

A comprehensive framework to evaluate energy efficiency in 5G Disaggregated / Open RAN networks.

White Paper

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List of Abbreviations

Abbreviation	Full Form
5G/6G	Fifth/Sixth-Generation Mobile Network
AI	Artificial Intelligence
AMF	Access and Mobility Management Function
API	Application Programming Interface
AVX512	Advanced Vector Extensions (512-bit)
BW	Bandwidth
CaaS	Containers-as-a-Service
C-plane	Control Plane
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
CU	Central Unit
CNF	Cloud-Native Function
DAC	Direct-Attach Copper
DU	Distributed Unit
E2E	End-to-End
eCPRI	Enhanced Common Public Radio Interface
EE	Energy Efficiency

FDD	Frequency Division Duplex
FR1	Frequency Range 1
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
KPI	Key Performance Indicator
L1	Layer-1 (Physical Layer)
LLS-C3	Low-Layer Split Class-3 Timing
M-plane	Management Plane
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
NIC	Network Interface Card
Open RAN	Open Radio Access Network
PA	Power Amplifier
PCIe	Peripheral Component Interconnect Express
PRB	Physical Resource Block
PTP	Precision Time Protocol
QAM	Quadrature Amplitude Modulation
QUIC	Quick UDP Internet Connections
RAN	Radio Access Network

RIC	RAN Intelligent Controller
RF	Radio Frequency
RU	Radio Unit
SCS	Sub-Carrier Spacing
SE/W	Spectral Efficiency per Watt
SNR	Signal-to-Noise Ratio
SMF	Session Management Function
SyncE	Synchronous Ethernet
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TRx	Transceiver
UE	User Equipment
UPF	User Plane Function
UDP	User Datagram Protocol
VM	Virtual Machine

Problem Statement

The deployment of Open Radio Access Networks (Open RAN, or O-RAN) in 5G and 6G systems introduces a paradigm shift toward disaggregated, multi-vendor architectures. While this openness fosters innovation and cost efficiency, it presents significant challenges in evaluating and optimizing energy efficiency across heterogeneous components. Unlike traditional single-vendor RANs, where energy metrics are tightly integrated and standardized, Open RAN environments involve diverse hardware and software stacks with varying performance profiles, telemetry capabilities, and power management strategies.

This lack of uniformity complicates the development of consistent energy efficiency (EE) benchmarks and impedes the ability to perform comparative analysis across vendors.

This paper addresses the methodological and architectural gaps in energy efficiency assessment for multi-vendor Open RAN systems. It proposes a unified approach to enable fair, reproducible, and actionable energy metrics/benchmarks across diverse network components.

Energy Efficiency in Disaggregated/Open RAN

As Open RAN evolves to address vendor lock-in and offer greater flexibility in selecting RAN components, energy efficiency alongside interoperability remains a longstanding and critical challenge in the wireless industry. Rising energy costs and growing environmental concerns have further intensified the need to reduce power consumption across communication networks. Within the disaggregated/O-RAN ecosystem, energy optimization has emerged as a key priority. Within the disaggregated ecosystem, reliable assessment of the energy efficiency of components delivered by different providers is an unexplored and additional challenge for E2E energy measurement.

Recent advancements have demonstrated that intelligent control mechanisms—especially those leveraging artificial intelligence (AI)—can dynamically adapt network operations to real-time conditions, leading to meaningful energy savings. These capabilities have been showcased in various global Plug-Fest events, where innovative solutions were implemented and tested under diverse scenarios.

However, despite the promising results, current energy efficiency (EE) evaluations lack consistency and comparability. Several challenges have been identified:

- To measure EE in a multi-vendor Open RAN 5G environment, we need standardized metrics, unified monitoring tools, and collaborative testing frameworks that normalize performance across diverse hardware and software stacks.
- Most experiments target specific use cases, without assessing the broader impact on the entire network.
- Results are highly sensitive to the testing scenario and the hardware-software stack used, making it difficult to generalize findings.
- Virtualized network functions introduce complexity in accurately measuring energy consumption.

These limitations highlight the urgent need for a unified, end-to-end Energy Efficiency testing framework. Such a framework should offer standardized procedures to benchmark energy usage across network components, validate the effectiveness of optimization strategies, and measure overall network efficiency in a consistent and reproducible manner. A first attempt has been provided by joint efforts of i14ylab and Rimedo Labs by proposing the [i14y Energy Efficiency Testing Framework](#).

