation: Dynamically allocating resources (bandwidth, power) to UEs based on their traffic demands and energy requirements.
- Employing techniques like power control, beamforming, and interference management to minimize power consumption while maintaining quality of service.
- Power Optimization: Implementing energy-efficient hardware components (e.g., power amplifiers, baseband processors).
- Implementing sleep modes and dynamic power management techniques in base stations and other network elements.

#### 4.3.4.3 UE-Side Optimization

- Power Saving Modes: Implementing various power saving modes (e.g., sleep mode, idle mode) to minimize power consumption when the UE is not actively transmitting or receiving data.

- **Transmission Techniques:** Employing energy-efficient transmission techniques, such as adaptive modulation and coding, to optimize data rate and power consumption.
- **Application-Level Optimization:** Optimizing application behavior to reduce power consumption, such as background data synchronization and data compression.
- **Battery Management:** Implementing intelligent battery management algorithms to optimize battery usage and prolong battery life

Effective collaborative power management requires close collaboration between the network and the UE. Leveraging context information (e.g., user location, traffic conditions, application requirements) to make informed decisions about power management.

AI/ML: Utilizing AI/ML techniques to predict traffic patterns, optimize resource allocation, and dynamically adapt power management strategies.

By effectively implementing these collaborative power management techniques, 6G and future wireless networks can significantly reduce energy consumption, enhance sustainability, and prolong battery life for mobile devices.

### 4.3.5 Techniques for energy optimization for Small Cell Deployments

Techniques for addressing power-related issues in small cell deployments

- **Energy-efficient hardware:** Utilizing more energy-efficient components, such as power amplifiers and processors.
- **Renewable energy integration:** Exploring the use of renewable energy sources, such as solar and wind power, to power small cells.
- **Intelligent power management:** Implementing intelligent power management techniques, such as sleep modes and dynamic power adjustment.
- **Improved battery technology:** Developing and deploying longer lasting and more efficient batteries.
- **Robust power infrastructure:** Investing in reliable and secure power infrastructure for small cell deployments.

### 4.3.6 Predictive Maintenance and Anomaly Detection

#### 4.3.6.1 Introduction

Predictive maintenance leverages data and analytics to anticipate equipment failures before they occur. By proactively addressing potential issues, it minimizes downtime, reduces maintenance costs, and improves overall equipment efficiency.

Anomaly detection involves identifying unusual patterns or outliers in data that deviate from expected behavior. In the context of predictive maintenance, anomaly detection helps pinpoint abnormal equipment behavior that may signal impending failures.

#### 4.3.6.2 Learning Algorithms

Several machine learning algorithms are employed in predictive maintenance and anomaly detection:

- Supervised Learning:
  - Predicts continuous values, such as the remaining useful life of a component and Classifies data into categories, such as "normal" or "faulty."
- Unsupervised Learning:
  - Groups similar data points together, identifying patterns and anomalies.
  - Use auto encoders to learn to reconstruct input data, with anomalies being poorly reconstructed.

#### 4.3.6.3 Predictive Maintenance with Hardware Sensors

Hardware sensors play a crucial role in collecting real-time data from equipment:

- Vibration Sensors: Monitor vibrations to detect imbalances, misalignments, and bearing wear.
- Temperature Sensors: Measure temperature to identify overheating, which can indicate potential failures.
- Acoustic Emission Sensors: Detect high-frequency acoustic emissions that can signal cracks, friction, or other anomalies.
- Pressure Sensors: Monitor pressure levels to detect leaks, blockages, or other issues.

#### 4.3.6.4 Predicting Energy Wastage and Overload

- **Energy Consumption Monitoring:** Sensors monitor energy consumption patterns over time.
- **Anomaly Detection:** Algorithms identify unusual spikes in energy consumption that may indicate inefficiencies, equipment malfunctions, or overloading.
- **Predictive Modelling:** Models predict future energy consumption based on historical data and operational patterns. This helps identify potential overload situations and optimize energy usage.

#### 4.3.6.5 Benefits of Predictive Maintenance

- **Reduced Downtime:** Minimize unplanned equipment failures, leading to increased production uptime.
- **Lower Maintenance Costs:** Proactive maintenance is more cost-effective than reactive repairs.
- **Improved Safety:** Identify and address potential safety hazards before they occur.
- **Increased Equipment Lifespan:** Prolong the life of equipment through timely maintenance and repairs.
- **Enhanced Efficiency:** Optimize equipment performance and reduce energy consumption.

By leveraging advanced analytics & sensor technologies, predictive maintenance can help optimize equipment performance, minimize downtime, & improve operational efficiency.

## 5 Sustainable 6G value chain in Indian ecosystem

### 5.1 Introduction

To build a truly commercial grade RAN and Core Telecom product, a solid and collaborative ecosystem is essential. No single company can carry the full spectrum of competencies required to create 6G solutions.

Moving into the 6G era, openness is no longer optional — it is mandatory. 6G should be built as a highly modular, plug-and-play system where each component (e.g. CU, DU, PHY, RIC, Core, AI/ML functions) can interoperate seamlessly. This provides a strategic opportunity to develop a sustainable 6G value chain in Indian ecosystem.

