White Paper

Sustainable 6G by Design

An SNS-Driven Vision for AI-Native, System-Level Sustainability

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SNS Sustainability Working Group

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List of Acronyms

AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
CAPEX	Capital Expenditure
CSRD	Corporate Sustainability Reporting Directive
ETSI	European Telecommunications Standards Institute
FR3	Frequency Range 3 (7–24 GHz spectrum range)
GHG	Greenhouse Gas
HaaS	Hardware-as-a-Service
ICT	Information and Communication Technology
IP	Intellectual Property
ISO	International Organization for Standardization
KPI	Key Performance Indicator
KVI	Key Value Indicator
LCA	LifeCycle Assessment
LCSA	LifeCycle Sustainability Assessment
ML	Machine Learning
NFV	Network Functions Virtualisation
NTN	Non-Terrestrial Networks
OPEX	Operational Expenditure
ORAN	Open Radio Access Network
RAN	Radio Access Network
SDG	Sustainable Development Goal
SDN	Software-Defined Networking
SNS JU	Smart Networks and Services Joint Undertaking
TRL	Technology Readiness Level

Executive Summary

Sustainability has become a defining requirement for future mobile networks, yet its practical integration into system design and operation remains uneven. As 6G networks evolve towards highly distributed, AI-native, and service-adaptive infrastructures, sustainability can no longer be treated as a secondary optimisation goal or a reporting exercise. This white paper examines how sustainability can be embedded *by design* into 6G systems, drawing on insights from European research and innovation activities to identify what is working, what is not, and what is required to move from intent to operational impact. While current practice and many examples in this paper reflect areas where methodologies are most mature—particularly energy efficiency—this work explicitly aims to extend sustainability considerations toward a more holistic, system-level perspective encompassing environmental, economic, and social dimensions and their interdependencies.

The analysis starts from the observation that current sustainability practice in ICT remains dominated by operational energy efficiency. While measurable progress has been achieved in this area, other critical dimensions—including lifecycle impacts, circularity, social and economic sustainability, and rebound effects—are addressed inconsistently. Metrics and methodologies are fragmented, and sustainability is often evaluated at component level rather than as a system-wide property. These limitations motivate the need for a more holistic, architecture- and control-driven approach to sustainable 6G. In this context, a system-level understanding of sustainability extends beyond technical architecture alone. It encompasses how network design interacts with business models, deployment contexts, stakeholder incentives, and policy frameworks. Sustainability outcomes therefore emerge not only from how components are engineered, but from how technical, economic, and societal factors are jointly structured and governed.

A central conclusion of this paper is that sustainability in 6G must be treated as a **system property**, shaped by how resources, intelligence, and control are distributed and orchestrated over time. AI-native programmability emerges as a key enabler, allowing networks to adapt dynamically to changing demand, energy availability, and sustainability constraints. At the same time, AI introduces new sustainability challenges of its own, including increased compute demand, hardware dependencies, and lifecycle impacts, which must be explicitly governed rather than implicitly assumed away.

The transition to highly distributed 6G architectures further amplifies both opportunity and complexity. Energy heterogeneity across core, edge, and access networks makes sustainability more actionable, but also more sensitive to orchestration decisions. Trustworthiness and resilience, traditionally treated as orthogonal design objectives, are shown to have direct sustainability implications due to their reliance on redundancy, monitoring, and verification mechanisms. Sustainable 6G therefore requires adaptive approaches that balance performance, robustness, trust, and energy use dynamically rather than through static over-provisioning.

To operationalise these trade-offs—such as those between energy consumption, performance, resilience, cost, and social impact—this paper highlights the importance of decision support and actionable interfaces. These trade-offs are not addressed by a single actor, but involve different stakeholders including network operators, system designers, policymakers, and, indirectly, end users whose needs and contexts shape decision priorities.

Network Digital Twins enable predictive analysis of sustainability outcomes before deployment, while Knowledge Graph-based design approaches provide traceability between requirements, enablers, KPIs, and KVIs, reducing bias and supporting explainable decision-making. When combined with intent-based control and closed-loop feedback from live systems, these mechanisms allow environmentally to be enforced dynamically rather than assessed retrospectively.

The lessons learned from early sustainable 6G research indicate strong progress in recognising sustainability as a design driver, widespread adoption of energy-efficiency optimisation, and promising results from AI-based control. However, they also reveal persistent gaps: fragmented methodologies, limited treatment of lifecycle and circularity, insufficient integration of business models, uneven integration of social and economic dimensions, and weak links to governance and standardisation. As a result, many promising solutions remain confined to project-level demonstrations.

Looking ahead, the paper identifies several priorities for future work. These include converging sustainability methodologies and metrics, validating closed-loop sustainability control at scale, embedding sustainability into standardisation and policy frameworks, and maintaining a strong human-centred focus on trust, transparency, and usability. Addressing these challenges is essential if sustainability is to become a durable and enforceable property of 6G systems rather than an aspirational goal.

In conclusion, sustainable 6G is achievable, but only through deliberate system-level design and coordinated action across technology, governance, and policy. By combining AI-native programmability, distributed architectures, adaptive trust mechanisms, and robust decision support, 6G networks can not only reduce their own footprint, but also act as a sustainability multiplier across the wider digital ecosystem.

This paper is intended for researchers, system architects, network operators, programme managers, and policymakers involved in the design, governance, and standardisation of future 6G systems.

1 Purpose, Evidence & Baseline

This white paper provides a **practitioner-oriented synthesis** of how sustainability can be embedded *by design* into future 6G networks. Its purpose is not to recap individual project results, nor to reproduce workshop presentations or deliverable summaries. Instead, it distils **recurring technical patterns, methodological gaps, and system-level tensions** observed across multiple European Smart Networks and Services Joint Undertaking (SNS-JU) projects, and translates them into a coherent set of design insights relevant to researchers, architects, operators, and decision-makers.

The paper is grounded in two complementary sources of evidence. First, it builds on the discussions and outcomes of the **EUCNC 2025 workshop on Technology Enablers for Sustainable 6G Design**, where contributors from across the SNS ecosystem jointly examined emerging approaches, limitations, and open challenges. Second, it integrates inputs from the **SNS-JU Sustainability Task Force**, which aggregates cross-project experience and reflections accumulated throughout the programme. Together, these sources provide a broad, experience-based perspective that goes beyond any single project's scope, while remaining firmly rooted in concrete research and engineering practice. Based on this evidence, the paper adopts a set of **explicit baseline premises** that frame the analysis in the following sections. These premises do not represent normative claims, but rather shared observations repeatedly encountered across SNS projects and related standardisation and research activities.

First, **energy efficiency currently dominates sustainability practice in mobile and communication networks**. Most projects focus on reducing operational energy consumption, often with measurable success. However, this emphasis tends to overshadow other critical environmental dimensions. At the same time, economic and social sustainability dimensions remain less systematically addressed. Economic sustainability includes the viability of business models, affordability, and long-term operational sustainability across different deployment contexts. Social sustainability includes aspects such as inclusion, equity, trust, accessibility, and the development of skills needed to ensure that technological advances translate into real societal value. These dimensions are not independent of environmental sustainability, but interact with it directly, influencing how solutions are adopted, used, and sustained over time.

Second, **circularity, maintainability, and renewable energy integration remain comparatively underdeveloped**. The sustainability implications of accelerated infrastructure refresh cycles remain insufficiently addressed. Telecom networks increasingly depend on short-lifecycle compute platforms, AI accelerators, radio systems, batteries, and edge infrastructures whose replacement dynamics are driven not only by technical evolution but also by software dependencies, interoperability constraints, and vendor support policies. Considerations such as component reuse, repairability, lifecycle extension, embodied carbon, and alignment with local renewable energy availability are addressed inconsistently and rarely integrated into system-level design or operational control. Sustainable 6G therefore requires explicit consideration of refurbishment, repairability, modular upgrades, secondary equipment markets, and recovery of critical materials as integral elements of system design and governance rather than end-of-life afterthoughts.

