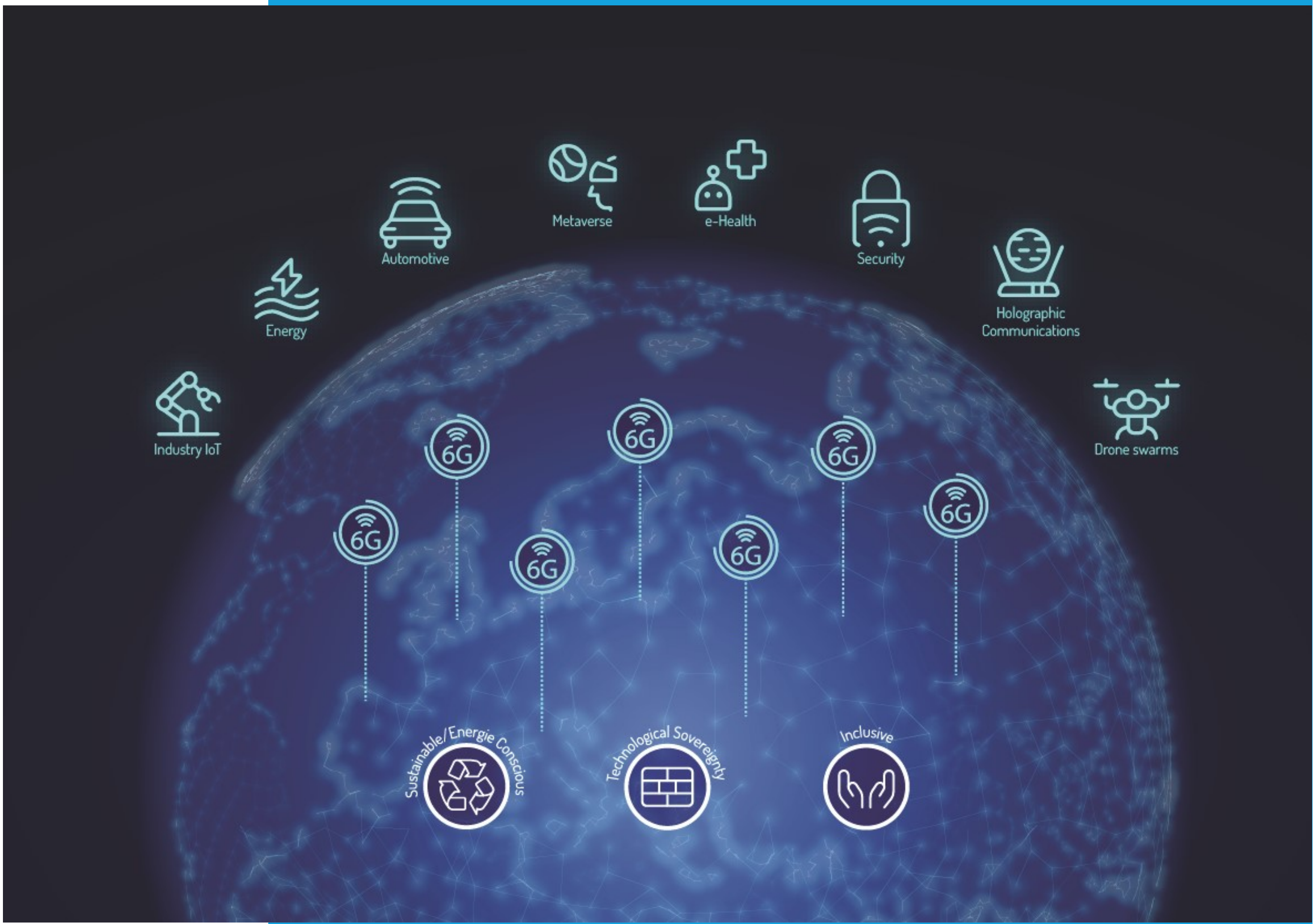
Smart Networks and Services Joint Undertaking (SNS JU)

SNS Technology Board – Sustainability Task Force



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WHITE PAPER

Sustainability in SNS JU Projects

Targets, Methodologies, Trade-offs and Implementation Considerations Towards 6G Systems

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EXECUTIVE SUMMARY

Communication networks are foundational to Europe's digital and green transitions. Sustainability of communication networks enables these dual transitions to be mutually reinforcing. This White Paper (WP), developed by the Smart Networks and Services Joint Undertaking (SNS JU) Sustainability Task Force (TF), outlines the current sustainability posture of a set of its research projects and identifies a strategic pathway towards embedding sustainability further in the European SNS ecosystem and future networks. Sustainability is understood through three interconnected pillars: environmental, economic, and social considerations.

This white paper (WP) presents a comprehensive analysis of how **27 projects funded by the SNS JU** address sustainability in their work on next-generation (6G) communication technologies. The analysis draws on detailed questionnaire responses and follow-up interviews, spanning four core themes: (i) sustainability targets, (ii) methodologies, (iii) trade-offs, and (iv) implementation considerations.

The insights presented reflect the diversity of approaches, opportunities, challenges, and emerging trends across projects operating primarily at low to mid Technology Readiness Levels (TRLs). The participating projects focused predominantly on **environmental sustainability**, with energy efficiency as the primary concern. Techniques such as AI-driven resource management, dynamic power scaling, and network optimisation were widely adopted. Broader environmental concerns such as greenhouse gas (GHG) emissions, circularity, and electromagnetic field (EMF) exposure were addressed less: while some projects experimented with renewable energy integration, many remained neutral regarding this goal, and this is an avenue for future work.

Economic sustainability was primarily framed around cost-efficiency, industrial growth, and technological innovation. Projects explored ways to improve affordability for stakeholders and enable new market opportunities. Few projects addressed the interconnections between economic sustainability and the environmental and social pillars, such as how cost-efficient technologies can reduce environmental impact, or how economic benefits can be distributed equitably across different social groups.

