Expressing Sustainability in ICT Systems: Resource Usage, Accountability, and Adaptability

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Abstract—**Foundational and rather conceptual approaches, such as the Brundtland definition and the three-pillar model, provide valuable high-level principles for expressing sustainability in general settings. However, the lack of specificity challenges their application in complex technical domains such as telecommunications and future 6G systems, for instance, during system design or configuration. This paper addresses this challenge by building on these frameworks while incorporating insights from planetary boundaries, Doughnut Economics, and resilience thinking. Specifically, we propose three context-specific guiding principles for sustainability: efficient resource utilization, accountability to all stakeholders, and design for adaptability and serviceability. By translating otherwise abstract sustainability principles into comprehensible criteria directly applicable to ICT infrastructures and communication networks, this framework helps close the gap between normative sustainability goals and concrete design choices, supporting more informed decision-making in digital infrastructures.**

I. INTRODUCTION

In an era marked by pressing global challenges, including climate change, resource depletion, and socio-economic disparities, the pursuit of sustainability has emerged as a critical imperative across all sectors. As Europe navigates its path toward a digital and sustainable future, it faces the dual challenge of enhancing technological sovereignty while addressing the environmental impact of its Information and Communications Technology (ICT) and telecommunications infrastructure. In particular, mobile communication systems and large-scale network deployments increasingly shape the energy consumption and resource footprint of the digital ecosystem [1]. This work addresses this gap by developing three applicable, qualitative guiding principles specifically designed for ICT systems that translate abstract sustainability principles into actionable engineering criteria across environmental, social, and economic dimensions.

Traditionally, definitions of sustainability have been framed within broad contexts, such as the Brundtland definition, which defines sustainable development as meeting the needs of the present without compromising the needs of future generations [2]. Another established framework is the Three Pillars of Sustainability, comprising Environmental, Social, and Economic dimensions [3]–[5], established by various international bodies. While these frameworks provide valuable insights into sustainability's overarching goals, environmental stewardship, social equity, and economic viability, they often lack specificity when applied to technical domains like ICT.

To address this gap, we need a sustainability framework that connects high-level principles to practical engineering decisions, sufficiently precise to guide concrete choices yet sufficiently flexible to work across different ICT contexts, from mobile network infrastructure and hardware design to software systems and operational practices.

While motivated by our research activities in SUSTAINET-guardian [6], this work targets broad use in ICT systems. That is, the proposed guiding principles are intended to steer sensible decision-making without mindlessly following metrics. The goal is to provide clear criteria that enable researchers, technology providers, and policymakers to evaluate sustainability trade-offs with only minimal technical knowledge.

The framework integrates environmental, social, and economic considerations, focusing on aspects that ICT practitioners can directly influence: technology design choices, resource allocation, operational efficiency, and system lifecycle management. It provides tools to evaluate how technical decisions impact energy consumption, material use, service accessibility, system resilience, and long-term cost-effectiveness.

The contribution of this work is the proposal of three simple guiding principles for sustainability that are easily applicable in wireless and general ICT contexts. Exemplary use cases are presented in Section IV and Section V. The goal of those principles is to influence design choices without blindly optimizing complex quantitative metrics, and they are therefore suited for users with all levels of technical expertise.

II. RELATED WORK

Existing definitions and guiding principles for sustainability appear very broad for ICT. Therefore, it is difficult for practitioners to derive actionable applications of those principles. Consequently, qualitative guiding principles are needed that assist design choices.

A. World Commission on Environment and Development

In 1987, the World Commission on Environment and Development published the Brundtland Report, which remains the foundational reference for sustainable development. It defines sustainability as the ability of humanity to make development sustainable so that it meets the needs of the present without compromising the ability of future generations to meet their own needs [2, Chapter 3, paragraph 27].

Beyond this core formulation, the report recognizes that sustainability involves limits, though not absolute ones. These limits arise from the current state of technology, social organization, and the biosphere's capacity to absorb human impacts. However, it also acknowledges that technological and societal progress can expand these boundaries and enable new forms of development within ecological constraints. In this sense, the Brundtland definition offers a normative and future-oriented vision rather than a detailed operational framework.

Still, its practical application raises difficult questions. How can we anticipate the needs of future generations when technological and social conditions evolve unpredictably? This uncertainty introduces complexity into defining what sustainable development should entail. A cultural reference illustrates the challenge well: at the end of the film Back to the Future [7], Doc Brown fuels his time machine with household waste—a fictional but thought-provoking metaphor for sustainability. It captures how problems of the present, such as waste and resource depletion, may become sources of innovation and renewal in the future.