Why Accurate Energy Measurement Matters in Disaggregated and 5G Open RAN

- The Radio Access Network (RAN) consumes ~70-80% of total network energy for mobile operators. [\[1\]\[2\]\[3\]\[6\]](#)
- With 5G's high data rates, massive MIMO, and dense deployments, energy demands are skyrocketing.
- Open RAN's flexibility comes with new energy-management challenges.
- As a result, it is necessary to define unified energy-consumption metrics, a standardized framework, and Key Performance Indicators (KPIs) that enable consistent measurement across multi-vendor deployments and diverse configurations.

E2E Energy Measurement Challenges

1. Lack of Unified Metrics
 - No universal standard for measuring energy across disaggregated components.
 - Metrics vary by vendor, hardware, and software stack.
2. Granularity and Real-Time Visibility
 - Fine-grained, real-time energy data is hard to collect across Radio Unit (RU), Distributed Unit (DU), Central Unit (CU).
 - Existing tools often lack visibility into dynamic power states or sleep modes.
3. Standardization Gaps
 - O-RAN Alliance and 3GPP are working on energy Key Performance Indicators (KPIs), but adoption is uneven. [\[7\]\[8\]\[9\]](#)
 - Many operators jump to optimization without robust measurement foundations.

End-2-End Power Measurement Architecture for Disaggregated RAN

The 5G disaggregated RAN test-line architecture is shown in [Figure 1](#). It creates a complete 5G network within a controlled laboratory environment. Its purpose is to validate interoperability between multi-vendor components, ensure standards compliance, and provide an accurate environment for end-to-end (E2E) energy-efficiency measurement. The test-line includes all essential elements of a real deployment: emulated User Equipment (UEs) for traffic generation, a 5G Radio

Unit (RU), baseband processing hardware, and the RAN workload stack, where the Central Unit (CU) and Distributed Unit (DU) may operate on **separate, disaggregated compute platforms** to reflect realistic multi-vendor and multi-hardware deployments. The setup also integrates the full 5G Core Network, service layers for data and application traffic, and dedicated test tools used to trigger, monitor, and evaluate energy-efficiency scenarios.

This controlled architecture mirrors the behavior of a production 5G system while enabling the precision and repeatability needed for energy-measurement experiments. By allowing the CU and DU to run on different hardware platforms, the test-line supports evaluation across diverse configurations, workload distributions, and vendor implementations. It provides a structured environment for executing standardized E2E energy-measurement test cases—aligned with the framework defined in this white paper—and for analyzing how various conditions, loads, and disaggregated components influence total power consumption across the entire RAN system. The red-highlighted block identifies the components that are the primary focus for E2E power-consumption measurements in the disaggregated 5G RAN.