Societal sustainability showed more opportunities for progress out of the three pillars of sustainability. While a majority of projects (85%) reported an attention to the creation of social impact and value – targeting primarily digital and social inclusion – the rich diversity in the focus and scope of interpretations highlighted the need for a better definition and outline for this concept. Although specific metrics for evaluating social impact are not yet defined, this gap suggests a valuable direction for future development. Similarly, the limited representation of the health, well-being, cultural, social cohesion and ethical dimensions of the concept opens the door for deeper exploration and research**.**

Policy and regulatory engagement emerged as a key horizontal realm for further integration. Only one project—a Coordination and Support Action (CSA)—affirmatively declared active involvement in this area, pointing to significant potential for growth. The use of standardised sustainability frameworks (e.g., UN Sustainable Development Goals (SDGs), ITU, ISO) showed partial consistency, and while only a minority of projects used formal impact assessment tools like Life Cycle Assessments (LCA), this points to an opportunity to broaden the adoption of holistic approaches, including greater attention to supply chain and end-of-life impacts.

While many projects incorporated user-centric design approaches and use cases, sustainability concerns were often secondary to technical feasibility, which is an expected posture given the relatively lower TRL targets of the projects. Among others, **Key Value Indicators (KVIs)** were often referenced. The results indicate that KVIs were applied with some variation in interpretation and limited connection to project-level sustainability outcomes in use cases —highlighting valuable questions around KVIs for future research.

Sustainability-by-design was often included in project strategies but largely focused on energy efficiency and savings, with limited adoption of alternative trade-off strategies (e.g., favouring sustainable components over performance). **Circularity and eco-design principles** were minimally adopted. There is therefore a large room for research and action in this regard.

Modularity, scalability, and reconfigurability were widely reported as architectural principles, often driven by performance goals. A clear distinction between projects targeting first-order effects (reducing the environmental impact of technology itself) and second-order effects (enabling sustainability in other sectors) was evident, although quantitative measurement of either remained rare.

Architectural and design trade-offs were acknowledged in several projects. Common dilemmas included centralised versus distributed infrastructure, dedicated hardware versus cloud virtualisation, and latency versus energy optimisation. However, complexity-related trade-offs (e.g., increased computational demands versus sustainability benefits) were rarely explored. A few projects pursued co-optimisation strategies, balancing energy savings with performance, but these were often conceptual rather than fully implemented.

Implementation strategies focused primarily on energy and resource efficiency. Measures included energy-aware protocols, AI-optimised local processing, sleep cycle orchestration, and network-wide dynamic scaling. A few targeted projects explored zero-energy devices and advanced radio unit design.

Four thematic areas defined project-level implementation considerations: (1) efficiency (e.g., orchestration, reduced signalling), (2) scalability and maintainability (e.g., modular architectures), (3) circularity (e.g., lifecycle extension, though rarely applied), and (4) social and ethical factors (e.g., inclusion and fairness, inconsistently addressed). Maintainability, such as upgradeability or repairability, was considered by fewer than 30% of projects.

To summarise, this WP provides a holistic understanding of how sustainability is being incorporated into the European funded communication research ecosystem. The key general insights are as follows:

- **Energy efficiency dominates current sustainability discussions** within the SNS ecosystem, due to its relative measurability and compatibility with existing projects' skills, objectives and TRL targets.
- **Other sustainability dimensions** and **policy and regulatory concerns** are underexplored, offering clear opportunities for deeper engagement.
- Projects often assume **positive sustainability impact** through **performance improvements**, though this may lead to **rebound effects**.

- **Trade-offs** are acknowledged, presenting a valuable opportunity for **more holistic and systematic analysis and quantification towards co-optimization**.
- **Interdisciplinary expertise** is emerging, highlighting a potential to **strengthen sustainability integration** through broader collaboration.
- There is **limited uptake** of policy frameworks, circular economy principles, and lifecycle impact assessments, presenting valuable opportunities for further developments.
- **Sustainability-by-design is growing:** modularity, scalability, and resource sharing are generally used, although typically aimed at performance rather than explicit sustainability goals.
- **KVIs are frequently used,** yet refining their definitions, baselines, targets, validation, and alignment with societal sustainability outcomes offers meaningful potential for improvement.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

The 6G SNS JU TB Sustainability Task Force (TF) has been established under the umbrella of the Smart Networks and Services Joint Undertaking (SNS JU)[1] Technology Board (TB) to investigate, analyse and present the vision, work and approach of the SNS JU projects with regards to Sustainability. As part of this effort, a questionnaire was developed and circulated to all the SNS JU projects to understand their sustainability posture, based on the pioneering work of some of the projects, completed with insights from the entire Sustainability TF. The questionnaire contained 60 questions grouped into four main areas:

- Sustainability Targets,
- Sustainability Methodologies,
- Sustainability Trade-offs,
- Implementation Considerations.

Projects were initially asked to develop their responses to the questionnaire with the involvement of the project leaders and the sustainability-oriented experts in the consortia. Subsequently, detailed interviews were carried out for each project with the participation of the project representatives and the Sustainability TF lead, to go over the responses and make applicable updates.

27 SNS JU projects in total (16 from Call 1 & 11 from Call 2)[2] responded to the questionnaire. Corresponding interviews with the 27 projects were carried out over a period of 7 months within 2024. The 27 projects that participated in this exercise and contributed towards the creation of the overview presented in this paper are mentioned in the *Supporting Projects* section at the end.

All the project responses were analysed by a core team of Sustainability TF experts and editors as mentioned in the *List of Editors & Reviewers* at the end of the document. For each question, a numerical/graphical analysis was made, as well as the generation of key observations, insights and conclusions.

The current document shares the findings of this extensive survey, with the intention to reflect the sustainability posture of the responding SNS JU research projects, their understanding and use of sustainability definitions and methodologies as well as the sustainability impact they target with their execution. Certain gaps have been identified as well as recommendations for action as a result of the analysis of the responses. The target of this work is to provide the readers with insights on how advanced 6G technology research projects tackle sustainability and what support and collaboration they might need to further advance on their sustainability impact targets.