To establish India as a frontrunner in 6G, it is required to develop a complete and collaborative ecosystem, spanning hardware, software, radios, devices, and AI-native modules. India can take the lead in building a “6G Made in India” ecosystem, bringing together:

- Radio and hardware platform vendors
- PHY software and protocol stack developers
- AI-native RAN software providers
- RIC/xApp/rApp ecosystem players
- 6G Core developers
- UE/device innovators

### 5.2 Core Ecosystem Pillars

Below are some considerations for the core ecosystem pillars that India must invest in order to create a sustainable product value chain for 6G and beyond:

#### a. COTS Hardware Ecosystem for Macro 6G Solutions

**Objective:** High-performance COTS servers and accelerator platforms capable of handling multi-terabit throughput and ultra-large MIMO antenna arrays.

**Requirements:**

- High-capacity CPUs and GPUs, optimized for 6G workloads (AI-native RAN, ISAC, THz PHY).
- Advanced interconnect accelerator NIC card.
- Ruggedized, carrier-grade servers for Indian telecom operators.

**Outcome:** Availability of telecom-grade compute via enabling HPC/COTS industry in India.

#### b. NPU/SoC Ecosystem for Integrated 6G Small Cells & Edge Units

**Objective:** Next-Gen SoC/NPU platform to port NG-CU/NG-DU integrated small cells, enabling compact, power-efficient 6G Indoor solutions.

**Requirements:**

- SoC which can handle acceleration on-chip for real-time scheduling, beamforming, and semantic comms for NG-CU/NG-DU Software stack to support sub-THz and mmWave PHY layers.

- Low-power, edge-optimized designs for dense small-cell deployments.

**Outcome:** Position India as a global silicon hub for small cell 6G SoCs.

**c. PHY Software & Hardware/Acceleration Ecosystem**

**Objective:** PHY software IP and acceleration SoCs, as PHY is critical part of 6G performance.

**Requirements:**

- Accelerator-based SoCs (FPGA, ASIC, RISC-V + AI cores) to handle channel coding, massive MIMO precoding, ISAC processing.
- AI-driven PHY functions (learned decoders, channel estimation with ML).
- Support for sub-THz, mmWave, and new 6G waveforms.
- Reconfigurable Intelligent Surfaces (RIS) for beam steering and coverage extension.
- Radios capable of ISAC (communication + radar sensing).
- Low-cost, power-efficient designs for rural and dense-urban deployment.

**Outcome:** India develops a strong 6G front-end market with investments in PHY IP + accelerator silicon which can serve the local and global markets. Continue to build on India's success in 5G O-RAN RRUs (e.g., VVDN) to become a global 6G Radio manufacturing hub.

**d. Protocol Stack & Core Software Ecosystem**

**Objective:** Commercial-grade NG-CU, NG-DU, and NG-Core protocol stacks as per 3GPP compliance.

**Requirements:**

- 3GPP-compliant NG-CU/NG-DU protocol stack (PDCP, RLC, MAC, scheduler).
- Next-gen 6G Core functions (service-based architecture, UDSF, AI-native slicing).
- New software modules unique to 6G:
  - SMO (Service Management & Orchestration)
  - RIC (Near-RT & Non-RT)
  - ISAC Function (Integrated Sensing + Comms)
  - Semantic Communication Modules
  - Energy-aware & Green-Networking Functions
  - Compute Offload Manager (edge-cloud integration).

**Outcome:** Position India ecosystem as a key development hub of RAN & Core software products which can serve the local and global markets.

**e. 6G UE & Device Ecosystem**

**Objective:** 6G UE (mobile device, IoT, modules) ecosystem for early PoC, testing, and commercial deployment.

**Requirements:**

- 6G baseband SoC and protocol stack development (today, no such ecosystem exists).
- Support for AI-native features, XR devices, digital twins, and semantic communications.
- Early prototypes of 6G smartphones, IoT modules, and industrial UEs.

**Outcome:** India develops cost-effective devices and end-user equipment, completing the end-to-end 6G chain.

If India invests in building these ecosystem pillars - COTS hardware, NPU/SoC, PHY IP, Protocol/Core stacks, Radios, and Devices, it will help India to develop capabilities to drive a sustainability aspects into all components of the 6G value chain.

## 6 Conclusion

Energy efficiency is a paramount concern in the deployment of 6G networks. By adopting innovative techniques and technologies, it is possible to mitigate the energy consumption challenges associated with 6G and ensure a sustainable future for wireless communications. Sustainability is therefore becoming a central focus in the design of future networks, with energy efficiency emerging as a critical KPI alongside traditional metrics such as throughput and latency. A comprehensive approach, informed by insights from existing network deployments—highlights the benefits of optimizing different aspects of networks for improved efficiency.

Coverage requirements, traffic behavior, and user mobility patterns reveal numerous opportunities for power reduction through strategic radio network densification. Transport networks—especially optical infrastructure—are essential for building scalable, sustainable network architectures. Hardware (particularly PHY/RF) and software design consideration (e.g. radio) need to be carefully evaluated and benchmarked for not only performance but also energy efficiency aspects. System design aspects (e.g. waveform) must also adapt to dynamic factors like traffic variability and adjacent spectrum usage, balancing conventional goals like capacity and interference management with energy-saving considerations.

Beyond energy efficiency, sustainability also encompasses principles of fairness, transparency, and inclusivity. As AI becomes deeply integrated into network systems, it is vital to uphold these values throughout the entire lifecycle of AI—from design and development to deployment and operation.

Continued research and development are essential to unlock the full potential of energy-efficient and sustainable 6G networks.