Thus, sustainability is not only about preserving resources but also about the continuous capacity to innovate, repurpose, and adapt. This vision closely aligns with contemporary ideas such as the circular economy and zero-waste systems, which aim to transform limitations into opportunities, emphasizing both responsibility for the present and imagination for what lies ahead.

Therefore, this ethical foundation remains essential: intergenerational equity directly connects to our responsibility for critical infrastructure design choices that have lasting impacts far beyond typical product cycles. However, this principle does not translate into engineering practice without additional structure. When designing ICT infrastructure, engineers face interconnected decisions, choosing between hardware options with different resource profiles, balancing performance against consumption, determining upgrade cycles, which require elements the Brundtland framework does not provide: *e.g.*, acceptable resource budgets, prioritization rules when goals conflict, and lifecycle assessment criteria.

B. The Three Pillars of Sustainability

Building on the foundational ideas formulated in the Brundtland Report, efforts to make the concept of sustainability more tangible led to the development of the three-pillar model: three interrelated dimensions that together describe and support sustainability as a whole [8]. Over time, this perspective evolved into the common view of sustainability, emphasizing the environmental, social, and economic dimensions as mutually reinforcing foundations. These pillars are embedded, explicitly or implicitly, in several foundational policy frameworks, including Agenda 21 (UN Conference on Environment and Development, 1992), the World Summit on Sustainable Development (Johannesburg, 2002), and the UN 2030 Agenda for Sustainable Development (2015) [3]–[5].

In line with established sustainability frameworks, the three pillars represent those key dimensions through which sustainability is commonly approached:

- **Environmental:** concerning the state and integrity of natural systems, including the use of resources, emissions, and impacts on ecosystems and biodiversity.
- **Social:** relating to human well-being and societal structures, encompassing equity, inclusion, health, and the stability of communities.
- **Economic:** addressing the generation and equitable distribution of value, the efficient and prudent use of resources, and the long-term resilience and viability of economic systems and activities.

The environmental, social, and economic dimensions should be understood as complementary perspectives for assessing sustainability. Each captures a distinct aspect of how systems persist and develop over time: environmental integrity provides the ecological foundation, social well-being ensures legitimacy and equity, and economic viability enables continuity of activity. Understanding their interaction helps to capture the systemic nature of sustainability, where long-term progress depends on maintaining coherence across all pillars.

Similar to the Brundtland report, taking the three pillars of sustainability into account in the proposed definition ensures that we do not neglect social (reliability of emergency services, inclusion) or economic viability (total cost, supply risk), which are central for networks as critical infrastructure. Furthermore, it enables a familiar framing of sustainability achievements that aligns with policy and corporate reporting.

However, the three-pillar model also has limitations. It invites "trade-off thinking" and offers no rules for when environmental limits must be treated as hard constraints rather than balanced against, potentially short-term, performance gains [8]. Additionally, while environmental impacts can be quantified with Life Cycle Assessment (LCA), social and macroeconomic impacts are much harder to measure.

C. Further Sustainability Considerations

As sustainability challenges have become increasingly complex and global, new conceptual approaches have emerged to complement the foundational ideas of Brundtland and the three-pillar model. While they provide normative and structural foundations, they have been criticized for being too vague and for having a limited capacity to capture systemic constraints. Subsequent frameworks try to refine and extend them by integrating new scientific insights and addressing contemporary societal challenges.

One prominent example is the planetary boundaries framework [9], [10], which grounds sustainability in terms of the biophysical limits of our planet. It defines nine boundaries in different dimensions within which humanity has a "safe operating space", which includes aspects such as climate change, biodiversity loss, and chemical pollution. Exceeding these boundaries increases the risk of irreversible environmental changes at the planetary scale, potentially leading to cascading and catastrophic consequences. Such abrupt shifts are often referred to as tipping points, highlighting the system's sensitivity to crossing critical thresholds [11].

While some dimensions, like climate change, operate at a global scale, others result from local and regional processes that add up. For ICT infrastructure, this matters: a single router or protocol choice might seem small, but when multiplied across millions of systems worldwide, these decisions start affecting planetary-scale boundaries—especially climate change, resource use, and chemical pollution.

Building on the planetary boundaries framework, the Doughnut Economics model [12] extends the purely ecological perspective by explicitly incorporating social and economic dimensions. In this model, sustainable development is conceptualized as a "safe and just space" between a social foundation that ensures human well-being, equity, and access to essential resources, and the ecological ceiling defined by planetary boundaries. By linking ecological limits with societal goals, the Doughnut model provides a framework for understanding the interactions, trade-offs, and synergies that must be managed to achieve sustainability.