This report is organized in 4 core sections that discuss the findings from various perspectives, beginning with an assessment of sustainability targets (Section 2). It examines the interplay between values, use cases, technology enablers, and sustainability outcomes, differentiating between first and second order effects. The discussion extends to environmental, economic, and social sustainability considerations. Section 3 discusses sustainability methodologies, covering key metrics, indicators, and

[1] https://smart-networks.europa.eu/

[2] At the time of the interviews, SNS JU Call 3 projects had not been started yet.

standards such as Life Cycle Assessment (LCA). It further investigates methods for measuring and assessing sustainability, ultimately exploring structured frameworks for integrating sustainable practices. Section 4 addresses sustainability trade-offs, highlighting the delicate balance between performance, resilience, and sustainability. The emphasis is on transitioning from trade-offs to co-optimization, ensuring that technological advancements align with broader sustainability objectives. Section 5 considers sustainability implementations, emphasizing an end-to-end perspective and the role of technology enablers in driving sustainable outcomes. Key principles and priorities for effective implementation are outlined, offering guidance on embedding sustainability into innovation ecosystems. The report ends with an outlook and recommendations section.

2 SUSTAINABILITY TARGETS

This section describes the specific sustainability targets or objectives that the projects aim to achieve, as well as exploring the sustainability values that underpin and motivate those objectives. The goal is to provide an overview of how sustainability is currently being considered—identifying what is covered, which trends are prioritized, and supporting further analysis of existing gaps, future needs, and areas for continued effort.

This analysis is framed within the broader context of each project's goals, including their Technology Readiness Levels (TRLs), primary technological and innovation aims, and intended impact. With this context established, the section moves on to examine the first- and second-order effects—both positive and negative—that the projects seek to avoid or realize. This helps paint a clearer picture of the types of sustainability impacts the projects are aiming to manage or create.

The section then offers a more detailed look into each of the three pillars of sustainability. First, it reviews how the projects are addressing **environmental sustainability**, with Energy Efficiency (EE) emerging as a common focus area, frequently highlighted in responses to interview questions. Next, it considers **economic sustainability**, where cost-efficiency, innovation, and knowledge sharing are key motivators across the projects. Finally, it discusses **societal sustainability**. The responses here revealed a wide range of interpretations and methods of expressing targets, from guiding principles to measurable KPIs. The section concludes with a brief discussion of how policy and regulatory considerations are being addressed across the projects.

2.1 Sustainability through Use Cases and TRLs

In order to correlate the sustainability posture of the projects to TRLs, the questionnaire investigated the expected TRLs of the project outcomes, as an indication of the maturity levels of the technology components projects intend to deliver. In general, projects with lower TRL levels are concerned with formulating the basic functions and requirements of technologies and demonstrating their feasibility through proof of concepts (TRL3) and lab validations (TRL4, 5) often targeting component level experiments. Only at higher levels would system considerations come into play. It is also often only at the higher levels that specific use cases, stakeholders, and impacts are considered. Individual sustainability considerations like EE and savings can be included at component level as requirements. For low TRL projects, it becomes challenging and nearly impossible to bring system-level sustainability targets since they have limited ways of implementing, testing or evaluating them. This includes, for example, social and economic sustainability targets as well as end-to-end considerations in the environmental domain.

Many projects offered an estimation of a start and end TRL, or a range of TRLs, so minimum and maximum TRL levels have been analysed, as depicted in Figure 1. The average TRL level of the responding projects is around 4. Accordingly, it is deduced that most projects on average consider component level lab validation of their technologies. It can be expected that they would have limited opportunities to demonstrate (much less evaluate) the system level impact of their technology, in terms of societal, economic or environmental values and goals. Stream C and Stream D projects, which target trial level technology demonstrations, would be exceptions as demonstrated by the average targeted maximum TRL levels of 6. Only one of the projects target operational level demonstrations (TRL 7).

In the following sections, the environmental, social and economic sustainability targets of the responding projects will be described. While projects often set targets based on projections, these are typically viewed as expectations and, at the associated lower TRL levels, are not normally taken as evaluated and verified outcomes.

Similarly, it is important to contextualise the sustainability targets in the use cases. Projects cover a diverse array of 6G technology enablers and use cases, mostly focused on technology enabler feasibility in conceptual or lab experimentation level. EE and the pervasive use of AI to deliver optimizations are by far the most addressed aspects. Well established 6G technological enablers such as Reconfigurable Intelligent Surfaces (RIS), Integrated Sensing and Communication (ISAC), Open RAN (O-RAN), Non-terrestrial Networks (NTN) are also common.

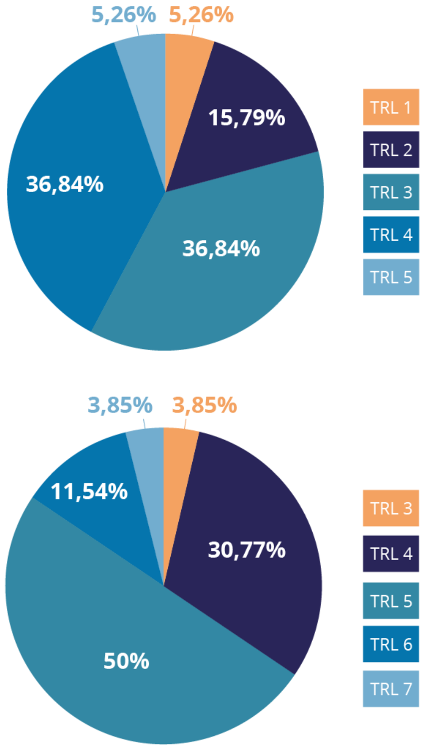

Figure 1: Min & Max TRL Targeted by SNS JU Projects

Concerning use-cases, they are often designed around the technology itself by the developers to showcase what a technology can achieve in terms of features and performance. In general, due to the composition of project consortia being limited in interdisciplinary participation, use cases are not framed by their users: they do not emerge from the perspective of their diverse stakeholders to solve societal, individual, economic or environmental challenges, nor do they necessarily have the opportunity to incorporate or target corresponding social values, as would be the case in the presence of a Key Value analysis process.

2.1.1 First order versus second order effects

Overall, there is an expectation that technology will deliver positive change. Enablement effect, or second order effects, within the context of sustainability considerations, was generally understood by the projects as the positive impact of technology in its use phase in other sectors or processes. The standardized definitions of first and second order effects, which could be negative or positive, have been less differentiated in how they are used. This has a subsequent impact on target setting and assessment of sustainability, as demonstrated in the following subsections.