Third, **rebound and second-order effects receive limited systematic attention**. Improvements in efficiency at the component or service level enables increased demand or new usage patterns, potentially offsetting or even reversing environmental gains. Without explicit mechanisms to detect and manage such effects, sustainability risks being reduced to a narrow optimisation problem rather than treated as a systemic property.

A further baseline observation concerns **measurement and evaluation**. While a wide range of performance Key Performance Indicators (KPIs) and emerging Key Value Indicators (KVIs) exist, their **definition, selection, and application remain fragmented**. Metrics are often chosen opportunistically, lack clear baselines, or fail to capture trade-offs across environmental, economic, and social dimensions. In addition, **component-level specifics**—such as the maturity of enablers, their dependencies, and their differentiated impact across deployment contexts—are not yet sufficiently understood to support robust end-to-end system design.

As a result, **sustainability-oriented design methodologies are still in an early stage of development**. Existing approaches depend heavily on the availability and quality of data, as well as on assumptions that may not hold across technologies, domains, or time scales. This creates a strong need for methodologies that can **evolve continuously**, integrate new evidence, and operate as **closed-loop processes** linking design-time assumptions with operational feedback. Such methodologies are essential to provision systems that deliver not only technical performance, but also sustained business value and positive societal impact.

Unless otherwise specified, sustainability in this paper is understood as a multi-dimensional concept encompassing environmental, economic, and social aspects. However, many current approaches—and several examples discussed in the following sections—focus primarily on environmental sustainability, in particular energy efficiency, reflecting the current maturity and availability of methodologies and tools.

Taken together, these premises define what this white paper “takes as given”. They motivate the need to move beyond isolated efficiency improvements towards **AI-native, programmable, and sustainability-aware 6G systems**, supported by actionable metrics, decision support mechanisms, and governance structures. The remainder of the document builds on this baseline to explore how these objectives can be realised in practice.

2 Making ICT Services Count: Energy and Carbon Accountability Across Stakeholders

The main contribution of the Information and Communication Technology (ICT) sector to society lies in the services it provides to individuals, commercial enterprises and various types of organisations. ICT services constitute immaterial equivalents of physical products. Unlike manufactured goods, they do not themselves have production, distribution and disposal phases that contribute directly to material resource use or embedded emissions. While the hardware estate underpinning ICT services does entail embodied impacts, the environmental footprint of services is predominantly concentrated in the use phase, determined primarily by the energy consumed during operation and by the carbon intensity of that energy. This service-centric perspective is essential for understanding energy and carbon impacts, as it aligns environmental accountability with the way value is created, delivered, and consumed in modern digital systems.

Service-Level Measurement as the Basis for Energy and Carbon Accountability

For the ICT sector to credibly engage with sustainability objectives, in addition to the classical ICT products, it must assume responsibility for systematic measurement and reporting of the energy and carbon impacts of the services it provides. Without reliable and comparable measurements of its main output, the sector effectively operates as if in a “blind flight mode”, unable to quantify its environmental footprint or evaluate the efficacy of mitigation measures. The absence of standardised data precludes meaningful benchmarking: without today’s measurements, there can be no substantiated claims of tomorrow’s improvements. Across SNS-JU projects, this lack of reliable, comparable service-level data repeatedly emerges as a fundamental barrier to credible environmental sustainability assessment and optimisation, particularly in terms of energy and carbon impacts.

The current state of discourse illustrates this immaturity. A well-known example is the divergence between estimates of the energy consumption of video streaming published by the International Energy Agency (IEA) and The Shift Project in France. Their final, corrected figures still differ by approximately a factor of seven. Notably, neither estimate originated from within the ICT sector itself—the very sector responsible for providing the service under analysis. This discrepancy underscores the lack of established methodologies and consistent data within ICT when it comes to environmental accounting. The purpose of this example is not to arbitrate between estimates, but to illustrate the absence of an internally agreed, service-level environmental accounting methodology within the ICT sector.

Attribution and Data Exchange Across Organisational Boundaries

A further challenge arises from organisational and stakeholder boundaries. Direct measurement of energy consumption is technically feasible only when the equipment providing the service is under the operator's control. In other cases, the service provider must disclose the environmental cost of service sessions to users, which requires an allocation mechanism that attributes an appropriate share of the system's total energy consumption to individual service instances. To ensure credibility and comparability, such attribution must follow a transparent, scientifically sound, and broadly accepted methodology. Without such methodologies, environmental sustainability information (in particular energy and carbon data) cannot be consistently trusted, compared, or acted upon across organisational boundaries.

Measurement alone is insufficient if sustainability information does not influence economic incentives and operational decision-making. When energy and carbon information crosses organisational domains, issues of trust, verification, and conflicting incentives emerge. Providers may be motivated to report low consumption values to demonstrate technical efficiency, yet this simultaneously reduces the share of environmental responsibility attributed to consumers. Conversely, inflated figures might reduce short-term accountability for operators but may prove detrimental to competitiveness in the long term.

Hence, in the presence of multiple stakeholders contributing to the provision of a service (e.g., the infrastructure, network and application are owned by separate entities), there is a need for: *i*) a thorough assessment and representation of metrics characterising the consumption ascribable to each stakeholder, *ii*) the means to exchange these metrics in a secure and trustworthy manner, and *iii*) the creation of an ecosystem, preferably in the context of a business model, that promotes the cooperation of all stakeholders towards joint sustainability targets (e.g., energy efficiency and decarbonisation). Such approaches must be grounded in viable business models that align incentives across stakeholders, ensuring that sustainability objectives translate into economically sustainable deployment and operational decisions.

From Measurement Capability to Actionable Energy Efficiency

Specifically in mobile networks, there are several methods potentially suitable for inferring the energy consumption ascribable to an application or a network slice[1]. As a means to exchange such information, network slices could be enriched with energy and carbon performance intents. In fact, the latest version of the GSMA GST (Generic Network Slice Template)[2] includes an optional energy efficiency attribute describing whether the network slice supports the energy efficiency KPI, but this attribute is very high level, not providing sufficient granularity nor detail regarding expected slice behaviour. 3GPP TS 28.554[3] defines a number of Energy Efficiency and Energy Consumption KPIs, but again they only relate to pure energy consumption and not to the carbon intensity of the energy used. The inclusion of additional metrics, such as the energy efficiency indicators from the Body of European Regulators for Electronic Communications (BEREC)[4], would allow customers to express decarbonisation expectations more comprehensively, going

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[1] A. Bellin, M. Centenaro and F. Granelli, "A Preliminary Study on the Power Consumption of Virtualized Edge 5G Core Networks," 2023 IEEE 9th International Conference on Network Softwarization (NetSoft), Madrid, Spain, 2023, pp. 420-425, doi: 10.1109/NetSoft57336.2023.10175489.

[2] GSMA Official Document NG.116 - Generic Network Slice Template, available at https://www.gsma.com/newsroom/wp-content/uploads//NG.116-v10.0-1.pdf

[3] 3GPP TS 28.554, “Management and orchestration; 5G end to end Key Performance Indicators (KPI)”, v17.15.0, September 2024.