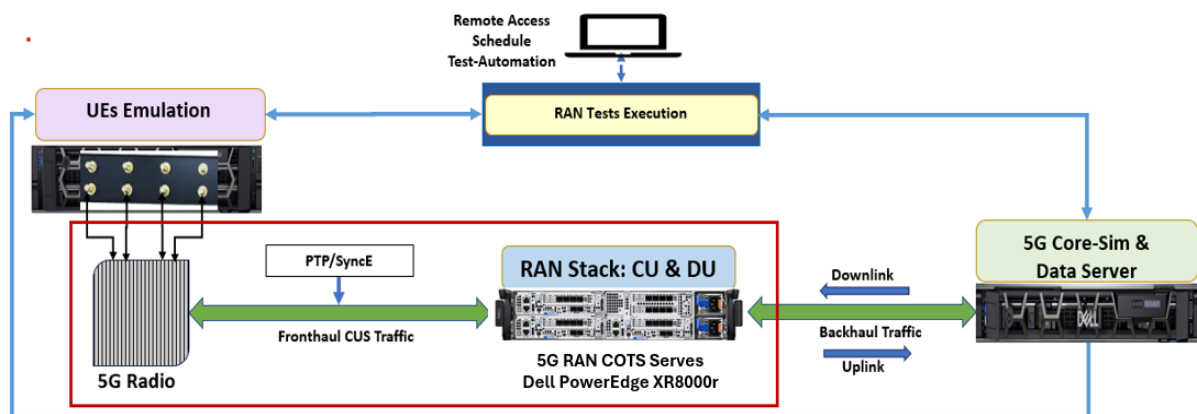


Figure 1: A Reference 5G Disaggregated / Open RAN Test-Line

Key Components & Their Roles, As Shown in [Figure 1](#),

Component	Description
UEs Emulation	Simulates multiple User Equipment (smartphones, IoT devices) to generate realistic traffic and mobility patterns.
5G Radio	Physical Radio Unit (RU) that connects to the RAN Stack via Fronthaul (Option 7.2). Handles RF transmission and reception.
RAN Stack: CU & DU	<p>Split architecture:</p> <ul style="list-style-type: none"> • CU (Central Unit) handles higher-layer protocols. • DU (Distributed Unit) manages lower-layer protocols and real-time processing. <p>Disaggregated architecture: Both are hosted on COTS servers (e.g., Dell XR8000r).</p>
5G Core & Data Servers	Simulates the 5G Core Network functions (AMF, SMF, UPF, etc.) and manages data traffic. Enables testing of end-to-end connectivity.
5G RAN Test-Tools	Manages automated testing of the Radio Access Network (RAN), including remote access, scheduling, and KPIs data collection.

Traffic Flow Breakdown

The components of the Open RAN test line are interconnected using a variety of communication interfaces and protocols, as described below.

- **Fronthaul (Option 7.2) CUS Traffic:**
Connects the 5G Radio to the DU/CU stack. Carries user and control plane data using eCPRI protocol encapsulated in ethernet packets.
- **PTP/SyncE (IEEE 1588v2/ITU G.826x):**
Provides precise timing and synchronization between radio and RAN components.
- **Downlink Traffic (HTTP, RTP, iPerf, UDP/TCP, QUIC):**
Flows from the RAN Stack to the Core-Sim & Data Server, simulating data delivery to users.

- **Uplink Traffic (HTTP, RTP, iPerf, UDP/TCP, QUIC):**
Flows from the Core-Sim & Data Server back to the RAN Stack, simulating user-originated data.
- **Backhaul Traffic:**
Connects the RAN Stack to the 5G Core Network Functions, enabling full end-to-end communication.
- **5G RAN Test-Tools:**
Connects to the UEs emulator and Data Servers to trigger and monitor uplink and downlink desired data traffic as per the framework mentioned in this document.

A Comprehensive Framework for Overcoming E2E Energy Measurement Challenges

Measuring and comparing energy KPIs across different system configurations is inherently challenging. The large configuration space and complex interdependencies between components make direct comparisons difficult and, in many cases, misleading. In addition, individual components may employ diverse and dynamically activated energy-saving mechanisms, further complicating attribution and normalization of results. Representative examples are outlined below to illustrate these challenges.

Energy Saving Techniques and the Challenges

1. Advanced Sleep Modes
 - Dynamically deactivated antenna elements or transceivers like the PA during low traffic.
 - Challenge: Requires precise traffic prediction and QoS assurance.
2. Transceiver (TRx) Control
 - Activate/deactivate RF bands, antenna ports, or beams based on load.
 - Challenge: Coordination across M-plane and C-plane is complex in multi-vendor setups.
3. Cell On/Off Strategies
 - Temporarily shut down cells in low-demand areas.
 - Challenge: Risk of coverage gaps and handover failures.
4. Virtualization and Cloud Optimization
 - Consolidate network functions and share infrastructure with AI workloads.
 - Challenge: Cloud data centers add their own energy footprint.
5. Full Stack Acceleration

- Use specialized hardware (e.g., Inline L1 and look aside Accelerators,) to reduce energy consumption.
- Challenge: Hardware diversity complicates orchestration and monitoring.

Taking into account the variety of possible configurations even of the same hardware, setup, and potential utilization of energy-saving features, to bring clarity and precision to our evaluation framework, we introduced two distinct parts: **Part 1 - “Common Configuration”** and **Part 2 - “Mutually Exclusive Configuration”**.

Part 1 - Common Configurations (see Part 1 Common Configuration table below) include elements that can coexist and be layered as needed—allowing to capture realistic, multi-dimensional scenarios. For samples, see IDs 1-15 in [Example 1](#) and [Example 2](#) tables.

Part 2 - Mutually Exclusive Configurations (see Part 2 - Mutually Exclusive Configurations table below) contain options where only one can be selected at a time—ensuring clean, non-overlapping comparisons. For samples, see IDs 16-26 in [Example 1](#) and [Example 2](#) tables.

This structured approach simplifies the measurement process while preserving its impact, enabling us to isolate variables and draw meaningful insights from each configuration. The approach is to have a minimum of 3 Cells active for effective energy measurement.