In general projects expect that the use cases they developed will be helpful and induce positive change. A few projects indicated that they are targeting some form of impact, like affordability and inclusion, impact on various industries, and discussion on KVIs. At the time when the interviews were held, these were mostly indirect inferences not following standardised measurement or assessment methodologies for enabled changes. Based on their use cases, industries like Automotive/Transport/Logistics, Smart Cities, Industry 4.0/Manufacturing, entertainment and IT services were targeted to be positively impacted as well as remote healthcare and education applications. Overall, there is an expectation that through better performance in various aspects, cost savings will be achieved, which eventually should translate into a more economically viable outcome in the user space.

Often, the benefits in these sectors are tied to technology enabling certain functionalities in the use cases, in the sense of "making it work". They are not necessarily tied to sustainability of other sectors or verticals themselves or impacting beyond a user nor are they (yet) demonstrated by the associated measurable/assessable targets and indicators. This is understandable since most projects are working on technology functionality feasibility and lab demonstrations and not so much on impact analysis.

The next sections, provide more specifics about the project sustainability targets.

2.2 Environmental sustainability targets

2.2.1 Stated targets within the projects

Within the projects, distinct trends have emerged regarding their approaches to environmental sustainability. A strong emphasis is placed on targets related to energy and power, indicating that these are seen as the most immediate and tangible areas for environmental sustainability impact. As illustrated in the chart in Figure 2, the SNS projects demonstrate a relatively uniform approach to environmental objectives, prioritizing energy/power efficiency and energy/power minimization. In contrast, only a limited number of projects consider affordability or cost efficiency as environmental motivators apart from a business/economic priority.

However, while these energy/power-focused objectives are critical components of environmental responsibility, the data reveals a notable gap in addressing other broad and impactful environmental sustainability challenges. Specifically, targets such as greenhouse gas (GHG) emission reduction or circularity, encompassing the full value chain from raw material sourcing to waste management, and guided by principles like modularity and reusability are significantly underrepresented. These omissions point to a limited engagement with more holistic and systemic environmental strategies that are essential for addressing long-term challenges like climate change and resource sustainability. Moreover, the absence of considerations such as electromagnetic field (EMF) exposure control, an issue of growing societal concern, highlights a misalignment between current project priorities and broader public expectations. This gap underscores the need for a more inclusive and forward-thinking approach to sustainability that balances environmental goals with economic viability and societal well-being, highlighting the interconnectedness of all the three pillars of sustainability.

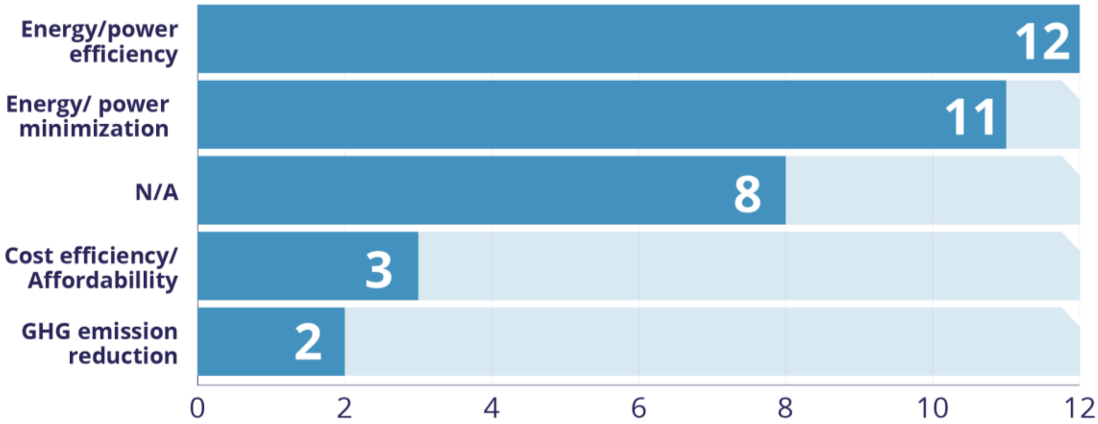

Figure 2: Environmental sustainability targets set by SNS JU projects.

2.2.1.1 Energy Efficiency, Energy Savings improvement targets

Responses gathered from more than 25 projects on energy targets highlight multiple technologies and methods for improving EE and achieving the targeted energy savings in next generation networks (as shown in Figure 3). They also demonstrate how the projects tie sustainability to enabling certain functions. Among the most popular technologies are AI for energy prediction, dynamic spectrum management, edge computing, energy-aware routing and advanced resource allocation**.** Moreover, the main approaches adopted by the SNS JU initiatives include architecture design with energy-efficiency considerations, novel resource allocation approaches, incorporation of intelligence in next generation networks and localized processing.

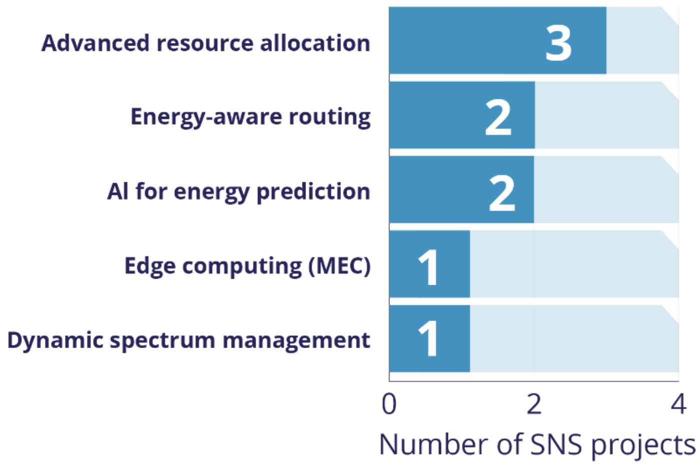

Figure 3: Energy efficiency, energy savings improvement targets set by SNS JU projects.

Specifically, approaches include:

- The adoption of energy-aware principles for the design and optimisation of the network architecture is emphasized through various technologies. Sophisticated network architectures that strive to improve overall EE are being developed by several projects. For instance, one project explores how space division multiplexing can be used in optical access networks. Another project focuses on improving the understanding of the impact of design decisions in service-based network architectures on end-to-end EE by developing a target-value methodology.