[4] BEREC, "Report on Sustainability Indicators for Electronic Communications Networks and Services", BoR (23) 166, October 2023 [Online]. Available: https://www.berec.europa.eu/system/files/2023-10/BoR%20%2823%29%20166%20Final%20Report%20on%20sustainability%20indicators%20for%20ECN%20ECS.pdf

beyond raw consumption to include carbon emissions and renewable energy usage. Stemming from the stream of work on energy as service criterion at 3GPP, the TS22.261[5] contains a novel set of energy-related requirements for the 5GA system amongst which there are requirements to track the energy consumption of all components and to report energy consumption to authorized third parties. Taken together, these initiatives demonstrate growing technical capability, but they do not yet constitute an end-to-end, service-level framework for energy and carbon accountability.

While 5G and future 6G networks are increasingly capable of measuring and enabling energy efficiency indicators, **technical capability alone is insufficient to drive adoption of greener services**: key stakeholders operate under diverse objectives and constraints, often prioritising cost and performance over environmental impact. This misalignment can lead to suboptimal sustainability outcomes. To address this, effective technical and economic mechanisms are needed to incentivise the deployment, operation and selection of green network slices—for example through differentiated tariffs, green SLAs, or regulatory reporting frameworks. Without such incentives, energy and carbon efficiency goals are unlikely to be met. SNS project experience indicates that, in the absence of such incentives, energy efficiency features are rarely prioritised in deployment or procurement decisions.

In summary, **the sustainability of ICT should be reflected within the energy and carbon performance information provided within its services**. This idea could be periphrased as eco-labels for ICT services. The feasibility of the latter depends on accurate, standardised, and verifiable measurement of energy use by logical entities and would additionally profit from the addition of carbon intensity at runtime of the latter. Technical means for measuring energy consumption and attributing it to logical entities do exist and have been successfully demonstrated in the compute, storage and networking areas. However, regulation (pull) and technical agreements on metrics and the measurement/attribution modalities (push) are required for their operationalization. Ultimately, only through consistent methodologies, transparent reporting, and mechanisms for cross-domain verification can the sector evolve from current estimations and often unfounded assumptions towards a mature, evidence-based approach to environmental accountability. This vision, consistently echoed across SNS projects, positions service-level energy efficiency information as a prerequisite for meaningful accountability, informed choice, and systemic impact.

3 AI-Driven Programmability & Sustainable Execution

6G networks will be the first mobile systems conceived as *AI-native*, evolving from static, pre-configured infrastructures into programmable, self-optimising, and sustainability-aware digital ecosystems. This transformation responds to three converging pressures:

- exponential service complexity across sectors,
- pervasive virtualisation from the RAN to the edge–cloud continuum, and,
- the imperative for radical gains in energy efficiency and resource utilisation.

AI-driven programmability and **sustainable execution** together form the backbone of this transition, enabling deterministic performance while aligning with Europe's twin goals of *digital sovereignty* and *climate neutrality*[6,7]. This section synthesises recurring architectural patterns and execution principles observed across multiple SNS JU projects, rather than proposing a single reference architecture.

AI-Native Programmability Across the Network Stack

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[5] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3107

[6] SNS JU and 6G-IA, "Strategic Research and Innovation Agenda (SRIA) 2025–2027," European Commission, 2024. [Online]. Available: https://smart-networks.europa.eu

[7] 6G-IA, "European Vision for the 6G Network Ecosystem," White Paper, June 2021. Available: https://6g-ia.eu/wp-content/uploads/2021/06/WhitePaper-6G-Europe.pdf

Programmability in 6G extends far beyond the SDN/NFV paradigms of 5G. It introduces a continuously adaptive control plane where *agentic* AI models, intent-based interfaces, and declarative network policies enable operators, verticals, and even applications to dynamically influence network behaviour. In practice, foundation and large language models (LLMs) augment traditional network automation by translating high-level intents—such as "minimise energy per bit for FR3 traffic" or "guarantee 5 ms latency for holographic telepresence"—into optimised configurations spanning RAN, core, and edge domains, reducing operational complexity and the risk of human error (e.g., ETSI ZSM and 3GPP SA6 intent-based management).

Within the RAN and edge, 6G programmability will rely on open and interoperable frameworks such as O-RAN and AI-RAN Alliance interfaces. ML techniques—including geometric deep learning for beamforming, reinforcement learning for distributed scheduling, and foundation models for radio resource management—support fine-grained, real-time optimisation across heterogeneous cell types, spectrum bands (including FR3), and non-terrestrial networks (NTN).

These capabilities are coordinated through cross-domain orchestration mechanisms that integrate fine-grained telemetry, graph-based observability, and executable network digital twins, supported by CI/CD-style pipelines. Executable digital twins enable safe, low-disruption testing of new policies, models, or slicing strategies prior to rollout, helping programmable functions remain verifiable, auditable, and robust against failures or adversarial perturbations. At the same time, the computational and data overhead of continuous twin execution must itself be considered, to avoid shifting energy and resource consumption burdens upstream, with potential negative impacts on overall sustainability.

Sustainable Execution: From Energy Efficiency to Climate-Aligned Operations

Sustainability in 6G is not a post-hoc optimisation; it is a first-principle design goal. Without intervention, network energy consumption could double by 2030[8,9]. Embedding sustainability-aware decision-making into every architectural layer is therefore essential, and it operationalises the service-level energy and carbon accountability challenges discussed earlier in this paper.

AI-enhanced orchestration can account for carbon intensity, thermal conditions, server load, and renewable availability when scheduling workloads. This enables dynamic migration across cloud, edge, and device layers to optimise both performance and environmental impact—for example through traffic-adaptive activation of radio units, per-slice sustainability constraints (such as maximum CO_2 per bit budgets), and multi-objective optimisation that balances quality of experience, energy consumption, and cost.

Execution environments will increasingly favour lightweight, resource-efficient AI models—including pruned and quantised networks, federated or split-learning schemes, and "Green-AI" pipelines that reduce compute and memory footprints—while aligning with evolving regulatory sustainability expectations (e.g., EC AI Act considerations and the Energy Efficiency Directive). Such approaches are critical to ensure that increasing network intelligence does not undermine environmental sustainability objectives, particularly energy efficiency, through rising compute demand.

Lifecycle intelligence also becomes an execution-time concern. Beyond operational optimisation, sustainability-aware orchestration—particularly in terms of environmental sustainability—should increasingly account for infrastructure lifecycle characteristics, including embodied carbon, remaining hardware lifetime, repairability, and upgrade potential.

This is particularly important for AI-native infrastructures, where rapid accelerator obsolescence risks creating significant electronic-waste streams and material dependencies. Future orchestration frameworks

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[8] ITU-T Recommendation L.1470, "Greenhouse gas emissions trajectories for the ICT sector compatible with the UNFCCC Paris Agreement." Available: https://www.itu.int/rec/T-REC-L.1470

[9] 6G-IA, "Sustainability KPIs for 6G," 6G Smart Networks and Services Industry Association, 2024. Available: https://6g-ia.eu/sustainability/

should therefore incorporate lifecycle-aware placement and scheduling policies capable of favouring reusable, repairable, or longer-lived infrastructure resources whenever operationally feasible. Coupling AI-based prediction of hardware ageing and embodied carbon with trusted ledgers for sustainability reporting across environmental dimensions (e.g., energy, carbon, lifecycle metrics) can support auditable records aligned with European Green Deal and Corporate Sustainability Reporting Directive (CSRD) requirements. In turn, this strengthens accountability and interoperability of sustainability metrics across vendors and operators.