The United Nations' Sustainable Development Goals (SDGs), adopted in 2015 as part of the 2030 Agenda [5], complement these conceptual frameworks by providing 17 concrete goals and 169 associated targets integrating environmental, social, and economic dimensions. The SDGs translate broad sustainability concepts into operational objectives for governments, organizations, and communities, ranging from climate action and biodiversity conservation to reduced inequalities and sustainable cities.

Complementing these normative frameworks, Environmental, Social, and Governance (ESG) criteria have gained prominence as a mechanism for translating sustainability into actionable corporate reporting [13], [14]. Unlike the three-pillar model, which provides a conceptual categorization, ESG formalizes the 'Governance' dimension—emphasizing transparency, corporate ethics, and stakeholder accountability—to manage sustainability-related risks. While ESG frameworks help organizations align internal performance with broader sustainability objectives such as the SDGs, they are primarily designed for financial and corporate disclosure.

On another note, resilience thinking emphasizes the capacity of social–ecological systems to absorb disturbances, adapt to changing conditions, and transform when existing structures are no longer viable [15], [16]. Within this framework, three interrelated aspects are central: resilience, which refers to the ability of a system to retain its essential functions and structure despite shocks; adaptability, the capacity of actors within the system to adjust responses to evolving circumstances; and transformability, the ability to create fundamentally new system configurations when necessary.

While each of these frameworks provides complementary insights into what sustainability is, they also have their limitations. The planetary boundaries framework, although strong in defining ecological limits, focuses primarily on environmental aspects and does not explicitly integrate social or economic considerations. Doughnut Economics broadens the perspective to include social foundations and human well-being, but it remains largely conceptual. The SDGs, despite their broad scope, leave unresolved trade-offs between goals—particularly where social, economic, and environmental objectives conflict—and offer limited prescriptive guidance for technical or sector-specific implementation [17]. The ESG criteria focus on high-level reporting metrics rather than the granular engineering decisions or technical trade-offs required for the design of sustainable ICT infrastructure. Resilience thinking provides a useful lens for understanding adaptive capacity and system robustness. However, it is descriptive rather than prescriptive, and quantifying resilience, adaptability, or transformability for technical applications is challenging [18]. Taken together, these frameworks highlight multiple perspectives on sustainability but do not directly address the combined considerations required for designing, operating, and managing ICT infrastructure.

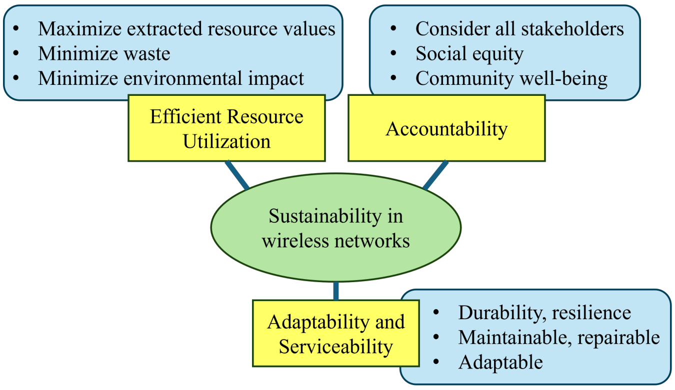

Fig. 1: Schematic overview of the proposed three distinctive guiding principles of sustainability.

III. PROPOSED DEFINITION OF SUSTAINABILITY

To move from abstract principles to actionable guidance, we propose a definition focused on practical implementation by grounding sustainability in informed decisions and enduring design. By centering cost-benefit trade-offs, resource efficiency, social equity, and system longevity, this framework translates lofty ideals into clear criteria for projects and policies.

This is not a universal or general definition, but a specific working definition intended for ICT and wireless networks.

A. Definition

Sustainability refers to balanced decision-making that integrates environmental, social, and economic considerations, accounting for both immediate and long-term impacts. The definition encompasses the following aspects, illustrated in Figure 1:

Efficient Resource Utilization: Maximizing the value extracted from every resource while minimizing waste and environmental impact.

Accountability: Ensuring that all stakeholders are considered and that solutions contribute to social equity and community well-being.

Design for Adaptability and Serviceability: Creating durable and adaptive solutions that remain resilient, maintainable, supportable, and repairable as conditions change, enabling ongoing fixes and upgrades, while allowing for replacement when it clearly increases sustainability.

B. Discussion

Moving on, we discuss how the proposed definition is embedded into the topical landscape and which scope it covers.