## 7 Appendix: Global Sustainability Research Initiatives

### 7.1 Overview

Sustainability is one of the key pillars of 6G. The below figure shows the various standardization or industrial forums across the globe that are working to build a sustainable 6G. Below sections explore sustainability activities of some of these standardization or industrial forums.



Figure 4 : Global efforts on sustainable 6G

### 7.2 ITU-T and ETSI

The recommendation and standard ITU-T L.1331<sup>4</sup> were developed jointly by ETSI TC EE and ITU-T Study Group 5 and published by ITU and ETSI as Recommendation ITU-T L.1331 and ETSI Standard ETSI ES 203 228<sup>5</sup> respectively, which are technically equivalent. ETSI also has collaboration with 3GPP SA5 & RAN3 and is supported by GSMA with valuable suggestions & contributions.

- The scope of these standards is to provide a better understanding of the energy efficiency of mobile networks in particular networks' evolution in different periods of time. The focus of this Recommendation is on metrics for energy efficiency and methods of assessing (and measuring) energy efficiency in operational networks.
- As the world steps into 6G, beyond the mobile network has newer services & newer services characteristics, capabilities and different deployment options to suit the needs of the consumers. This brings a need to enhancement the assessment of mobile network energy efficiency. ITU-T and ETSI are undertaking revisions of their work.
- Investigate the definition of new EE KPIs which consider aspects such as e.g. coverage area, user experience, reliability of URLLC network slice based on the

<sup>4</sup> L.1331 - Assessment of mobile network energy efficiency, <https://www.itu.int/rec/T-REC-L.1331>

<sup>5</sup> ETSI ES 203 228, Environmental Engineering (EE); Assessment of mobile network energy efficiency, [https://www.etsi.org/deliver/etsi\\_es/203200\\_203299/203228/01.04.01\\_60/es\\_203228v010401p.pdf](https://www.etsi.org/deliver/etsi_es/203200_203299/203228/01.04.01_60/es_203228v010401p.pdf)

Study TR L.Sup.MDEE "Study of Multi-dimensional network energy efficiency metrics". This study introduces the following EE considerations and concepts

- o Multi-dimensional EE considering three common performance dimensions:
  - ♣ Service volume e.g. data volume delivered, the area covered, the number of supported connections, etc.
  - ♣ Service quality, measuring the quality of the service provided e.g. user throughput, coverage or connection quality.
  - ♣ Service availability, typically measure the availability of the service.
- o Different 5G, 6G use case families (e.g. eMBB, mMTC or uRLLC) will not necessarily use the same KPIs on the above three performance dimensions.
- o EE KPIs for Cloud computing for Core network consumption

### 7.3 ATIS NextG Alliance Green G WG

With the focus on minimizing the environmental impact of future generations of wireless technology the ATIS NGA Green G working group addresses the below key areas of sustainability:

- Drive environmental sustainability in 6G systems through collaboration across the Information and Communications Technology (ICT) sector and other industries
- Aggregate information from across the ICT sector and beyond to educate our industry, other industries, and consumers
- Enable other industries to be more sustainable by using wireless technology

Key highlights from the report on Evolution of Sustainability Indicators for Next-Generation Radio Network Technologies<sup>6</sup>:

- Evolution of Sustainability Indicators for Next Generation Radio Network Technologies is based on Observability, Choice, and Circular Economy.
  - o Observability: Track and report environmental indicators.
  - o Choice: Empower users to choose sustainable 6G services.
  - o Circular Economy (9Rs): refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover.
- Circular Economy Processes and Product Circularity Assessment based on UN environment program life cycle.

Key highlights from the report on Evolution of Sustainability Indicators for Data Centers and Next Generation Core Networks<sup>7</sup>

- Data centers and core networks are responsible for approximately 19% of total energy consumption in mobile networks

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<sup>6</sup> Evolution of Sustainability Indicators for Next-Generation Radio Network Technologies, [https://nextgalliance.org/white\\_papers/evolution-of-sustainability-indicators-for-next-generation-radio-network-technologies/](https://nextgalliance.org/white_papers/evolution-of-sustainability-indicators-for-next-generation-radio-network-technologies/)

<sup>7</sup> Evolution of Sustainability Indicators for Data Centers and Next Generation Core Networks, [https://nextgalliance.org/white\\_papers/evolution-of-sustainability-indicators-for-data-centers-and-next-generation-core-networks/](https://nextgalliance.org/white_papers/evolution-of-sustainability-indicators-for-data-centers-and-next-generation-core-networks/)

- Sustainable operations in data centers are crucial for achieving Net Zero emissions across the ICT sector
- The ICT industry's commitment to Net Zero by 2050 includes addressing Scope 1, 2, and 3 emissions
- The shift to cloud-based services in 5G and beyond increases the need for sustainable data center practices

Key highlights from the report on Sustainable AI in Telecom: Promises and Challenges in 6G<sup>8</sup>

- Evaluating the entire lifecycle of AI systems, from inception to retirement is important.
- Strategies to reduce embodied emissions in AI infrastructure, transition to renewable energy sources, and minimize the energy consumption of Machine Learning (ML) processes.
- Enhance energy efficiency across key areas, including Radio Access Networks (RAN), core networks, User Equipment (UE), and data centers by using AI.
- The Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) play an important role in assessing the effectiveness of these strategies.
- Integration of AI with quantum computing, Non-Terrestrial Networks (NTNs), and AI to enhance spectral efficiency and enable intent-based automation in networks.