Convergence of Programmability and Sustainability: Agentic 6G Networks

The convergence of programmability and sustainability leads to *agentic* 6G networks—cognitive infrastructures capable of self-reasoning and negotiation. In this vision, nodes anticipate failures and self-heal, negotiate cross-domain resource allocation based on sustainability budgets (e.g., energy or carbon constraints), learn continuously via self-supervised and federated paradigms, and enforce energy, security, and compliance constraints jointly. Programmability becomes the vehicle for sustainable execution, where each service request is mapped to the most responsible combination of compute, spectrum, and hardware resources.

Challenges Ahead and European Outlook

The transition to AI-native, sustainable 6G exposes challenges that extend beyond individual projects and require coordinated European responses. Key challenges include: data availability and sovereignty (domain-specific datasets remain scarce and fragmented); AI compute and hardware dependencies (continued reliance on non-European chipsets and accelerators); interoperability and standardisation pace (harmonised APIs and semantics for intent-driven control are still maturing across 3GPP/ETSI/O-RAN/AI-RAN); verification, safety, and regulatory alignment (methodological challenges around explainability, liability, and continuous-learning systems under high-risk classifications); and the economic and skills ecosystem (cross-disciplinary talent requirements spanning AI engineering, energy systems, and network operations).

Europe’s areas of strength include leadership in open, standardised architectures (e.g., O-RAN, ETSI ZSM, 6G-IA SRIA), strong policy frameworks linking AI trustworthiness, data sovereignty, and sustainability (e.g., the AI Act, the Data Act, and the Green Deal), collaborative R&D through SNS JU projects, and an early focus on sustainability metrics (including energy, carbon, and lifecycle indicators) and KVIs. Areas where Europe may fall behind include AI hardware and semiconductor sovereignty, constrained large-scale data access and foundation-model pre-training due to privacy and fragmentation, and slower venture-scale commercialisation in fragmented markets.

Taken together, AI-driven programmability and sustainable execution are not merely technical enablers; they are foundational pillars for a socially, economically, and environmentally responsible 6G ecosystem. They require purpose-built governance, shared metrics, lifecycle-conscious model design, and policies that reconcile innovation with public values—so that Europe’s ambitions for digital sovereignty and climate neutrality can be achieved without leaving social equity behind.

Sustainability in AI-driven 6G networks (SNS-JU perspective)

The transformation of 6G into an AI-native, self-optimising ecosystem has implications not only for technical performance, but also for long-term sustainability across environmental, social, and economic dimensions. Drawing on case-study evidence from SNS JU projects (as synthesised in the SNS JU Sustainability White Paper), several themes complement and deepen the vision of AI-driven programmability and sustainable execution.

Sustainability and trade-offs. Many SNS JU projects adopt ambitious environmental targets motivated by energy-efficiency considerations, such as reducing energy consumption, minimising carbon emissions, and increasing circularity in hardware design. However, these goals involve trade-offs: the resource demands of AI (compute, memory, data) can undermine energy-efficiency aims unless addressed explicitly. This reinforces the need to embed sustainability-aware optimisation across architectural layers—optimising not only network orchestration (energy per bit) but also the AI models themselves for eco-efficiency. SNS JU work also emphasises methodologies such as life-cycle assessment, embodied-carbon accounting, and eco-design to measure and mitigate environmental footprint. It calls for cooperation on standardised sustainability metrics (e.g., carbon per bit, hardware circularity) so that projects can compare impacts meaningfully and converge on best practices. This aligns closely with the AI-native execution layer, where lightweight and resource-efficient models (pruned, quantised, federated) reduce compute overhead and the carbon footprint of continuous learning and decision-making.

Sine-qua-non layers: economic and social sustainability. SNS JU analysis indicates that sustainability in 6G must go beyond environmental concerns. Many projects treat economic and social dimensions as equally important. In the economic dimension, KVIs are used to assess operational expenditures, total cost of ownership, and business-model viability; in the social dimension, trust, equity, and data sovereignty emerge as critical values. Within an AI-native 6G paradigm, these social and economic goals translate into concrete design requirements. For example, intent-based policy control can include sustainability “budgets” such as CO_2 constraints not only per slice but also per actor (operators, verticals). The network’s intelligence can then negotiate resource use that optimises both cost and environmental impact while preserving fairness and transparency for different user groups. Compliance with EU regulation—such as the CSRD—also becomes increasingly relevant. By embedding logging and reporting mechanisms into network operation (e.g., via trusted ledgers), 6G systems can contribute to auditable and verifiable sustainability reporting, helping operators meet emerging obligations.

Implementation considerations and governance. SNS JU projects frequently report tensions between short-term performance KPIs and long-term sustainability goals. Methods such as lifecycle modelling or digital-twin simulation can increase development complexity and cost, but are often justified by long-term payoffs through more efficient operations, better reuse of infrastructure, and alignment with regulatory frameworks. To address governance challenges, cross-project coordination and shared monitoring mechanisms for KVIs and sustainability are recommended, implying that programmability and sustainability efforts should be supported by a governance framework spanning projects and verticals to ensure consistent measurement, shared objectives, and collective accountability.

Equity and social impact. Sustainability in AI-native 6G is not just about energy and cost, but about social inclusion and equitable access. There is a risk that advanced, AI-driven networks could exacerbate digital divides unless deliberate equity measures are built in. Intent-based control policies can therefore be designed to prioritise underserved areas or user groups, balancing an environmental ceiling with a social floor—optimising not only for efficiency, but also for fairness. Moreover, crowdsourced data via federated learning helps build more representative models, improving both technical performance and the social legitimacy of system intelligence.

All in all, to stay competitive, Europe must combine policy leadership with technical execution, ensuring that AI-driven programmability becomes both a sovereign capability and a sustainability multiplier.

4 Distributions in the 6G Network

The architecture of 6G will be fundamentally shaped by the geographical and logical dispersal of resources, intelligence, and control across the network continuum, from user devices and radio access to the far edge and centralised cloud. This marks a clear departure from hierarchical, centrally orchestrated models towards a dynamic, service-aware fabric. The drivers of this shift are not purely technical; they arise from the combined demands of ultra-low latency, massive data processing, and sustainability by design. As a result, the central challenge is no longer simply where resources are placed, but how their distribution is continuously managed to optimise performance, resilience, and environmental impact over the full lifecycle of services.

The future 6G network operates as a tightly integrated mesh of heterogeneous resources. Access, transport, compute, data, and intelligence are no longer cleanly separable layers but interdependent elements of a distributed system whose composition evolves at runtime, as reflected in recent surveys of 6G requirements and architectural trends. Within this fabric, the following dimensions characterise how distribution manifests across the network continuum:

- **Access:** Hyper-dense, cell-free deployments integrating terrestrial (including mmWave and sub-THz) and non-terrestrial nodes, dynamically forming service-specific clusters[10].
- **Transport:** Programmable, slice-aware connectivity fabrics capable of adapting routing decisions based not only on traffic demand but also on energy availability and carbon considerations.
- **Compute & Data:** A compute continuum spanning devices, edge, and cloud, with a pronounced shift towards edge processing for latency-sensitive and data-intensive workloads, supporting both AI inference and large-scale training.
- **Intelligence:** AI as a distributed capability rather than a centralised service, with real-time radio resource management in the RAN, federated learning coordination at the edge, and large-scale optimisation in the cloud[11].

Together, these elements form an inherently dynamic fabric in which service compositions and resource allocations are expected to reconfigure frequently in response to mobility, demand fluctuations, and explicit sustainability intents.

Energy heterogeneity fundamentally reshapes how distribution must be optimised. The sustainability of this distributed fabric hinges on its power profile, particularly energy consumption patterns. 6G nodes will operate under markedly heterogeneous energy conditions, combining stable grid-supplied power at core and high-reliability sites with opportunistic and independent energy sources at the edge and access. The increasing role of non-terrestrial platforms and aerial access infrastructures further amplifies this heterogeneity[12]. In parallel, advances in RF energy harvesting and self-powered wireless systems enable new classes of autonomous and low-power nodes[13]. As a consequence, energy availability varies significantly across space and time, rendering assumptions of uniform or static power supply increasingly invalid.