Part 1 - Common Configurations

ID	Configuration	Common Options
1	Number of Radios (All 3 are from the same Vendor)	3
2	CU/DU Server HW	Dell PowerEdge XR8620t
3	RAN Workload CPU Resource Allocation CPU, Generation & Number of Cores	Intel Xeon Gen4 6433N 32C
4	NIC Cards	2xIntel E810-XXVDA4T 4P 25G
5	Memory	256GB
6	Nominal Server Inlet Temperature	X degree Centigrade (25-30)
7	BIOS, AVX512	Enabled

8	Working CPU Frequency	2.5GHz
9	Time & Synchronization	LLS-C3
10	Carrier band & SCS	FR1, FDD: 15kHz, TDD: 30kHz
11	MCS 28 (SNR 30 or more)	256 QAM 8-bits
12	MCS 10 (SNR below 15)	16-QAM 4-bits
13	Spectrum Size: Cell MIMO * BW-MHz * Number-of-Cells	(2 4) * 100MHz * 3 = (600 1200MHz)
14	Energy Measured on (Components)	RU + DU + CU
15	TCP Data Traffic	HTTP
16	UDP Data Traffic	iPerf
17	Load Interval and Measurement Point	Run the test until the energy KPIs stabilize and then record power consumption once the values are consistent.
18	Traditional RAN Energy KPIs for same common config.	XYZ Performance/Watt

Part 2 - Mutually Exclusive Configurations

ID	Configuration	Mutually Exclusive Options
1	RAN Workload Type	A. BareMetal (No virtualization enabled) B. CaaS (Virtualization enabled, e.g., VMs or CNFs)
2	Transceiver Types	A. Copper (DAC) B. Optics
3	Carrier Duplex Method	A. FDD (Frequency Division Duplex) B. TDD (Time Division Duplex)

4	L1 Acceleration	A. Look-aside L1 (Acceleration in CPU) B. Inline L1 (Acceleration using external PCIe Card)
5	UEs Density (Subscribers per Cell)	A. 1 UE/Cell B. 16 UEs/Cell
6	RF Channel Conditions (Fading, SNR)	A. Strong Signal to all UEs (SNR more than 30) B. 50% UEs with Strong and 50% with Weak Signal
7	Data Traffic Type	A. UDP B. TCP
8	UEs Traffic Load	A. Idle (No UEs attached) B. Full Load (All Airframe PRBs fully loaded)
9	Energy Measurement Conditions	A. Ground 0 (No RAN workload deployed) B. Idle State (RAN workload deployed but no UEs attached) C. Full Load (All Cells are fully loaded with data traffic)
10	Near-RT RIC	A. Not deployed or Deployed but Not Active B. Fully Active
11	CU & DU	A. Collocated (Running together on the same server) B. Isolated (Running on the different servers)

The mutually exclusive part provides two options for each configuration, which makes the 5G RAN setup a unique configuration.

Note: Before we compare one setup vs. another, the mutually exclusive configuration parameters should exactly match.

Fully Configured Examples for the Specific Test-Cases

Example1:

3 Cell Carriers with FDD, bandwidth 20MHz, 2x2 MIMO, SCS 15kHz, full load, SNR 30+.

ID	Configuration	Value
1	Number of Radios	3
2	CU/DU Server HW	Dell PowerEdge XR8620t
3	RAN Workload CPU Resource Allocation CPU, Generation & Number of Cores	Intel Xeon Gen4 6433N 32C
4	NIC Cards	2xIntel E810-XXVDA4T 4P 25G
5	Memory	256GB
6	Nominal Server Inlet Temperature	27 degrees Centigrade
7	BIOS, AVX512	Enabled
8	Working CPU Frequency	2.5GHz
9	Time & Synchronization	LLS-C3
10	Carrier band & SCS	FR1, FDD: 15kHz
11	MCS 28 (SNR 30 or more)	256 QAM 8-bits
12	Spectrum Size: Cell MIMO * BW-MHz * Number-of-Cells	2*2 * 20MHz * 3 = 240MHz
13	Energy Measured on (Components)	RU + DU + CU
14	TCP Data Traffic	HTTP