ATIS NGA Green G WG also published reports on Green G: The Path Toward Sustainable 6G<sup>9</sup>, 6G Sustainability KPI Assessment Introduction and Gap Analysis<sup>10</sup>, Sustainable 6G Connectivity a Powerful Means of Doing Good<sup>11</sup>

## 7.4 SUSTAIN 6G

Sustain 6G<sup>12</sup> is a consortium with 24 partners from 10 European countries. Partners are from 7 telecommunications (operators and manufacturers), 4 large vertical industries, 5 academia (universities and research institutes), 8 SME (vertical and telecommunication sectors). Timeline is from 01.01.2025 – 30.06.2027 (2.5 years) with budget and effort total funding of 13 M€.

The key motivation is “Sustainable 6G ‘by design’ needs to look at the whole ecosystem holistically, end to end and full lifecycle”. Sustainability is much more than energy efficiency and Sustain 6G research focuses on the 6 pillars which are formed by the intersection of vertical dimensions - Economic, Societal and Environmental with horizontal aspects of Sustainable 6G and 6G for sustainability.

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<sup>8</sup> Sustainable AI in Telecom: Promises and Challenges in 6G, [https://nextgalliance.org/white\\_papers/sustainable-ai-in-telecompromises-and-challenges-in-6g/](https://nextgalliance.org/white_papers/sustainable-ai-in-telecompromises-and-challenges-in-6g/)

<sup>9</sup> Green G: The Path Toward Sustainable 6G, [https://nextgalliance.org/white\\_papers/green-g-the-path-towards-sustainable-6g/](https://nextgalliance.org/white_papers/green-g-the-path-towards-sustainable-6g/)

<sup>10</sup> 6G Sustainability KPI Assessment Introduction and Gap Analysis, [https://nextgalliance.org/white\\_papers/6g-sustainability-kpi-assessment-introduction-and-gap-analysis/](https://nextgalliance.org/white_papers/6g-sustainability-kpi-assessment-introduction-and-gap-analysis/)

<sup>11</sup> Sustainable 6G Connectivity A Powerful Means of Doing Good, [https://nextgalliance.org/white\\_papers/sustainable-6gconnectivity-a-powerful-means-ofdoing-good/](https://nextgalliance.org/white_papers/sustainable-6gconnectivity-a-powerful-means-ofdoing-good/)

<sup>12</sup> Sustain 6G, <https://sustain-6g.eu/>

Sustain 6G aims to

- Define sustainability framework considering common E2E goals and values, use cases, 6G values, metrics and Trade-offs
- Sustainable 6G technologies for RAN/Core/Optical, Energy savings, security, privacy, Sustainable AI, Network/service/data management
- 6G for sustainable applications Integration of 6G with vertical use cases (focused on healthcare, energy smart grid and agriculture)
- Sustainability assessment methodology and framework for evaluation of E2E sustainability impact (device to application).

The research activities are supported by proof of concept for implementation and integration for evaluation of E2E sustainability impact. The results of the research would be consolidated towards guidelines, strategic roadmaps and policies.

## 7.5 Progression towards 3GPP 6G

The following figure shows the brief history of KV<sup>i</sup> and KVI<sup>ii</sup> related research. It was initially introduced by Hexa-X<sup>13</sup>, further extensive research was taken forward by 6G-IA<sup>14</sup>, Hexa-X-II<sup>15</sup> and NEXT G Alliance<sup>16</sup> Advanced research and standardization works are ongoing in Sustain 6G and 3gpp standardization.

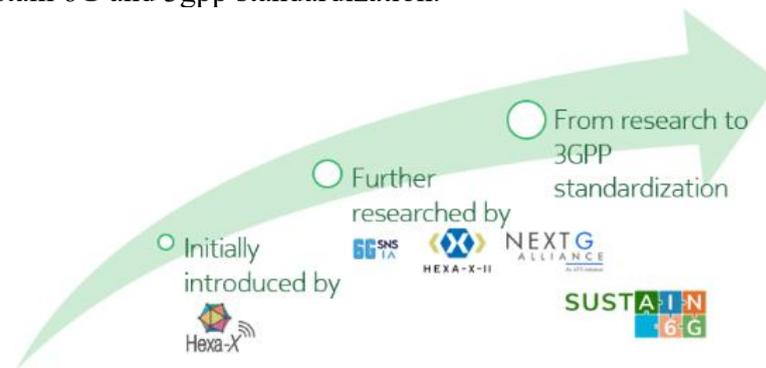


Figure 5 : Progression towards research to 3GPP standardization

3GPP has considered the KVI framework published in Key value indicators: A framework for values-driven next-generation ICT solutions<sup>17</sup>.

<sup>13</sup> Hexa-X, European level 6G flagship project, <https://hexa-x.eu/>

<sup>14</sup> 6G-IA, <https://6g-ia.eu/>

<sup>15</sup> Hexa-X-II, European level 6G flagship project, <https://hexa-x-ii.eu/>

<sup>16</sup> ATIS NEXT G Alliance, <https://nextgalliance.org/>

<sup>17</sup> Key value indicators: A framework for values-driven next-generation ICT solutions, <https://www.sciencedirect.com/science/article/pii/S0308596124000752>