1) Relationship to Existing Frameworks: The proposed definition builds on established frameworks, such as the Brundtland definition and the Three Pillars model, while addressing their limitations in technical contexts. Where traditional definitions provide high-level principles, this definition translates those principles into actionable criteria specific to ICT systems. The three aspects—resource utilization, accountability, and adaptability—directly map to the environmental, social, and economic pillars while making them actionable and applicable to technology deployment decisions.

2) Recursive Nature of the Definition: The definition is deliberately recursive: it uses "sustainability" within its own criteria, particularly in "Design for Adaptability and Serviceability," which allows replacement when it "clearly increases sustainability." Rather than providing absolute external standards, this self-referential structure acknowledges that sustainability assessment is iterative and context-dependent. Like a recursive function, each application of the definition refines understanding based on previous evaluations, enabling continuous improvement as technologies and circumstances evolve.

3) Rationale for the Three Aspects: These three aspects were chosen based on the focus on telecommunications infrastructure:

- **Efficient Resource Utilization** addresses the environmental impact of energy-intensive ICT systems, particularly relevant for 5G/6G networks and edge computing.
- **Accountability** ensures that technology deployment benefits all stakeholders, not just operators, addressing digital divides and equitable access.
- **Design for Adaptability and Serviceability** recognizes that ICT infrastructure must evolve over decades, requiring long-term thinking beyond initial deployment.

4) Scope and Limitations: This definition is specifically tailored to guide the research activities in this context and may not encompass all sustainability dimensions relevant to other contexts. It focuses on aspects within the project's control, system design, deployment strategies, and operational practices, while acknowledging that broader factors, such as legislative frameworks and market structures, lie outside the project's scope. The definition does not attempt to quantify absolute sustainability but rather provides comparative criteria for evaluating design alternatives and trade-offs.

5) Practical Application: Existing approaches to evaluating sustainability with quantitative metrics are very complex for non-technical stakeholders to apply to a use case and can lead to blindly optimizing metrics, rather than advancing a sensible sustainability goal [19]. We address this by presenting three qualitative guiding principles that are easy to apply, as shown in an exemplary use case. The subsequent sections demonstrate how the three qualitative guiding principles guide concrete technical decisions across these domains.

IV. USE CASE EXAMPLE (SOFTWARE): CODE OPTIMIZATION FOR SIGNAL PROCESSING IN OPEN RAN

To illustrate how the proposed working definition of sustainability can guide concrete engineering decisions, we consider a use case from the telecommunications domain: code optimization for real-time signal processing in Open RAN and virtualized RAN deployments. Mobile networks consume substantial amounts of energy, with the radio access network (RAN) accounting for the largest share. Within base stations, the radio and power amplifier remain among the largest contributors to power consumption [20], [21]. At the same time, Open RAN introduces several mechanisms that can influence resource usage and energy consumption, including hardware choices, virtualization overhead, runtime power management, and software efficiency [22]–[24]. Because more baseband functionality is executed on general-purpose processing platforms in Open RAN and vRAN systems, implementation efficiency is a relevant factor for improving resource utilization in such systems [22].

In traditional mobile network equipment, many signal-processing functions were executed on highly specialized hardware such as ASICs or FPGAs. In Open RAN and vRAN settings, a larger share of these functions is executed on general-purpose processors in distributed or centralized units. Several studies indicate that virtualization and software-based implementations may introduce additional processing and power overhead compared to more specialized or tightly integrated solutions [22], [23]. At the same time, recent work shows that strict real-time requirements often constrain how aggressively CPU power-saving mechanisms can be applied in current vRAN deployments [24]. In this setting, software optimization should not be understood as the only, or necessarily dominant, energy consumption factor, but rather as a practical means to reduce computational demand and improve resource efficiency within a broader design space [24].

A. Scenario

In this use case, a mobile network operator deploys Open RAN software on commercial off-the-shelf servers for distributed baseband processing. The considered optimization target is the real-time processing chain in Layer 1, where functions such as FFT/IFFT, channel estimation, equalization, demapping, rate matching, and channel decoding are executed continuously and under tight timing constraints. Prior work shows that a relatively small number of such functions account for most of the computational demand in softwarized RAN implementations [25].

In this context, software optimization becomes an important factor for reducing the computational resources required for baseband processing while preserving radio performance. Possible optimizations include improved algorithms, vectorization through SIMD instructions, cache-aware data layouts, reduced memory movement, and the use of optimized kernel libraries. In the software-defined radio domain, VOLK is a well-known example of this approach, providing vector-optimized kernels with architecture-specific implementations. In parallel, platforms such as FlexRAN provide a programmable environment in which such optimizations can be evaluated in a realistic RAN setting [26], [27].