Energy-source-aware orchestration becomes a prerequisite for sustainable distribution. Task placement, data routing, and workload scheduling must therefore evolve to account for both performance constraints and the temporal characteristics of energy supply. Deferrable or non-critical tasks, such as background optimisation or AI model training, can be aligned with periods of high renewable availability, while latency-critical services may continue to rely on more stable energy sources. In this way, distribution decisions contribute not only to service quality, but also to improved utilisation of renewable energy and

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[10] C. Alwis, et al., "Survey on 6G Frontiers: Trends, Applications, Requirements, Technologies and Future Research," in IEEE Open Journal of the Communications Society, 2021, doi: 10.1109/OJCOMS.2021.3071496.

[11] A. Alzailaa, et al., "A Review of the Current Usage of AI/ML for Radio Access Network (RAN)," in IEEE Access, 2025. doi: 10.1109/ACCESS.2025.3586800.

[12] N. Dao, et al., "Survey on Aerial Radio Access Networks: Toward a Comprehensive 6G Access Infrastructure," in IEEE Communications Surveys & Tutorials, Second Quarter 2021. doi: 10.1109/COMST.2021.3059644

[13] S. Arinze, et al., “RF Energy-Harvesting Techniques: Applications, Recent Developments, Challenges, and Future Opportunities,” Telecom, 2021. https://doi.org/10.3390/telecom6030045

reduced systemic waste, including the avoidance of curtailment during periods of surplus generation.

Distributing intelligence requires explicit accounting for the cost of AI. AI-native operation is a defining feature of 6G, yet AI workloads—particularly large foundation models—introduce substantial energy, hardware, and latency costs. If these costs are not explicitly considered, the efficiency gains promised by AI-driven optimisation risk being offset by increased compute demand. Environmentally sustainable distribution therefore requires deliberate choices regarding where and how intelligence is deployed, favouring lightweight, pruned, and quantised models for pervasive inference, constraining the use of large models to cases where they deliver clear value, and hosting compute-intensive workloads where low-carbon energy is available. Recent analyses of AI-related rebound effects highlight the importance of addressing these trade-offs explicitly[14].

Lifecycle considerations extend sustainability beyond operational energy, to include embodied carbon, material use, and infrastructure longevity. In a highly distributed infrastructure, sustainability also depends on how long resources remain useful. Designing for longevity and lifecycle consistency becomes critical. Hardware such as massive MIMO arrays, edge servers, and embedded devices must support repairability, modular upgrades, and extended lifetimes in order to reduce embodied environmental impact. Software-defined functionality can further extend the usefulness of physical assets by enabling new capabilities without wholesale replacement, provided that lifecycle attributes are integrated into system-level design and operational control.

Eco-powered orchestration must balance local optimisation with system-level effects. At the system-level, these considerations converge in the role of the orchestrator. An environmentally sustainable 6G network requires an eco-powered orchestration function capable of making holistic placement and routing decisions across the distributed fabric. Such an orchestrator must evaluate migration thresholds and timing, determining when the sustainability benefit of relocating a service outweighs the energy and latency cost of migration itself. Crucially, it must also detect and mitigate rebound effects, where improvements in efficiency per task or per bit stimulate increased demand and lead to higher overall consumption[14].

Distribution also enables circularity to become an operational concern. This perspective extends beyond embodied carbon alone. Distributed orchestration can also support circular infrastructure management by integrating visibility into refurbishment state, maintenance history, software support status, and recoverable material value. Such capabilities enables runtime optimisation strategies that minimise premature infrastructure replacement, extend operational lifetimes, and reduce dependence on critical raw materials and external supply chains. In this sense, sustainability-aware distribution becomes not only an environmental optimisation problem, but also a strategic resilience and sovereignty mechanism. If orchestration systems have visibility into embodied carbon, remaining service life, and hardware health, runtime decisions can favour resources with lower embodied impact or longer remaining lifetimes. In this way, distribution supports not only short-term efficiency optimisation but also long-term resource conservation and circularity.

Current research shows strong progress, but market-scale validation remains limited. Recent research efforts within European 6G programmes demonstrate strong conceptual convergence around sustainability-by-design and increasing maturity in energy- and carbon-aware optimisation. At the same time, experimental work on AI-driven green orchestration illustrates the feasibility of runtime sustainability control. However, most results remain validated in simulated or controlled environments. Large-scale, multi-stakeholder pilots in live networks are still scarce, and the absence of standardised, open interfaces for exchanging granular sustainability data continues to constrain interoperability and large-scale adoption.

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[14] A. Luccioni, et al., “From efficiency gains to rebound effects: The problem of Jevons' Paradox in AI's polarized environmental debate,” ACM Conference on Fairness, Accountability, and Transparency, 2025.

In summary, distribution is a first-order sustainability lever in 6G. By tightly coupling resource placement, energy awareness, and intelligent orchestration, the network evolves from a passive consumer of energy into an active participant in a broader energy ecosystem. Achieving this transformation requires treating distribution as a dynamic, sustainability-aware control problem, primarily driven by energy efficiency and environmental constraints—one that reconciles immediate service constraints with the long-term imperative of operating within planetary boundaries.

5 Balancing Sustainability with Resilience & Trustworthiness

Resilience, trustworthiness, and sustainability—particularly environmental sustainability—are tightly interwoven objectives in the design of future 6G networks, yet they are not always aligned in current practice, due to how they are addressed across technical, organisational, and economic domains. These tensions are therefore not inherent, but emerge from current design choices, incentive structures, and disciplinary separation in how these objectives are addressed. Mechanisms that improve resilience and trustworthiness—such as redundancy, continuous monitoring, cryptographic verification, and anomaly detection—typically increase resource consumption and energy demand. Conversely, aggressive optimisation for energy and cost efficiency can weaken robustness and erode trust. This inherent tension places resilience and trustworthiness at the centre of sustainability-by-design considerations, rather than treating them as orthogonal system properties[15].

Resilience and trust often compete directly with environmental and economic sustainability goals. Highly resilient systems rely on redundant links, backup compute resources, replicated data, and continuous health monitoring to ensure service continuity under failures or attacks. Trust-enhancing mechanisms such as encryption, authentication, integrity verification, and AI-based threat detection similarly strengthen system reliability and user confidence, but introduce computational overhead and additional signalling. When such mechanisms are applied uniformly and persistently, they increase operational energy consumption and infrastructure utilisation, creating a direct trade-off with environmental and economic sustainability objectives.

Adaptive reliability and selective trust enforcement emerge as key enablers of robust operation under sustainability constraints, particularly energy efficiency. Rather than maintaining maximum redundancy and security at all times, future 6G systems increasingly rely on dynamic adaptation of resilience and trust mechanisms to operational context. Reliability levels, monitoring intensity, and verification depth can be scaled based on risk, service criticality, and system state. When risk is low or energy availability is constrained, protection mechanisms can be relaxed without compromising overall system integrity; when risk increases, additional safeguards can be activated temporarily. This adaptive approach avoids systematic over-provisioning while preserving robustness where it is genuinely required.

Trustworthiness mechanisms must themselves become sustainability-aware. Trust in 6G networks is increasingly mediated by computational processes, including cryptographic protocols, AI-based anomaly detection, policy engines, and reputation mechanisms. The “cost of trust” is therefore multi-dimensional, encompassing energy consumption, latency, and system complexity. Sustainability-aware trust design requires explicit consideration of these costs, favouring lightweight verification where appropriate, reducing unnecessary re-authentication, and aligning trust enforcement with service-level requirements rather than applying uniform policies across all contexts.