- Resource allocation strategies that consider EE are one of the most common approaches adopted by SNS JU initiatives. One of the targeted KPIs by a project is to achieve approximately 15% better resource usage efficiency throughout not only use cases that have very diverse performance requirements but also those that have extremely stringent ones. In addition, dynamic resource management depends on allocating resources by taking energy consumption and demand estimations into consideration. This requires accurate measurement and assessment of energy consumption. To that end, some projects are working on the development of energy frameworks that allow the use of as many renewable energy sources as possible. This could enable networks to operate in the energy-efficient regime with approximately threefold EE gains compared to traditional networks.
- The use of AI for tasks such as prediction, dynamic management, and optimisation of energy consumption is widely accepted across the projects. In addition, intelligent approaches to orchestration, task offloading, and caching are reported by a plethora of projects, spanning from high-level innovative semantic communications to low-level intelligent thread-management within the Linux kernel. One framework for analysing and benchmarking EE improvements in networks has been developed that aims to provide deeper insights on the impact of AI on energy consumption.
- Localized processing is adopted by various initiatives and is expected to reduce energy consumption by lessening the requirement for centralized operations. Reported practices include adopting hardware-accelerated application, optimizing real-time RAN intelligent controllers, and more. The energy reduction due to the use of localized processing amount to more than 40% in radio units, 70% in centralized servers, and more than 20% on edge servers.

Projects are taking a range of different approaches and working towards different improvements. For instance, improvements by a factor of 2-5 are expected when you take into account the energy that is saved through more efficient operation of functionally similar devices. However, energy reduction by 10 times or more can be achieved when adopting different architectural or design modalities, while even reduction greater than 1000 times in terms of energy per bit has been reported when adopting revolutionary technologies.

2.2.1.2 Overall Energy Consumption targets, limits, and boundaries

Although some projects have set concrete targets, others refer to benchmarks against current wireless network energy consumption as a boundary, as depicted in Figure 4. This highlights a comparative performance assessment that aims to significantly outperform existing systems. For certain innovative use cases, setting specific, quantifiable targets can be challenging because the baseline energy use is not easily measurable. In such instances, the focus is on improving the existing methodologies towards more concise energy consumption targets.

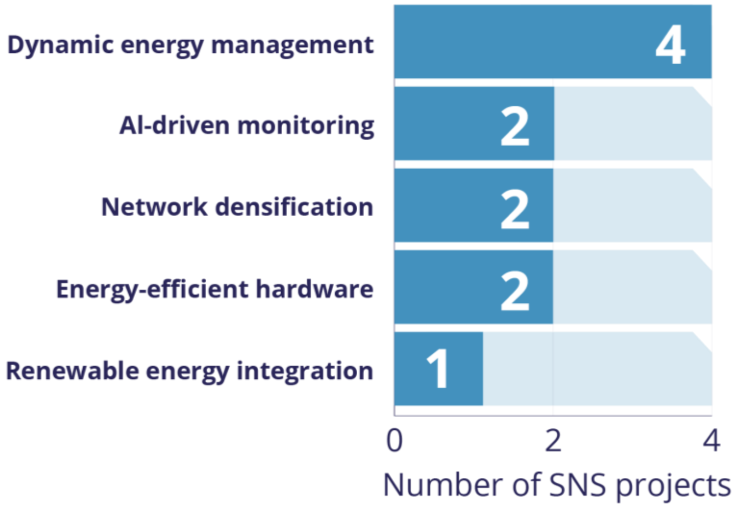

Figure 4: Overall energy consumption targets/limits/boundaries of SNS JU projects.

In more detail:

- The design of hardware that uses less energy is emphasized in several projects. These include the development of radio units and base stations that draw less power. One project, for instance, aims to set a new standard for power consumption at 100 Gb/s capacity communications. It targets a reference power of just 10W, dwarfing the current 10 nJ/bit standard. Another project targets a 35% reduction in energy use from the networks (fixed and mobile) and aims to improve total EE by a factor of 2 compared to current network designs.
- Sleep modes and dynamic power scaling are implemented by several initiatives to enable dynamic energy management based on traffic demand. A common target is a 50% reduction in energy consumption, which is achieved through various measures. For instance, one project aims to achieve this target through energy optimization strategies that allow to scale power level, while still maintaining accurate task execution. Another approach capitalizes optical transceiver design to reach the targeted energy use at the sufficient optical bandwidth under optical line termination.
- Strategies for network densification are being developed to optimize energy use by deploying small cells in high-demand areas. Some projects are rethinking the architecture of cell-free massive MIMO systems so that they can operate in a more resource-efficient manner. For instance, a target of more than 10% power savings (including the savings at the level of the RAN, the fronthaul, and processing) has been set for a small-cell system that has to serve the same high-demand area and a low number of users at the same time.
- Energy monitoring systems that take advantage of recent AI breakthroughs are under development in a few projects to set and track consumption targets in real time. Such approaches are integrated with efforts toward network optimization, where sensing data are utilized to make deployment decisions that further our EE objectives.
- Renewable energy sources have been adopted as a means to counter overall energy consumption. Efforts examine not only how to work with harvested energy but also strive to

design systems that can operate solely on harvested and stored energy alone. For instance, several projects state that they use harvested energy, such as light and radio frequency signals, to power Internet of Things (IoT) nodes.

Establishing total energy consumption targets and limits is crucial for ensuring the environmental sustainability of future networks. Projects are setting reduced consumption targets (in kWh, in kWh per task) that go well beyond anything currently deployed to demonstrate a real commitment to mitigating the impact of networks on the environment. There is focus on this topic across the board even with efforts that seem to be yielding limited impact (e.g., defining commitments in terms of cumulative effects over the life of a network rather than annual budgets) still drives conversations that enhance understanding of power consumption in real-world use cases. Just knowing that certain tasks take certain amounts of power is a useful sort of knowledge to have.

2.2.1.3 Possible increase of renewable energy use

The findings reveal a fragmented landscape with only a minority of projects explicitly targeting renewable energy integration, while many others remain neutral or unengaged with this goal. As shown in Figure 5, only 6 projects reported efforts to boost the use of renewable energy, either explicitly or implicitly. From them, three projects directly target the use of renewable energy and adopt different approaches to achieve this goal. For instance, one project is targeting more than 75% renewable energy; another aims to take advantage of regionally available renewable energy; and the third focuses on seamless switching of network infrastructure energy sources between the power grid and renewables.