B. Guiding Principles-based Sustainability Assessment

After introducing the use case, we now assess its sustainability using the proposed guiding principles.

1) Efficient Resource Utilization: From the perspective of efficient resource utilization, this use case is directly relevant. If the same radio functionality can be provided with fewer CPU cycles, less provisioned compute capacity, or more timing slack, the resource demand of the baseband platform can be reduced. Even when real-time constraints limit immediate power savings, reducing computational load can still improve resource efficiency by lowering required hardware capacity or enabling additional power-management opportunities. This aspect is particularly relevant in Open RAN, where software inefficiency is no longer hidden inside specialized hardware but appears directly as additional server-side resource demand. Optimized implementations can therefore help reduce operational energy demand, lower cooling requirements, or delay the need for additional compute hardware, depending on system-level power management and deployment constraints. In that sense, better code extracts more value from the same physical resources and reduces waste [24], [25].

2) Accountability: From an accountability perspective, energy savings alone are insufficient. Code optimization is only sustainable if it preserves the required functionality and service quality. In a telco setting, these service-specific needs include meeting real-time deadlines and maintaining relevant radio and service KPIs such as throughput, latency, reliability, and error performance. Otherwise, a nominal CPU saving could be traded against degraded network performance or reduced user experience. Accountability, therefore, requires that optimization results are documented transparently and evaluated not only against software metrics such as CPU load, but also against communication-system metrics that matter to operators and users.

3) Design for Adaptability and Serviceability: From the perspective of adaptability and serviceability, the use case also shows an important trade-off. Highly aggressive micro-optimizations can improve short-term efficiency, but they may create maintenance problems if they are tied too closely to a specific processor generation or vendor-specific implementation details. Sustainable optimization should therefore prefer approaches that remain portable and maintainable, for example, modular kernel libraries, runtime-selected vector implementations, and clearly documented assumptions. This allows the optimized code to evolve together with future CPU generations, accelerators, and Open RAN software stacks rather than becoming technical debt [22], [26], [27].

This use case demonstrates that sustainability in telecommunications is not only about new hardware or reduced traffic demand. In increasingly softwareized mobile networks, code quality becomes a relevant sustainability consideration. Especially in signal processing, where computational hotspots run continuously at large scale, efficient implementations can reduce resource demand while preserving the openness and flexibility promised by Open RAN.

V. USE CASE EXAMPLE (HARDWARE): OPEN RAN SITE MODERNIZATION

To complement the software-oriented example, we consider a hardware-focused use case from the telecommunications domain: the modernization of an Open RAN cell site. In such a scenario, an operator must decide whether to replace the complete site hardware or selectively upgrade components such as the radio unit (RU) and antenna system while reusing the underlying compute platform hosting DU and CU functions [22], [28].

1) Efficient Resource Utilization: From the perspective of efficient resource utilization, selective hardware upgrades can significantly reduce material consumption and embodied emissions compared to full site replacement. If the required coverage and capacity can be achieved with improved radio efficiency or better antenna design, fewer physical resources and less operational energy are required, avoiding overdimensioned deployments [29].

2) Accountability: From an accountability perspective, hardware modernization is only sustainable if it preserves network performance and service availability. This includes maintaining coverage, reliability, and quality-of-service guarantees, particularly for critical services such as emergency communications, ensuring that efficiency gains do not come at the cost of user experience or accessibility.

3) Design for Adaptability and Serviceability: From the perspective of adaptability and serviceability, modular and interoperable hardware architectures, as promoted by Open RAN, enable incremental upgrades and targeted replacements. This allows individual components such as antenna systems to be repaired or upgraded without discarding the entire site infrastructure, reducing long-term waste and supporting evolving technology requirements.

VI. CONCLUSION

This work presents guiding sustainability principles for ICT and communication systems. By translating broad, established frameworks into three simple guiding principles, this work supports transparent decision-making in the design and operation of digital infrastructures and mobile communication networks. The examples discussed illustrate the sustainability trade-offs inherent in modern telecommunications systems and highlight the importance of adaptable and resilient network design. Automation and AI provide promising opportunities to optimize resource utilization in large-scale communication infrastructures, while also introducing new energy considerations. The proposed framework provides a structured basis for evaluating such trade-offs and supporting more sustainable development and deployment of future communication networks.

ACKNOWLEDGMENT

This work was funded by the Federal Ministry of Research, Technology and Space (BMFTR) in Germany under the grant number 16KIS2239K, 16KIS2240, 16KIS2243, 16KIS2251, of the SUSTAINET-guardian project. The responsibility for the content of this publication lies with the authors.

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