Risk- and context-based security supports both trust and sustainability objectives. A key convergence point between trustworthiness and sustainability lies in risk-based and context-aware security models. By

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[15] This section synthesises insights and technical patterns derived from SNS research activities, with primary inputs drawn from the SNS projects NATWORK, Hexa-X / Hexa-X-II, SAFE-6G, XTRUST-6G and iTrust6G.

continuously assessing contextual information—such as threat level, service criticality, and operational environment—networks can tailor access control, isolation, and monitoring strategies dynamically. This reduces the need for blanket enforcement of high-overhead security mechanisms, limiting energy and compute costs while preserving protection where it is most needed.

Trust, resilience, and sustainability extend beyond technical mechanisms into social and economic dimensions. Trustworthiness is not solely a technical attribute; it is also shaped by transparency, explainability, and user perception. Systems that dynamically adapt security and resilience must remain understandable and predictable to operators, regulators, and users. From a sustainability perspective, this is critical: opaque optimisation decisions can undermine trust even if they improve energy efficiency. Explainable and user-centric trust management is therefore a prerequisite for long-term societal acceptance and sustainable deployment of 6G services.

In summary, environmentally sustainable 6G requires rethinking robustness and trust as adaptive, not static, properties. Balancing sustainability with resilience and trustworthiness cannot be achieved through fixed design margins or maximal protection strategies. Instead, it requires systems that continuously negotiate trade-offs between energy use, robustness, and trust, guided by context, risk, and service intent. By embedding adaptive reliability, sustainability-aware trust enforcement, and transparent decision-making into the network fabric, 6G systems can achieve high levels of robustness and trust without compromising environmental and economic objectives.

Evidence and analysis supporting the above observations are reported across European 6G research activities on sustainable and trustworthy network design, including work on adaptive cybersecurity, selective trust enforcement, risk-based security, explainable trust management, and sustainability–trust trade-offs.

6 Decision Support & Actionable Interfaces

Sustainability-by-design in 6G cannot be realised through metrics and optimisation alone; it requires decision support mechanisms that translate sustainability insights into concrete, operational actions. As networks become increasingly complex, distributed, and AI-driven, both human operators and automated control systems need interfaces that make sustainability impacts visible (e.g., energy use, carbon intensity, resource consumption), interpretable, and actionable across design-time and run-time horizons.

Decision support in 6G must bridge intent, system behaviour, and sustainability outcomes. Future 6G systems are expected to operate under multiple, often competing objectives, spanning performance, resilience, trustworthiness, cost, and sustainability. Decision support mechanisms therefore need to connect high-level intents—expressed by operators, verticals, or policy frameworks—to low-level system configurations and observable impacts. Without such a bridge, sustainability risks remaining an abstract aspiration rather than a controllable system property.

Network Digital Twins enable predictive and exploratory energy and environmental sustainability analysis. Network Digital Twins provide a data-driven representation of network behaviour that can be used to assess and anticipate the energy and environmental implications of design and operational choices. By supporting "what-if" analyses, digital twins allow alternative deployment, configuration, or orchestration strategies to be evaluated before they are applied to live systems. This capability is particularly important for emerging 6G technologies, where performance and sustainability outcomes are highly sensitive to environmental conditions and configuration choices. At the same time, the energy and resource cost associated with maintaining and executing digital twins, and their broader sustainability implications must itself be considered, as excessive model fidelity or data retention can undermine the intended benefits.

Knowledge Graphs provide traceability and structure to complex sustainability decisions across

environmental, economic, and social dimensions. Designing end-to-end 6G systems that satisfy both KPI and KVI requirements across diverse use cases involves navigating complex interdependencies between enablers, constraints, and trade-offs. Knowledge Graphs[16] offer a structured way to represent these relationships explicitly, linking requirements to system components, design principles, and resulting performance and sustainability impacts. By making such dependencies transparent, Knowledge Graphs support traceability from high-level objectives to concrete design decisions and enable systematic exploration of trade-offs between performance-oriented and sustainability-oriented solutions. This explicit representation also helps reduce implicit developer bias, which otherwise risks steering designs toward familiar or performance-dominant configurations.

Knowledge-driven decision support enables reduced-bias and adaptable system design. By encoding relationships between enablers, use-case requirements, and sustainability indicators (e.g., energy, carbon, lifecycle, and societal indicators), Knowledge Graph-based approaches allow alternative system designs to be compared on a consistent and explainable basis. This supports more balanced decision-making, particularly where sustainability objectives, in particular energy efficiency and environmental impact targets, might otherwise be overshadowed by short-term performance considerations. Importantly, such approaches do not replace human judgement, but augment it with structured, evidence-based insight that can be inspected, challenged, and refined.

Closed-loop integration of Digital Twins and Knowledge Graphs supports continuous adaptation. A key strength of combining Digital Twins with Knowledge Graph-based design lies in enabling closed-loop system evolution. Operational insights generated by digital twins—derived from live or synthetic data—can be fed back into the Knowledge Graph to reassess assumptions, update dependencies, and refine KPI/KVI targets. In turn, updated design insights can trigger controlled reconfiguration of the live system. This slow, closed-loop adaptation helps avoid over-provisioning, supports continuous improvement, and ensures that sustainability objectives remain aligned with real-world system behaviour rather than static design-time assumptions.

Actionable interfaces must embed sustainability into operational workflows. For decision support to influence day-to-day operation, sustainability insights must be surfaced through interfaces that align with existing operational practices. Lightweight dashboards, APIs, and northbound interfaces can embed sustainability feedback directly into monitoring and control loops, enabling operators and automated agents to observe how configuration changes affect energy use, carbon intensity, or resource utilisation. Sustainability information should therefore be contextual, timely, and actionable rather than confined to static reports.

Energy-budgeted intent enables practical sustainability control. An important evolution in decision support is the expression of sustainability objectives as explicit intents, such as energy or carbon budgets. When combined with Knowledge Graph-based design and Digital Twin analysis, such intents can act as triggers for controlled system reconfiguration. This closes the loop between intent, execution, and evaluation, enabling sustainability objectives to be enforced dynamically rather than retrospectively assessed.

Digital Product Passports (DPP) should be created to expand the current focus on carbon to include **Critical Raw Materials (CRM)** and **Rare Earth Elements (REE)**. A 6G sustainability ledger should incorporate a **DPP** for every network element. This passport must track the concentration of materials such as Gallium, Indium, and Neodymium. By leveraging Distributed Ledger Technology (DLT), the DPP provides recyclers with an automated 'teardown recipe,' identifying precisely which components contain hazardous substances or high-value minerals, thereby increasing the economic viability of urban mining and material recovery, and being

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[16] Jain, Akshay, et al. "Knowledge Graph-Based approach for Sustainable 6G End-to-End System Design." arXiv preprint arXiv:2507.08717 (2025).

easily reflected into a component in Knowledge Graphs.

In summary, Knowledge Graphs are a foundational element of sustainable 6G decision support. By combining Knowledge Graphs for traceable system design, Digital Twins for predictive analysis, and intent-based interfaces for operational control, 6G networks can move from static sustainability targets to continuous, evidence-based optimisation. Decision support thus becomes the mechanism through which sustainability is operationalised, governed, and evolved over time, transforming sustainability from a reporting obligation into an intrinsic system capability.