15	UDP Data Traffic	iPerf
16	RAN Workload Type	BareMetal (No virtualization)
17	Transceiver Types	Copper (DAC)
18	Carrier Duplex Method	FDD (Frequency Division Duplex)
19	L1 Acceleration	Look-aside
20	UEs Density (Subscribers per Cell)	1 UE/Cell
21	RF Channel Conditions (Fading, SNR)	Strong Signal to all UEs
22	Data Traffic Type	TCP
23	UEs Traffic Load	Full Load (100% PRB Utilization)
24	Energy Measurement Conditions	Full Load (100% ORB Utilization)
25	Near-RT RIC	Not deployed
26	CU & DU	Collocated

Example 2:

3 Cell Carriers with TDD, bandwidth 100MHz, 4x4 MIMO, SCS 30kHz, full load, SNR 30+.

ID	Configuration	Value
1	Number of Radios	3
2	CU/DU Server HW	Dell PowerEdge XR8620t
3	RAN Workload CPU Resource Allocation CPU, Generation & Number of Cores	Intel Xeon Gen 4 6433N 32C

4	NIC Cards	2xIntel E810-XXVDA4T 4P 25G
5	Memory	256GB
6	Nominal Server Inlet Temperature	X degree Centigrade (25-30)
7	BIOS, AVX512	Enabled
8	Working CPU Frequency	2.5GHz
9	Time & Synchronization	LLS-C3
10	Carrier band & SCS	FR1, FDD: 15kHz, TDD: 30kHz
11	MCS 28 (SNR 30 or more)	256 QAM 8-bits
12	Spectrum Size: Cell MIMO * BW-MHz * Number-of-Cells	4 * 100MHz * 3 = 1200MHz
13	Energy Measured on (Components)	RU + DU + CU
14	TCP Data Traffic	HTTP
15	UDP Data Traffic	iPerf
16	RAN Workload Type	BareMetal (No virtualization)
17	Transceiver Types	Copper (DAC)
18	Carrier Duplex Method	TDD (Time Division Duplex)
19	L1 Acceleration	Look-aside
20	UEs Density (Subscribers per Cell)	1 UE/Cell
21	RF Channel Conditions (Fading, SNR)	Strong Signal to all UEs

22	Data Traffic Type	TCP
23	UEs Traffic Load	Full Load (100% PRB Utilization)
24	Energy Measurement Conditions	Full Load (100% ORB Utilization)
25	Near-RT RIC	Not deployed
26	CU & DU	Collocated

Measuring Energy Consumption During Test Execution

Energy consumption must be measured across three distinct system states mentioned below, as per the defined configurations outlined in the standardized metrics. To ensure data consistency and avoid transient fluctuations, each test scenario must run **long enough** for KPIs and power measurements to reach a stable state. A duration of approximately 5-10 minutes could often be sufficient, but the exact time should be determined by the stabilization of KPIs being measured.

This stabilization period allows power consumption values to converge, providing reliable and reproducible measurements.

To ensure fair and meaningful comparison between different test scenarios, the underlying **measurement methodology must remain identical across all runs**. Any variation in how energy data is collected—whether through **on-socket power counters, Kepler/Kepler sensors, Redfish APIs, Intel RAPL interfaces, or IPMI/BMC readings**—can introduce discrepancies that invalidate cross-test comparisons. Therefore, the tests must clearly define and use the *same* power-measurement interfaces across all scenarios to ensure that any results being compared are consistent, reliable, and methodologically equivalent.

State 1: Ground 0 Energy Measurement

No RAN workload has been deployed yet. Only the HW to host CU, DU, RU functions is powered on with their respective Operating System.

ID	RAN Component	Energy Measurement (W)
1	Energy Consumed by Radio (RU1)	R1 Watts
2	Energy Consumed by Radio (RU2)	R2 Watts
3	Energy Consumed by Radio (RU3)	R3 Watts
4	Total Energy Consumed by Radios	$R1 + R2 + R3 = R$ Watts
5	Energy Consumed by DU	D Watts
6	Energy Consumed by CU	C Watt
7	Total Energy Consumed	$R + D + C = E$ Watts

State 2: Idle State (0% Load) Energy Measurement

RAN Workload deployed, and Cells are active, but no UEs are attached.

ID	RAN Component	Energy Measurement (W)
1	Energy Consumed by Radio (RU1)	R1 Watts
2	Energy Consumed by Radio (RU2)	R2 Watts
3	Energy Consumed by Radio (RU3)	R3 Watts
4	Total Energy Consumed by Radios	$R1 + R2 + R3 = R$ Watts

5	Energy Consumed by DU	D Watts
6	Energy Consumed by CU	C Watts
7	Total Energy Consumed	$R + D + C = E$ Watts
8	Performance/Watt at 0% Load	Total Spectrum MHz / Total Energy Consumed E Watts

State 3: Full Scale (100% Load) Energy Measurement

All UEs are attached, and all Cells are full soaked with downlink and uplink Data Traffic.