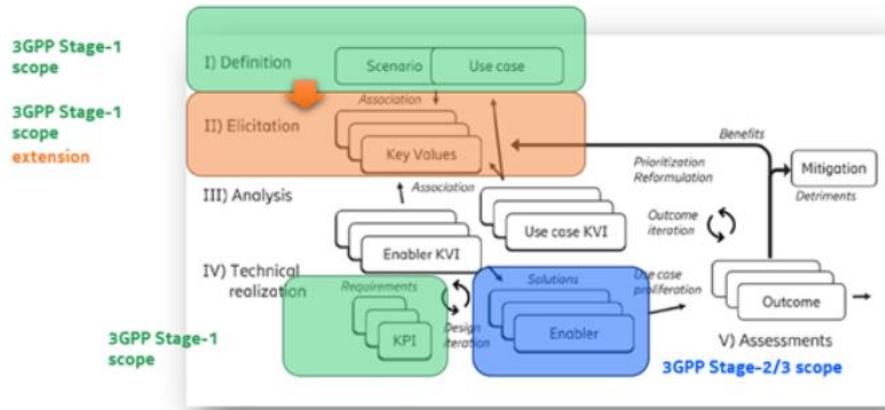


Figure 6 : Work process of KVI framework

The 3GPP has made progress on the work related to KVI in stage 1 group by endorsing way forward on key values for 6G<sup>18</sup> and have studied 6G service requirements including sustainability and KV analysis<sup>19</sup>.

The 3GPP work aims to focus on the environmental and socio-economic pillars of sustainability as part of the KV and KVI work. The following figure shows the direct and indirect UN SDG goals considered as KV goals.

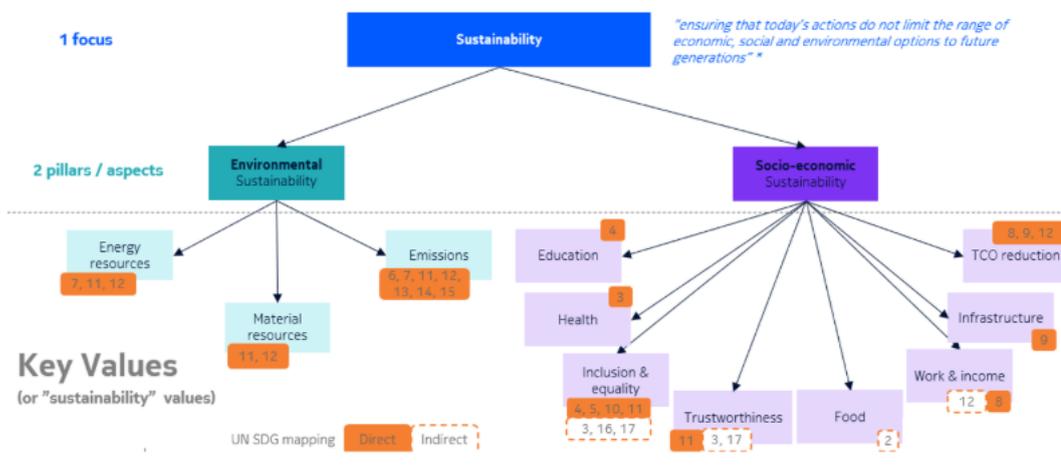


Figure 7 : Mapping of UN SDG goals with KV goals

<sup>18</sup> S1-242500: Proposed way forward on Key Values for SA1 6G Rel-20, [https://www.3gpp.org/ftp/tsg\\_sa/WG1\\_Serv/TSGS1\\_107\\_Maastricht/Docs/S1-242500.zip](https://www.3gpp.org/ftp/tsg_sa/WG1_Serv/TSGS1_107_Maastricht/Docs/S1-242500.zip)

<sup>19</sup> 3GPP TR 22.870: Study on 6G Use Cases and Service Requirements, [https://www.3gpp.org/ftp/Specs/archive/22\\_series/22.870/22870-031.zip](https://www.3gpp.org/ftp/Specs/archive/22_series/22.870/22870-031.zip)

## 8 Appendix: Energy Harvesting

For massive numbers of IoT/Zero-Energy devices, including ultra-low-power Internet of Things (IoT) and Zero-Energy Devices (ZEDs), harvesting energy is imperative. Even other devices may tap the ubiquitous electromagnetic energy in their spectra of operation. In fact, this solution may also be extended to small cells.

- **Energy Harvesting Technologies:**

Energy harvesting techniques like solar and the upcoming ambient radio frequency (RF) energy harvesting can help power small cells and reduce reliance on batteries. An example of RF energy Harvesting technology is found in:  
<https://www.onio.com/article/how-do-rf-harvesting-work.html>

- **Wireless Charging:**

Developing wireless charging technologies for small cells can eliminate the need for physical battery replacements, improving network uptime and reducing maintenance costs. A wireless powered base station is described in:  
<https://www.ericsson.com/en/news/2021/10/ericsson-and-powerlight-achieve-base-station-wireless-charging-breakthrough>

## 9 Appendix: Renewable Energy Sources as an Alternative for Conventional Energy Systems

### 9.1 Introduction

The transition to 6G networks presents telecom operators with both opportunities and challenges regarding energy procurement and sustainability. As energy intensity increases with network densification and the proliferation of edge devices, renewable energy sources emerge as a critical lever for reducing sectoral carbon emissions and achieving long-term operational resilience. This section evaluates the most salient renewable energy options currently available<sup>20</sup> to the telecom sector, analyzing their respective benefits, drawbacks, and scalability outcomes when integrated into 6G ecosystems.

### 9.2 Solar Photovoltaic (PV) Systems

Solar energy remains the leading renewable technology for telecom infrastructure, with proven utility across various geographies. In regions characterized by high solar irradiance, photovoltaic panels can generate substantial clean power for mobile towers, off-grid stations, and campus data centers.