7 Lessons Learned from Early Sustainable 6G Research

This section synthesises the main lessons emerging from early research and innovation efforts on sustainable 6G systems. The observations reflect both **subject-level insights**, concerning where the ICT sector currently stands with respect to environmental, social, and economic sustainability, and **programme-level insights**,

concerning how well research initiatives have translated sustainability intent into measurable and actionable outcomes. Taken together, these lessons highlight areas of genuine progress as well as structural limitations that must be addressed to move from exploratory experimentation to systemic impact.

7.1 What worked well

Sustainability has become a recognised design driver rather than an afterthought. Across the research portfolio, sustainability is no longer treated as a purely external constraint or reporting obligation. Many initiatives explicitly integrate sustainability considerations into system architecture, orchestration strategies, and evaluation frameworks. This marks a significant cultural shift compared to earlier generations, where sustainability was often addressed only implicitly through energy-efficiency improvements.

Energy efficiency provides a strong and measurable anchor. Operational energy reduction has emerged as the most mature and consistently addressed sustainability dimension. The availability of established metrics, monitoring mechanisms, and optimisation techniques has enabled tangible progress and comparable results across diverse technical approaches. This shared focus has created a common baseline from which more complex sustainability dimensions can be explored.

AI-driven optimisation has demonstrated real sustainability potential. The application of AI and advanced optimisation techniques to resource management, traffic steering, and orchestration has delivered measurable energy gains while maintaining performance targets. These results illustrate AI’s dual role as both a performance enabler and a sustainability multiplier, particularly when embedded directly into control and management loops.

Modularity and flexibility are widely embraced as enablers of long-term sustainability. Architectural choices favouring modularity, virtualisation, and reconfigurability are now common. Such designs improve resilience and scalability while also supporting sustainability goals by enabling incremental upgrades, reuse of infrastructure, and adaptation to evolving requirements without wholesale replacement.

The use of KVIs signals progress towards holistic sustainability assessment. Although still immature, the increasing adoption of Key Value Indicators represents an important step beyond narrow KPI-centric evaluation. KVIs have helped broaden the sustainability discourse to include economic and societal dimensions, and they provide a conceptual bridge between technical performance and human-centred impact.

7.2 What did not work well

Sustainability methodologies remain fragmented and inconsistent. Despite broad agreement on the importance of sustainability, there is little methodological convergence. Definitions, baselines, target values, and validation approaches vary significantly, limiting comparability and making it difficult to aggregate results at programme level. This fragmentation weakens collective learning and slows the emergence of best practices.

Environmental sustainability is still narrowly defined. Energy efficiency dominates the sustainability narrative, often to the exclusion of other environmental dimensions such as circularity, material use, lifecycle impacts, and biodiversity. End-of-life considerations, component reuse, and refurbishment strategies remain largely underdeveloped or treated qualitatively rather than systematically. In particular, limited attention has been given to the operational realities of telecom infrastructure lifecycle management, including decommissioning, reverse logistics, refurbishment ecosystems, secondary equipment markets, and critical-material recovery. Limited attention has been given to the physical and operational challenges associated with infrastructure decommissioning, dismantling, material separation, battery handling, and recovery logistics across geographically distributed telecom infrastructures. As a result, sustainability discussions often remain focused on operational optimisation while underestimating the growing environmental and strategic impact of infrastructure replacement cycles, especially for AI-accelerated and edge-compute platforms. These aspects will become increasingly important as edge-cloud and AI-native deployments scale.

Social and economic sustainability are unevenly integrated. While many initiatives acknowledge social and economic dimensions in principle, they are often treated as secondary or indirectly inferred from technical performance. Broader societal effects—such as equity, trust, usability, or ethical implications—are rarely measured with the same rigour as technical metrics, reducing their influence on design decisions.

Early-stage research struggles to link innovation with measurable impact. Projects operating at lower technology readiness levels frequently find it difficult to translate architectural concepts into concrete sustainability outcomes. In the absence of lifecycle perspectives or operational data, sustainability remains abstract and decoupled from real-world constraints.

Limited engagement with policy and governance constrains impact. A recurring limitation across projects is that sustainability approaches remain fragmented and are not yet fully operationalised in real deployment contexts. While emerging frameworks such as KVIs represent an important step towards capturing broader sustainability dimensions, their application remains heterogeneous and at an early stage of maturity across projects. In addition, validation is frequently limited to controlled environments or small-scale pilots, which restricts confidence in the scalability and real-world applicability of proposed solutions. Finally, interactions with industrial practices, governance frameworks, and standardisation processes remain insufficiently structured, limiting the translation of project outcomes into widely adopted solutions. These challenges point to the need for more systematic approaches to integrating sustainability into operational workflows, validation processes, and ecosystem coordination, as further discussed in Section 8.

7.3 Overall lessons

Taken together, these observations suggest that **sustainable 6G research** is at a transitional stage. Strong intent, technical ingenuity, and early successes demonstrate that **sustainability by design** is feasible. However, the current phase is characterised by methodological diversity, uneven maturity across sustainability dimensions, and limited integration between technical, societal, and policy perspectives. Moving forward, greater emphasis is needed on harmonised methodologies, interdisciplinary collaboration, and **system-level validation**. Only by addressing these gaps can sustainability evolve from an aspirational design principle into a durable and measurable property of future 6G systems.

From a practical deployment perspective, several critical aspects have been overlooked in many discussions. On the one hand, **End-of-Life (EoL)** management and the **Secondary Market** are already realities today, particularly through the transfer of equipment from developed to developing countries. To extend this approach into the 6G era, the industry should move towards a **Hardware-as-a-Service (HaaS)** model, in which vendors retain ownership and responsibility for the EoL phase. Future policies should incentivise the creation of a **Certified Secondary Market for 6G assets**, standardising the *refurbishment-to-compliance* process. This would enable decommissioned, high-capacity urban nodes to be repurposed for rural connectivity, extending hardware lifecycles from the current 7–10 years to more than 15 years.

On the other hand, **software-induced obsolescence** must also be addressed. Sustainable 6G needs to tackle the "**hidden waste**" caused by software updates that render otherwise functional hardware obsolete. Sustainability strategies should therefore explore the software-defined networking (SDN) aspects of 6G, designing software architectures with backward-compatibility layers that enable ***Lean Execution Modes*** on legacy hardware. This would allow older 5G and early-generation 6G nodes to continue providing reduced but valuable functionality as core networks evolve, preventing the premature retirement of viable assets.

Taken together, these considerations imply that 6G sustainability also requires a shift in procurement and ownership models. HaaS approaches, where vendors retain ownership of physical assets, combined with mechanisms to mitigate software obsolescence, introduce a new economic paradigm for telecom infrastructure. This shift aligns manufacturers' incentives with hardware longevity, repairability, and efficient EoL recovery. Furthermore, **6G standardisation** efforts should provide the necessary technical hooks to support regulatory compliance with ***Right to Repair*** legislation, ensuring that third-party maintenance is feasible through open diagnostic interfaces and modular component availability.

8 Conclusions and Future Directions for Sustainable 6G

This white paper set out to examine how sustainability can be embedded *by design* into future 6G networks, moving beyond aspirational goals and isolated efficiency improvements toward systematic, operational integration. Drawing on evidence from European research and innovation activities, the analysis highlights both tangible progress and persistent gaps. Taken together, the findings confirm that sustainable 6G is technically feasible, but that its realisation depends on coordinated advances across architecture, control, metrics, and governance.

Sustainability in 6G must be treated as a system property, not a local optimisation. Across the paper, a consistent theme emerges: sustainability cannot be achieved through isolated improvements at component or subsystem-level. Energy-efficient radios, greener hardware, or optimised AI models are necessary but insufficient on their own. Sustainability outcomes are shaped by how resources are distributed, orchestrated, and adapted over time, and by how trade-offs are negotiated between performance, resilience, trustworthiness, and cost. This systemic perspective represents a fundamental shift from earlier generations, where sustainability was often equated with energy efficiency alone.