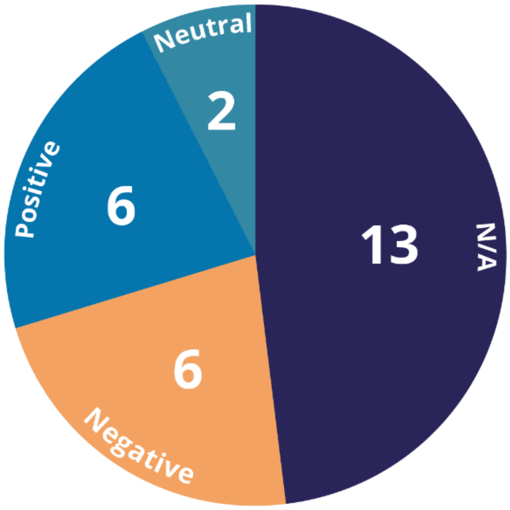

Figure 5: Responses of SNS JU Projects on increasing the use of renewable energy

Three of these initiatives suggest intrinsic capabilities related to the use of renewable energy. Specifically, NTN-focused projects aim to capitalize on solar power that is a mission-critical solution due to size, weight, and power requirements of satellites. The third project is focused on terrestrial networks and is exploring renewable ways to produce all the energy necessary to power the IoT nodes. While the overall energy requirement of a single node is small, the impact is considered substantial when considering high volumes and battery-less solutions.

Interestingly, two projects explicitly take a neutral stance on aiming for increased renewable energy use. One of them, although it is not aimed at promoting the use of renewable energy, acknowledges the potential to include carbon awareness depending on the availability of tools and methods for estimating carbon emissions from collected data. Similarly, the self-harvesting energy schemes developed in the second of the two initiatives could provide insights into the advantages of using renewable energy in next generation networks.

On the other end, six initiatives clearly indicate that they have no aim to raise the utilization of clean, renewable energy. In addition, thirteen projects did not answer the question about whether or not they have such a target. In general, the feedback received underscores the various kinds of ways that renewable energy is approached in the projects, with some making direct, intrinsic mention of it; others, neutral comments about it; some, explicit non-targeting of it; and, with a significant number of projects that did not provide a response.

2.2.2 Energy versus everything else

Energy efficiency (EE) is the most represented technology enablement aspect as concerns environmental sustainability targets. This however raises some points of reflection, as to the relation between EE and the achievement of other dimensions of environmental sustainability that appear underrepresented, such as for example renewable energy resources, sustainable material use, or circularity approaches.

- When contributes to widespread adoption of technologies at scale, there is a significant risk of creating the economic conditions for a rebound effect in which greater efficiency leads to increased use. This can ultimately result in higher energy use overall despite the fact that the individual technologies might save energy comparted to other solutions.
- In the SNS projects interviewed, only five projects declared explicit GHG emission or circularity related targets; this represents an increase considering that only two projects included GHG emission reduction at the level of their project descriptions. When asked if projects include some form of carbon awareness, such as in data routing optimizations, this number increases to 11 projects, although four of these 11 only consider carbon awareness indirectly.
- No projects have explicit targets related to biodiversity, however one project seeks to develop new key sustainability indicators for biodiversity and another expects indirect impacts by reducing reliance on European critical raw materials.
- A few projects point to modularity, ease of deployment/repair/refurbishment, low cost, and low power as enabling features to achieve wide scale deployment and therefore, consequently improving sustainability. However, by considering sustainability as a byproduct of greater use, these projects risk rebound effects and need careful consideration of whether overall improvements in sustainability can in fact be realized by the associated technologies.
- Finally, as concerns foreseeing an enablement effect in other sectors and verticals, 10 projects identify such impacts, while only seven propose methods to measure the impacts.

2.3 Economic sustainability targets

Projects were asked to explain their economic sustainability targets, as declared in the project description. Twenty-three projects responded to this question, the majority responding with more than one target – thus, there are more answers than there are projects. In addition, most projects responded describing their general approaches to relevant themes rather than specifying actual targets, with some noting they do not have defined targets. However, a couple of projects were able to state quantified targets (e.g., the project targets a 50% reduction in CAPEX; tenfold improvement in the cost efficiency of virtualized Radio Access Networks). The results are depicted in Figure 6.

The data from the questions were rich in content but unstructured in form. Answers were presented in the terms defined by the uniqueness and specificity of each project, often at different levels of granularity. This meant any analysis of the data required initial qualitative coding (e.g., systematically labelling) and clustering results into meaningful categories. This involved systematically assigning labels (or "codes") to text that represent specific concepts or themes. The aim was not to reduce the complexity of qualitative data, but to make that complexity analytically manageable, supporting pattern and variation recognition. Overall, a range of themes emerged with the primary focus on elements that support 6G growth. Three themes were well covered across the projects: cost-efficiency, industrial growth, and technology advancement, which will be described in more detail.

Cost-efficiency, cost savings, and related activities were key drivers across the projects, with 14 of the respondents articulating this target specifically. Specific approaches include focusing on the cost of energy, equipment, hardware, applications, network operations, service provision, repairs, maintenance and upgrades. Some projects aim at increased revenues with a focus on both operational and capital expenditures. Finally, a small number of projects explicitly highlighted how this impacts stakeholders by making the results affordable for customers or at least, making additional costs acceptable, by supporting increased acceptance or use allowing the vertical stakeholders to economically grow, and by reducing the need for travel.

Encouraging **Industrial growth** in various ways was equally prominent with 15 responses in this category. Answers within this category included a focus on the ability of industry to gain new market spaces or to grow customers, via diversification, novel and green business models, and expanded value chain. This included diversification and the creation of business opportunities via, for example, cross-fertilisation between traditional product lines with disruptive ones, opening the market to new players, or creating an API economy for telco networks. In addition, this included the ability to expand the 6G value chain to include, e.g. the edge, cloud and IoT ecosystems. For a small number of projects, it also included expanding the customer base or business models for verticals, not just 6G industry.

Technological advancement and innovation, bringing 6G to the next level, was the third most prominent target theme. This covered a range of elements that many individual projects are focusing on, including such features as flexibility, modularity, scalability, contribution to standards, new security frameworks, customizable services, new forms of connectivity access, and improving economies through AI automation. Each of these focuses on specific technical features that can be improved that are expected to provide economic benefit.