The primary advantage of solar PV installations lies in their emission-free operation, alongside reductions in ongoing energy costs once deployed. Solar systems are also notably modular, facilitating incremental scaling in line with network expansion. Nevertheless, they are subject to significant capital expenditure upfront and require maintenance for panels, wiring, and associated battery units. Their output fluctuates based on diurnal cycles and meteorological variability, which can limit reliability in regions with inconsistent sunlight or extended monsoon seasons. Additionally, solar PV deployments may be constrained in urban and tower-dense environments, where available surface area is limited, and shading from adjacent structures can reduce efficacy.

At scale, solar PV is particularly effective for rural deployments, where land is comparatively more accessible, and grid connections are unreliable or non-existent. The approach becomes less straightforward in heavily urbanized environments, suggesting the need for complementary solutions or off-site procurement strategies to supplement local supply.

### 9.3 Wind Energy

Wind energy presents a viable alternative, especially in locations that exhibit consistent and adequate wind speeds. Turbine deployment at telecom sites can provide a stable power source independent of solar availability, increasing system resilience through diurnal and seasonal complementarity. The inherently renewable nature of wind energy aligns with decarbonization goals and long-term energy security.

However, widespread implementation is hampered by a number of practical concerns. Wind turbines entail notable installation costs and can introduce maintenance complexities due to moving mechanical components. Performance is highly contingent upon local wind profiles, restricting scalability to regions with favorable meteorological

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<sup>20</sup> Other possibilities, such as using bioalgae resources as fuel, may become available later.

conditions. Additionally, community acceptance can be a limiting factor, particularly in populated or sensitive areas where visual and acoustic impacts pose significant barriers. As such, the role of wind is largely supplementary, enhancing energy self-sufficiency in select markets but not universally scalable across all telecom deployments.

## 9.4 Hybrid Renewable Systems

Hybrid systems, which combine solar, wind, and auxiliary technologies like batteries or bioenergy, aim to mitigate the intermittency of singular renewables. Such integrated microgrids can enhance power reliability and optimize resource utilization, ensuring a more continuous energy supply for mission-critical telecom operations.

The integration of hybrid systems, while technologically promising, introduces added complexity and cost to system design, requiring advanced controls and maintenance expertise. Hybrid solutions are particularly valuable for isolated sites or those exposed to volatile grid conditions, but achieving cost-effective standardization at scale remains an ongoing challenge. Long-term success depends on harmonization of hardware, controls, and lifecycle management, supported by sectorwide best practices for deployment and maintenance.

## 9.5 Direct Renewable Energy Procurement and Grid Tie-in

Where regulatory frameworks and infrastructure allow, telecom companies may procure green electricity directly from off-site renewable producers via power purchase agreements (PPAs) or by participating in utility green programs. This mechanism dispenses with the need for on-premises installation and provides access to large volumes of clean energy, thereby addressing both operational and sustainability objectives.

The scalability of direct procurement is contingent on grid maturity and policy support, as well as the availability of reasonably priced renewable energy within national and regional markets. While this approach affords flexibility for metropolitan clusters, data centers, and national operations, it is inherently reliant on external entities for energy delivery and may be affected by long-term contract constraints.

## 9.6 Vehicles of Renewable Energy Procurement

Telecom operators can utilise multiple models for renewable energy procurement:

- **Onsite Generation:** Deployment of solar PV panels or wind turbines directly at telecom towers, data centers, and operational facilities. This offers direct control, reliability in rural/off-grid regions, and avoids transmission losses.
- **Power Purchase Agreements (PPAs):** Securing long-term, off-site renewable energy from large solar or wind farms at pre-agreed prices. PPAs allow for scalability without upfront capital burden and are increasingly popular for urban networks and data centers.
- **Open Access and Green Tariffs:** Leveraging the Green Energy Open Access framework, operators can purchase clean energy from producers through utilities, bypass the regional grid, and benefit from state-level incentives. Composite billing solutions and grid tie-in models are being explored for broader adoption.

- **Renewable Energy Certificates (RECs):** Operators may purchase RECs as proof of renewable energy consumption, enabling progress towards green targets even when direct procurement or onsite generation is impractical.
- **Virtual Power Purchase Agreements (VPPAs) and Market Exchanges:** These innovative market models, including battery arbitrage and future-backed contracts, are emerging to facilitate clean energy procurement through flexible, scalable platforms.

## 9.7 India's Policy Framework: Current Position and Future Directions

India's draft National Telecom Policy 2025 (NTP-25) formalizes ambitious sustainability goals for the sector. The policy sets a target to reduce telecom carbon footprint by 30% and to power 30% of network towers using renewable energy by 2030. It aims to operationalize Green Energy Open Access, develop e-waste management protocols, and introduce sustainability standards for network components and infrastructure. Regulatory agencies, including the Department of Telecommunications and the Ministry of New and Renewable Energy, have coordinated initiatives to streamline adoption, facilitate partnerships, and create joint working groups for designing scalable renewable solutions at telecom sites.

The policy recognizes the financial and technological hurdles faced by operators, especially in rural India where reliance on diesel backup is significant. Provisions for fiscal incentives, capacity building, and energy passports are included, but practical mechanisms for monitoring, compliance, and funding remain less defined. Significant momentum is expected, provided policy is enacted effectively and state-level collaboration is strengthened.