Circularity, reuse, and strategic materials resilience. Beyond energy efficiency, we should promote a circular and sovereign lifecycle approach to European digital infrastructure. Telecom, cloud-edge, AI and device infrastructures developed under the 6G scope shall be designed for modularity, repairability, software-driven upgradeability, and partial hardware replacement, reducing premature equipment obsolescence and extending operational lifetimes. Industrial Innovation Facilities must support refurbishment, reuse, remanufacturing, and interoperability validation of network equipment and edge-compute platforms across multiple technology generations. Particular attention should be given to the recovery, traceability, and strategic management of critical raw materials and semiconductor-related components relevant to European technological sovereignty. Beyond environmental considerations, circular infrastructure management also contributes directly to European technological resilience by reducing dependence on external supply chains for semiconductors, rare earth elements, batteries, and specialised compute platforms. In this sense, circularity becomes not only a sustainability objective, but also a strategic sovereignty mechanism. Annual reporting should include indicators on equipment lifetime extension, reuse and refurbishment rates, recycled-material integration, recovery of critical materials, and reduction of electronic waste associated with infrastructure renewal cycles. Open and interoperable architectures shall be promoted not only for competition and innovation purposes, but also to reduce lifecycle waste and avoid unnecessary replacement of operational infrastructure.

AI-native programmability is a critical enabler, but also a source of new sustainability risks. AI-driven control and automation provide powerful tools for optimising resource use, adapting to dynamic conditions, and enforcing sustainability constraints at runtime. At the same time, AI introduces new energy, compute, and complexity costs that must be explicitly accounted for. The analysis shows that sustainable 6G requires not only *using* AI for optimisation, but also *governing* AI itself as part of the sustainability problem, including its lifecycle, placement, and interaction with human decision-makers.

Distribution, trust, and decision support are inseparable from sustainability outcomes. The transition to highly distributed 6G architectures amplifies both opportunities and challenges. Energy heterogeneity, edge intelligence, and dynamic service composition make sustainability more actionable, but also more complex. Trustworthiness and resilience, traditionally treated as independent design objectives, emerge as central sustainability factors due to their resource and energy implications. In this context, decision support mechanisms—such as digital twins, knowledge-graph-based design, and intent-driven control—become essential for translating high-level sustainability objectives into accountable operational behaviour.

Current research demonstrates strong intent and early success, but lacks systemic consolidation. As highlighted in the lessons learned, sustainability is now widely recognised as a design driver, and measurable progress has been achieved, particularly in energy efficiency and AI-based optimisation. However, methodological fragmentation, limited attention to lifecycle and circularity, uneven treatment of social and economic dimensions, and weak links to policy and standardisation constrain broader impact. Without greater alignment, many promising results risk remaining confined to project-level demonstrations rather than shaping the foundations of future 6G systems.

8.1 Future directions

Looking ahead, several priorities emerge as critical for advancing sustainable 6G from research vision to operational reality.

First, sustainability methodologies must converge and mature. Future work should focus on harmonising definitions, metrics, and validation approaches across environmental, economic, and social dimensions. This includes strengthening the role of KVIs, improving lifecycle and circularity assessment, and developing shared baselines that enable comparison and aggregation of results across initiatives. To support the transition from conceptual development to operational impact, greater emphasis should be placed on the practical integration of sustainability assessment approaches across projects. Rather than converging on a single methodology, efforts should focus on ensuring interoperability, alignment with regulatory frameworks, and consistency in measurement and reporting practices. Coordination mechanisms at SNS JU level can support this process by enabling cross-project comparability and continuous refinement through experimentation and validation. Detailed methodological development of specific frameworks, such as KVIs, will continue within dedicated working groups, including SNS Sustainability activities. In addition, future research should more explicitly develop lifecycle sustainability assessment, rebound-effect analysis, social impact modelling, and sufficiency-oriented approaches, which remain underrepresented across the current portfolio.

Second, closed-loop sustainability control must be validated at scale. While concepts such as energy-aware orchestration, intent-based sustainability constraints, and digital-twin-supported decision support are well established in principle, their real-world applicability remains insufficiently demonstrated. Advancing beyond isolated proofs of concept requires large-scale, multi-stakeholder experimentation environments capable of capturing realistic operational conditions. Concretely, this implies stronger use of federated and cross-project testbeds, integration of real operational data and constraints, and longer-term experimentation to capture system-level and lifecycle effects. It also requires the active involvement of multiple stakeholders, including operators, vendors, vertical industries, and public actors, to ensure that technical feasibility, interoperability, and economic viability are assessed jointly. Such approaches are essential to build confidence in the robustness and scalability of sustainability-driven control mechanisms and to support their transition into operational deployments.

Third, sustainability must be embedded into governance, standardisation, and policy processes. At present, structured mechanisms to translate project-level insights into standardisation and governance processes remain limited. In particular, there is a lack of systematic interfaces between research and innovation activities and standardisation bodies, as well as insufficient alignment between project timelines and standardisation cycles. To address this gap, more operational coordination mechanisms are needed.

These include *stronger alignment between SNS project outputs and standardisation planning*, as well as the early definition of structured standardisation pathways—ideally at proposal preparation stage or at project inception—aligned with relevant SDO timelines. Beyond individual contributions, greater emphasis is needed on *cross-project consolidation of results prior to standardisation*, the development of "translation" activities that convert research outputs into standardisation-ready artefacts, and the establishment of feedback loops between SDO engagement and ongoing project work. Stronger involvement of industrial stakeholders in prioritising standardisation topics, together with more coordinated SNS-wide positions, would further support the effective integration of sustainability considerations into widely adopted specifications. Cross-project coordination is also essential to ensure consistent positioning and to avoid fragmentation of sustainability approaches across initiatives. Such mechanisms would enable sustainability considerations to be more effectively embedded into widely adopted industrial and regulatory frameworks. Supporting structures such as a European Sustainability Observatory for 6G, a 6G Circular Economy Lab, and possible sustainability certification or labelling schemes could help translate project-level results into shared practices, benchmarked evidence, and standardisation-ready outcomes.

Furthermore, sustainable 6G must remain human-centred. Trust, transparency, usability, and societal acceptance are not secondary concerns but prerequisites for long-term success. Future work should therefore continue to integrate human-centred evaluation, explainability, and ethical considerations into the design and operation of AI-native networks.

Finally, in parallel, greater emphasis is needed on circular infrastructure ecosystems for telecom and AI-native networks. Future research and industrial initiatives should explore mechanisms for infrastructure refurbishment, secondary hardware markets, lifecycle-aware orchestration, and interoperable upgrade pathways capable of reducing unnecessary equipment turnover. Open and modular architectures may play an important role in this context by enabling incremental hardware evolution without wholesale infrastructure replacement. Stronger alignment between sustainability objectives, procurement practices, and lifecycle governance frameworks will be necessary to ensure that circularity becomes operationally viable at market scale.

In conclusion, sustainable 6G is achievable—but only through deliberate, system-level design and coordinated action. The transition from intent to impact requires treating sustainability as a first-class architectural and operational concern, supported by intelligent control, robust decision support, and shared governance. If these conditions are met, 6G has the potential not only to reduce its own footprint, but to act as a sustainability multiplier across the wider digital ecosystem. Long-term sustainability will ultimately depend not only on reducing operational energy consumption, but also on governing telecom infrastructure as a circular and strategically resilient material system.

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