Three other target areas are also being engaged, though by less projects. First are four projects that are considering different aspects about the resources used to develop, deploy, and implement 6G. This includes their reusability, extending the lifetime of products, resource efficiency, and improved resource management. Three projects focus on knowledge sharing and open collaboration as key to economic sustainability, by providing tools that enforce cooperation, promoting industry consolidation, encouraging and leveraging the transfer of knowledge between testbeds and key 6G stakeholders. Finally, three projects also target elements of economic equity, looking towards new market opportunities to bridge digital divide, improving digital skills, and considering the impacts of hyperconnectivity on work.

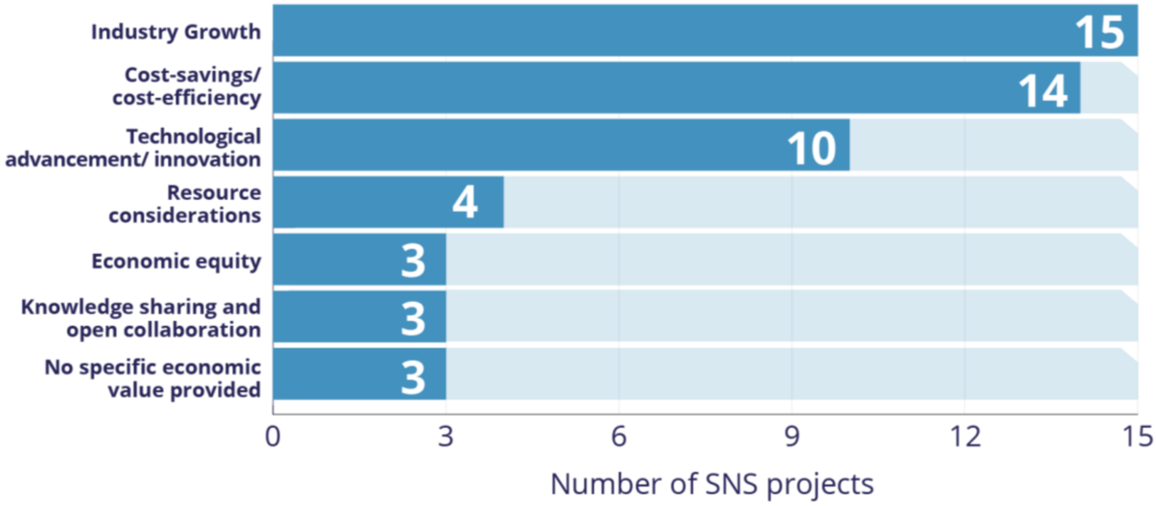

Figure 6: Economic sustainability targets set by SNS JU projects.

Overall, projects currently see cost savings or new market opportunities as key business/economic priorities. However, there is a diversity of language and foci within these broader economic themes that show that despite many projects working on these issues, further guidance as to what are the priority values, why, and how they matter to the projects would be beneficial to support comparison and alignment across these efforts.

Of note, the relationship between economic sustainability and the other two sustainability pillars is explored by a small number of projects, such as more efficient use of resources or digital skills. These could be further mainstreamed to enrich the relationship between economic actions and sustainability goals.

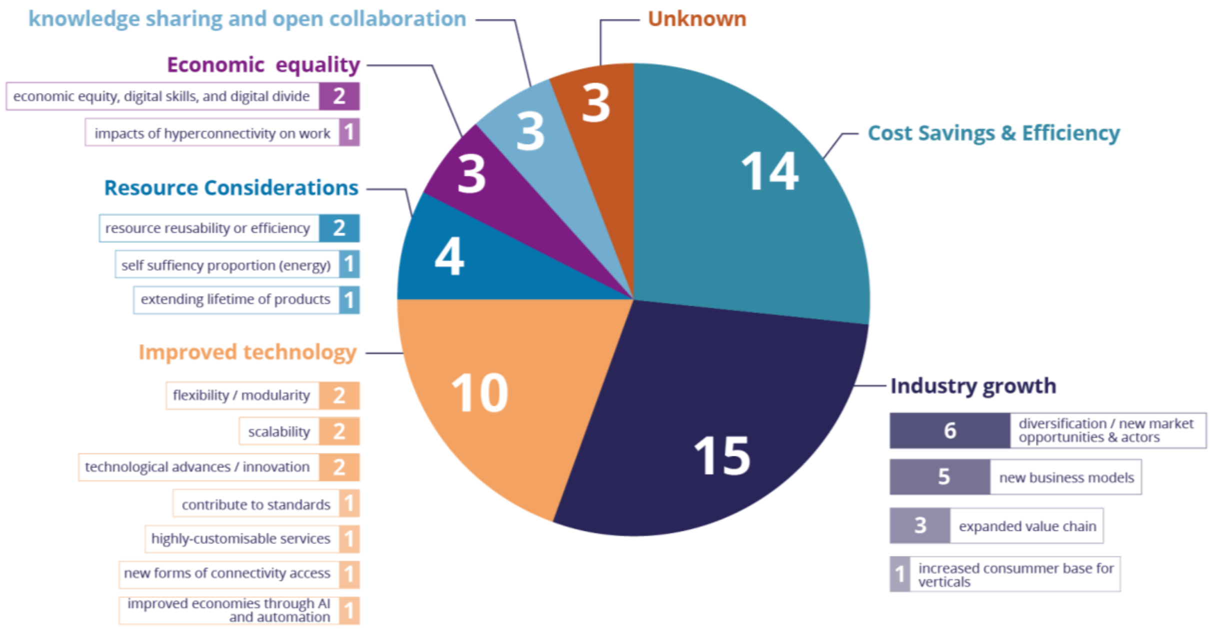

Figure 7: Mapping of the economic sustainability targets set by SNS JU projects.

Only a small number of projects reference an economic benefit outside the SNS ecosystem (e.g. for verticals, publics) with the priorities being growing markets and decreasing costs for industry and consumers. Similarly, it is important to highlight that there is a broader range of potential economic sustainability values and targets expressed in relevant policy guidance and industry strategy, such as improved job opportunities, digital skills, increased investment, education, new revenue streams, economic competitiveness and well-being, that were not amongst the answers provided by the projects. This both offers an opportunity to revisit priorities in the SNS ecosystem and suggests that further incentives (e.g. via proposal calls, vertical pushes, etc.) could be deployed.