## 9.8 Investment Trends and Visibility to 2030

A surge in investment marks India's renewable energy sector. The country is committed to installing 500 GW of non-fossil-based electricity generation by 2030, of which telecom is a growing consumer. Projections suggest installed renewable energy capacity will rise to approximately 170 GW by March 2025, with annual investments in renewables poised to exceed US\$ 16.5 billion in 2024 alone. The spread of PPAs, open access models, and e-mobility partnerships (e.g., with Tata Power) reflects robust private and public sector engagement, while green hydrogen and battery storage initiatives are accelerating integration of new technologies.

Market leaders highlight gaps in transmission infrastructure and point to the need for streamlined execution of evacuation projects, especially for rural telecom expansion. Incentives such as Goods and Services Tax (GST) reduction for green technology and Production Linked Incentive (PLI) schemes for domestic equipment manufacture are recommended to further stimulate the sector.

Visibility over the next five years is strong: cumulative investment is expected to drive rapid expansion of renewable procurement, diversify supply models, and propel the telecom sector towards measurable sustainability targets. However, effective implementation, financing, and inter-agency collaboration will be vital for converting

aspirations into real-world progress.

Collectively, India's telecom sector is advancing multi-pronged vehicles for renewable energy procurement, supported by a government policy framework that is increasingly comprehensive but still evolving in its practical details. The next five years promise significant growth driven by investment, regulatory clarity, and rising market engagement, positioning India as one of the world's leading green telecom hubs—provided that implementation challenges are thoroughly addressed.

## 10 Appendix: Test and Measurement methodology

### 10.1 Setup to measure<sup>21</sup> the energy efficiency RAN (mainly radio units)

The most economical solution for measuring O-RU power consumption is power supply. It also provides high measurement resolution and accuracy. Another option is to use an oscilloscope with current and voltage probes, a setup that can also capture very short pulses and spikes in addition to monitoring energy dynamics under various traffic conditions.

All tests can be fully automated with the VIAVI O-RU Test Manager Application. The solution supports the predefined ETSI ES 202706-1 V1.6.1 (2021-01) cases and generates user-specific test scripts.

#### 10.1.1 O-RU test setup for energy efficiency testing

- R&S®RTO6 oscilloscope with R&S®RT-ZC31 current probe and R&S®RT-ZHD07 high voltage differential probe, optionally with R&S®RT-ZVC multichannel power probe
- R&S®NGP power supply series
- R&S®FSVA spectrum analyzer (optional)
- VIAVI TM500 O-RU Tester
- VIAVI O-RU Test Manager Application

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<sup>21</sup> The equipment in this appendix has been proposed by a contributing organization. The Model numbers are identified to provide relatable examples. Bharat 6G Alliance does not prefer any specific vendor/make/model.

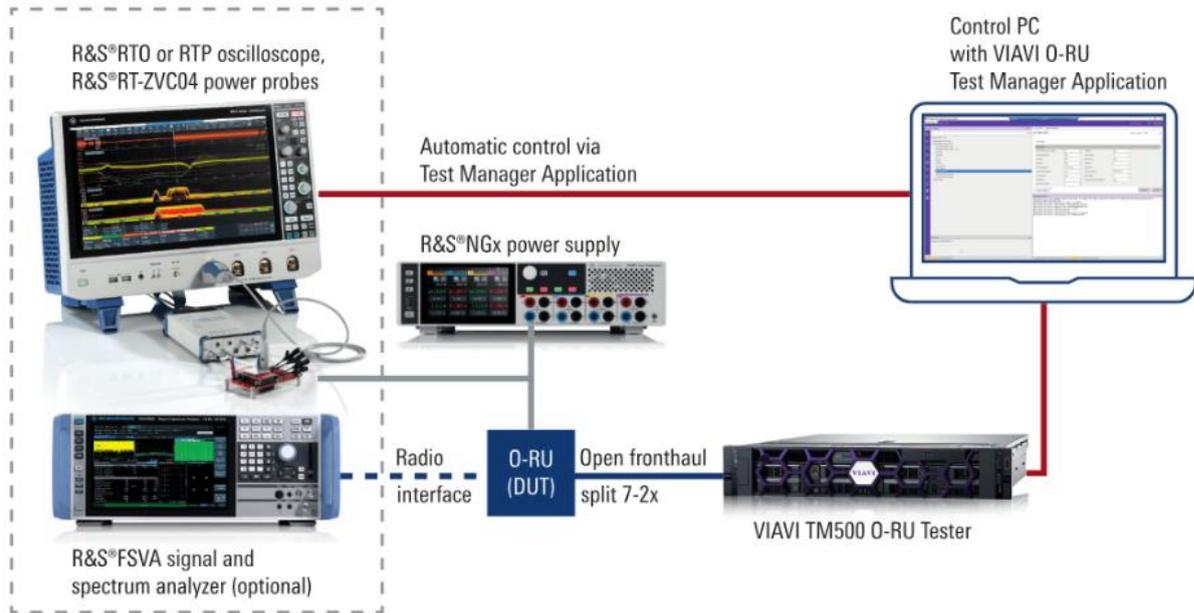


Figure 8 : Test setup for fully automated O-RU power consumption measurement.