No	RAN Component	Energy Measurement (W)
1	Energy Consumed by Radio (RU1)	R1 Watts
2	Energy Consumed by Radio (RU2)	R2 Watts
3	Energy Consumed by Radio (RU3)	R3 Watts
4	Total Energy Consumed by Radios	$R1 + R2 + R3 = R$ Watts
5	Energy Consumed by DU	D Watts
6	Energy Consumed by CU	C Watts
7	Total Energy Consumed	$R + D + C = E$ Watts
8	Performance/Watt at 100% Load	Total Spectrum MHz / Total Energy Consumed E Watts

Note: To ensure accurate and consistent radio-level energy measurements, record the key RU and cell configuration parameters that directly influence power consumption:

1. RF Output Power (per sector/antenna port)
2. Configured and Available PRBs

3. Antenna Gain and MIMO Configuration
4. RU Energy-Efficiency Specs from Vendor Data Sheet
5. (Optional) RU Power State Telemetry (active/sleep, PA activity, temperature)

Strategic considerations included

- Balance between energy savings and performance (Throughput/Watt) is critical.
- AI-driven orchestration can help—but needs accurate telemetry.
- Vendor interoperability and open APIs are essential for cross-layer optimization.
- Recommended to build the golden profiles using all the fine-tuned configuration for black-box measurements by changing one component at a time.
- To ensure repeatability and accuracy, measurements shall be recorded during a steady-state interval within a sufficiently long execution window (e.g., 5–10 minutes), once all relevant counters have stabilized. This minimizes transient effects and improves the consistency of reported KPIs.
- The test results should be well validated and repeatable.

The proposal of this foundation of framework and simplifying the design for overall E2E energy consumption measurements include:

1. Pin-point the current constraints, limitations, and issues.
2. Simplify architecture, test-lines, configurations, test-tools, and measurements
3. Publish the framework EE Optimization, measurement, and impact
4. Find out the energy consumption delta (Overall E2E – (RU+DU+CU)). Find out if the delta is noticeable?
5. Evaluate trends in energy consumption with different densities, loads, and conditions.
6. Compare with traditional data, if possible, by normalizing as performance per watt.

Scope and Future Work

This paper focuses exclusively on the development of a comprehensive and standardized framework and energy consumption metrics tailored for multi-vendor Open RAN environments. It lays the foundation for consistent, vendor-agnostic measurement of energy efficiency across disaggregated 5G network components.

The framework addresses the challenges of heterogeneity in hardware, software, and telemetry capabilities, proposing unified metrics to enable fair and reproducible evaluations.

To maintain clarity and depth, the broader research effort is divided into three sequential white papers:

- **White Paper 1** (this publication: *A comprehensive framework to evaluate energy efficiency in 5G Disaggregated / Open RAN networks*):
 - Design of the energy efficiency framework and definition of standardized metrics.
- **White Paper 2** (*Practical Implementation of an Energy Efficiency Evaluation Framework for 5G Disaggregated / Open RAN Networks: Measurements and Results*):
 - Implementation of the framework in a controlled multi-vendor Disaggregated / Open RAN testbed and collection of empirical results.
- **White Paper 3** (*Strategic Approaches to Address Energy Efficiency Gaps in 5G Disaggregated / Open RAN Networks*):
 - Analysis of the collected data, identification of optimization opportunities including RIC, and recommendations for fine-tuning energy-aware configurations.

Looking ahead, the transition to 6G will intensify the need for energy-conscious network design, making sustainability a core architectural principle. Green RAN initiatives and carbon accounting mechanisms will become integral to future network planning, driving the industry toward more transparent and accountable energy usage models. The standardized energy KPIs and open telemetry frameworks could be key enablers.

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About i14y Lab

The i14y Lab is an open lab for interoperability testing of disaggregated telco systems, such as OpenRAN, led by Deutsche Telekom together with project partners <names>, and supported with public funding from the German Ministry of Digital and Transport (BMDV).

The i14y Lab provides infrastructure for integration tests with the aim to evaluate market readiness and accelerate production readiness of multi-vendor disaggregated telco solutions. By creating and providing a vendor-independent environment, we promote the development of an innovative, open, and interoperable telco ecosystem. For more information, go to www.i14y-lab.com.

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