

Sustainable 6G by Design: considerations for new systems

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Summary

The paper examines how sustainability can become a foundational property of future 6G communication systems rather than a secondary optimization objective.

Key concerns

A) Energy management

The paper identifies energy management as one of the most critical challenges for future 6G systems. With increasing deployment of distributed edge computing, AI accelerators, non-terrestrial networks, and ultra-dense radio infrastructures, future communication systems risk substantial growth in energy demand unless sustainability is embedded directly into network orchestration and architecture. The paper therefore advocates for **AI-native programmability capable of dynamically adapting** workloads, network slices, and resource allocation according to real-time energy availability, carbon intensity, thermal conditions, and renewable energy generation. **Energy heterogeneity** across the future 6G network continuum is another major theme. The paper describe future infrastructures composed of grid-powered core sites, renewable-powered edge nodes, aerial platforms, and energy-harvesting devices operating under highly variable energy conditions. In this vision, telecom networks evolve from passive energy consumers into active participants in broader smart-energy ecosystems.

The concept of “**sustainable execution**” emerges as a core architectural principle. AI-driven orchestration systems are envisioned to continuously optimize network behavior by migrating workloads between cloud, edge, and access domains according to environmental constraints and operational priorities. This includes traffic-adaptive activation of radio units, carbon-aware workload scheduling, renewable-energy-aligned processing, and energy-budgeted service orchestration. Sustainable orchestration therefore requires energy-source-aware scheduling capable of aligning delay-tolerant workloads with periods of renewable energy surplus while preserving quality of service for latency-critical applications.

B) Waste management and circularity

A parallel argument of the paper is that current ICT sustainability practices remain overly focused on operational energy efficiency while **neglecting broader environmental impacts** such as electronic waste, embodied carbon, hardware obsolescence, circularity, and critical material recovery.

A major contribution of the paper concerns waste management and circularity in future telecom infrastructures. The paper highlights warn that **rapid infrastructure replacement cycles**, especially in AI-accelerated edge and cloud systems, risk generating significant

electronic waste streams and increasing dependency on critical raw materials such as rare earth elements and semiconductor materials. Existing telecom sustainability strategies often overlook the environmental implications of hardware refresh cycles, software-induced obsolescence, and decommissioning logistics. To address this, the paper proposes a transition toward circular infrastructure ecosystems based on repairability, modular upgrades, refurbishment, remanufacturing, and secondary equipment markets. To address this, the concept of **Hardware-as-a-Service (HaaS)**, where vendors retain ownership and lifecycle responsibility for telecom infrastructure is presented. Such models would incentivize manufacturers to design equipment for longevity, repairability, and end-of-life recovery rather than short replacement cycles. **Certified secondary markets** for 6G infrastructure assets, enabling equipment decommissioned from urban high-capacity deployments to be refurbished and reused in rural or developing regions, is also presented as a possibility. This approach could potentially extend telecom hardware lifetimes from the current 7–10 years to over 15 years, significantly reducing electronic waste generation and embodied carbon emissions.

Software-induced obsolescence is identified as another hidden source of waste. Frequent software upgrades often render older but functional hardware incompatible with evolving network architectures, leading to premature disposal of viable equipment. It is recommended that software-defined networking approaches incorporating backward-compatibility layers and “lean execution modes” capable of preserving partial functionality in legacy infrastructure. This would allow older 5G and 6G nodes to continue operating with reduced capabilities instead of being discarded entirely.

Technology design directions for telecom sustainability

Decision support technologies are presented as essential operational tools for sustainable 6G management. Network Digital Twins, Knowledge Graphs, intent-based interfaces, and closed-loop sustainability control systems enable predictive analysis of energy and environmental impacts before deployment. These tools support **evidence-based orchestration decisions**, sustainability KPI/KVI management, and continuous system adaptation.

The paper concludes that **sustainable 6G** is achievable only through coordinated system-level design integrating AI-native programmability, lifecycle-aware orchestration, circular infrastructure management, energy-aware distribution, and harmonized governance frameworks. Sustainability must become an **enforceable operational property of future networks rather than a retrospective reporting exercise**. By combining intelligent orchestration, circular economy principles, renewable-energy integration, and strategic material resilience, future 6G infrastructures can significantly reduce their environmental footprint while acting as a sustainability multiplier across the wider digital ecosystem.