In the test setup, VIAVI’s TM500 O-RU Tester emulates the Distributed Unit (DU), which synchronizes and configures the O-RU and offers several test scripts to verify the O-RU energy efficiency under different load conditions and stimulating the advanced sleep modes supported by the O-RU. Rohde & Schwarz equipment can then monitor dynamic device activities versus power consumption. The R&S®RTO6 oscilloscope is the perfect tool for tracking fast load changes. It pairs seamlessly with the R&S®RT-ZC31 current probe and R&S®RT-ZHD07 high voltage differential probe. Depending on the application, one may also want to consider the R&S®RT-ZVC high dynamic power probe: it has up to eight voltage and eight current channels, which makes it ideal for debugging the power consumption of individual circuits like the power amplifier within the O-RU. For time correlated power measurements in combination with RF signal quality analysis, try the R&S®RTO6 with the R&S®VSE software and see how well your O-RU performs in different scenarios. The R&S®NGP power supply units are an excellent choice for powering an O-RU. They supply a stable output to the DUT and accurately measure the overall power consumption with an 8 ms time resolution. The measured data can also be logged for in-depth analysis and documentation. Optionally, the R&S®FSVA spectrum analyzer can be added to check O-RU transmitter characteristics like error vector magnitude (EVM). The full test setup is controlled and turnkey automated by the VIAVI O-RU Test Manager Application that executes ETSI ES202706-1 V1.6.1 (2021-01) cases or user-specific test scripts at the click of a button.

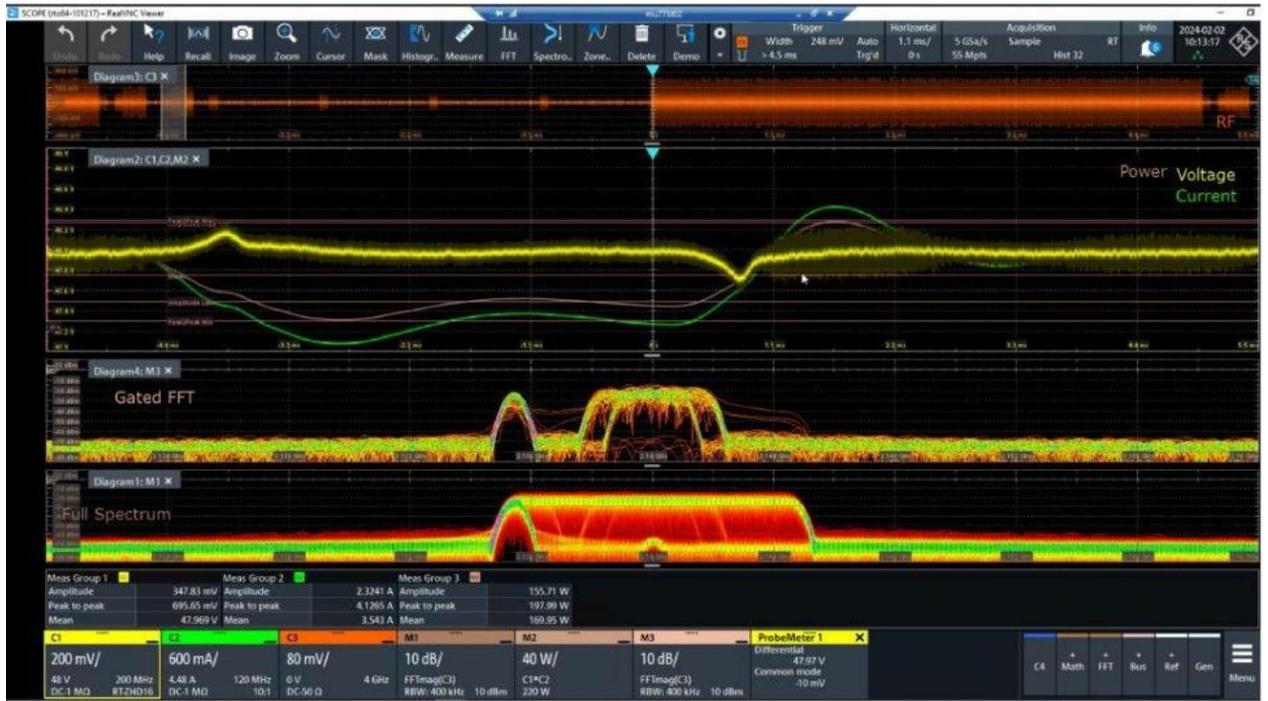


Figure 9 : Tracking fast O-RU load changes with the R&S@RTO6 oscilloscope: power ramps up (green curve) when 5G NR signal switches from SSB (low traffic load) to full allocation and TX simulating high traffic load (top graph).

# 11 Acknowledgement

## 11.1 Editors

1. Chair: Mr. Utkarsh Dubey, Bharti Airtel
2. Vice chair: Dr. Venkata Subramanian Viraraghavan, TCS

## 11.2 Contributing Organizations and Co-authors

Thankful to the following organizations for their contribution to different sections of the whitepaper.

In alphabetical order,

1. Bharti Airtel
  - Mr. Ambarish Bhattacharjee
2. Nokia Corporation
  - Mr. Niranth Amogh, Mr. Sankaran Balasubramaniam, Ms. Poonkuzhali E, Mr. Srinivas Garkipati, Mr. Satish K, Mr. Ashwani Kumar, Ms. Srilakshmi S
3. Rohde & Schwarz
  - Mr. Mahesh Basavaraju
4. Symbiosis Institute of Technology, Pune
  - Dr. Bhavna Ambudkar, Dr. Mangal Singh
5. Tata Consultancy Services Limited
  - Mr. Uday Ramesh
6. Techphosis Private Limited
  - Mr. Mangal Singh

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