2.4 Social sustainability targets

The concept of social sustainability is closely linked to economic sustainability but complements it by putting the accent on the capacity to ensure the equitable distribution of physical and social resources. In other words, social sustainability is achieved if the benefits of economic goals are reaped by the whole community. Also, *social sustainability* comprises and is defined by the intangible assets that characterise healthy and liveable communities, including for example a sense of belonging and fulfilment within the community, the promotion of good health and well-being, gender equality, the capacity to access quality education and healthcare.

In the survey, projects were asked to explain their social sustainability targets, as declared in the project description. 22 projects, corresponding to 85% of interviewed projects, declared to address some social sustainability target and their answers are depicted in Figure 8. The way social sustainability targets were described and captured in the answers is multifaceted: projects showed a wide variety of formulations, different levels of granularity, and project-specific foci reflecting a certain openness and subjectivity in the interpretation of the concept across the community. This suggests that there is lower agreement on the scope and focus of this concept, at a definition level as compared to the other two pillars of sustainability.

In order to facilitate the interpretation and comparability of answers, the variety of definitions and formulations used to refer to social sustainability targets were first qualitatively analysed and then organised into 13 main overarching concepts, different in nature and in level of granularity. The aim was not to reduce the complexity of qualitative data, but to make this complexity analysable and comparable, identifying patterns and recognising variations. The diagram shows the occurrence of the 13 main concepts across the replies of the 22 projects that declared to address social sustainability targets, mentioning most of the times more than one target

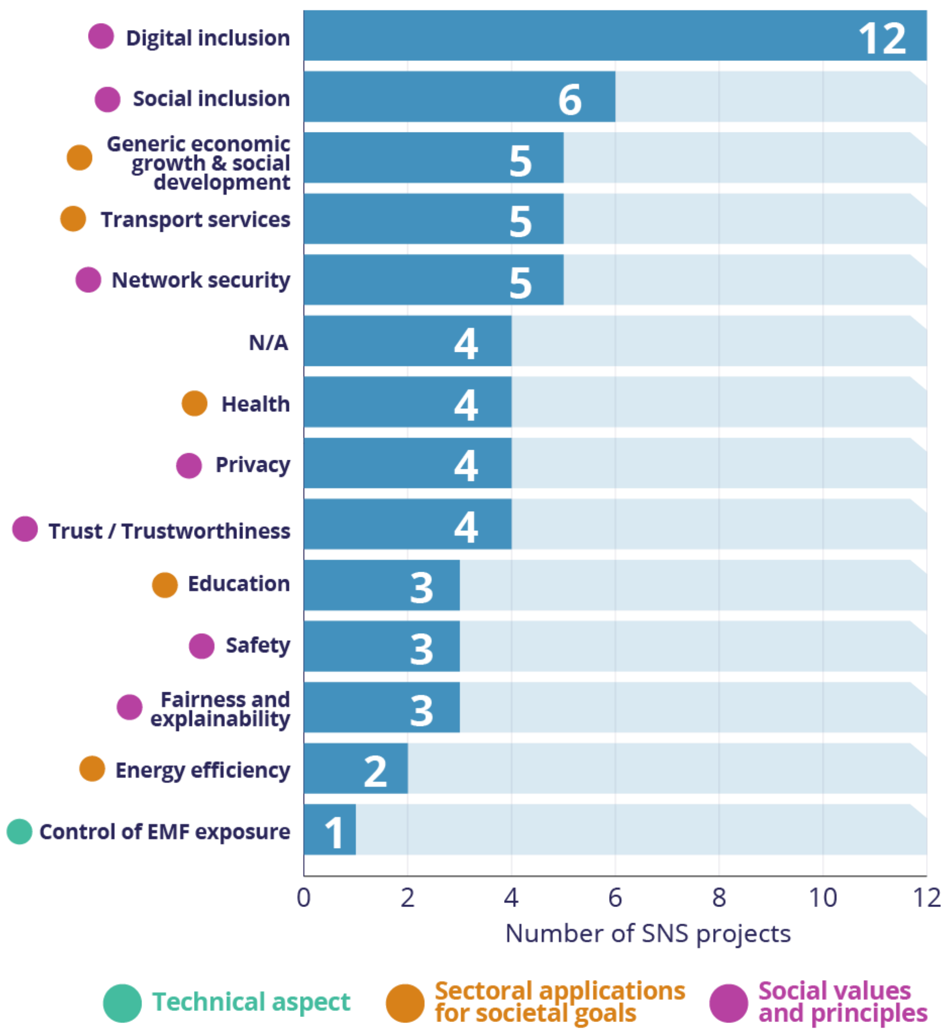

Figure 8: Social sustainability targets set by SNS JU projects.

Three main approaches can be identified as concerns the formulation of social sustainability targets:

- **Social sustainability targets related to enabling and reinforcing specific social values or principles.** The value of *digital inclusion* appears as the most frequent interpretation in terms of social sustainability targets, immediately followed by a more generic reference to *social inclusion.* Besides these interpretations, projects also focus on ensuring compliance with a number of ethically relevant requirements at the technological level, mentioning aspects such as trust/trustworthiness, privacy, security (of network), fairness and explainability of software and algorithms. The responses provided no indication of what indicators or metrics were being developed in relation to these targets. These values and principles can simultaneously express the function of founding criteria orienting actions and choices (including design choices), or of societal goals to be achieved. A better understanding of how they are used (as drivers or impact) is necessary to interpret the chosen targets. In addition, some of these values find an easier translation into technical requirements or practices than others.

- **Social sustainability targets taking the shape of sectoral services and applications for societal goods. Here sustainability is projected onto the sectoral area of impact, such as e**ducation, health, transport services, EE. Some projects mentioned more generic targets instead, such as economic growth and social development.
- **Social sustainability targets projected onto a specific technical issue**. One project identified as social sustainability target the control of EMF exposure. The relevance of this reference stems from its sensitivity to societal and environmental implications (e.g. health), as well as public perception and concerns.

To offer a picture of the diversity of responses received within societal sustainability, the concept map depicted in Figure 9 shows the richness and variety of phrasings and formulations, and how they were collated into groupings around the same value concepts, to identify the 13 concepts.

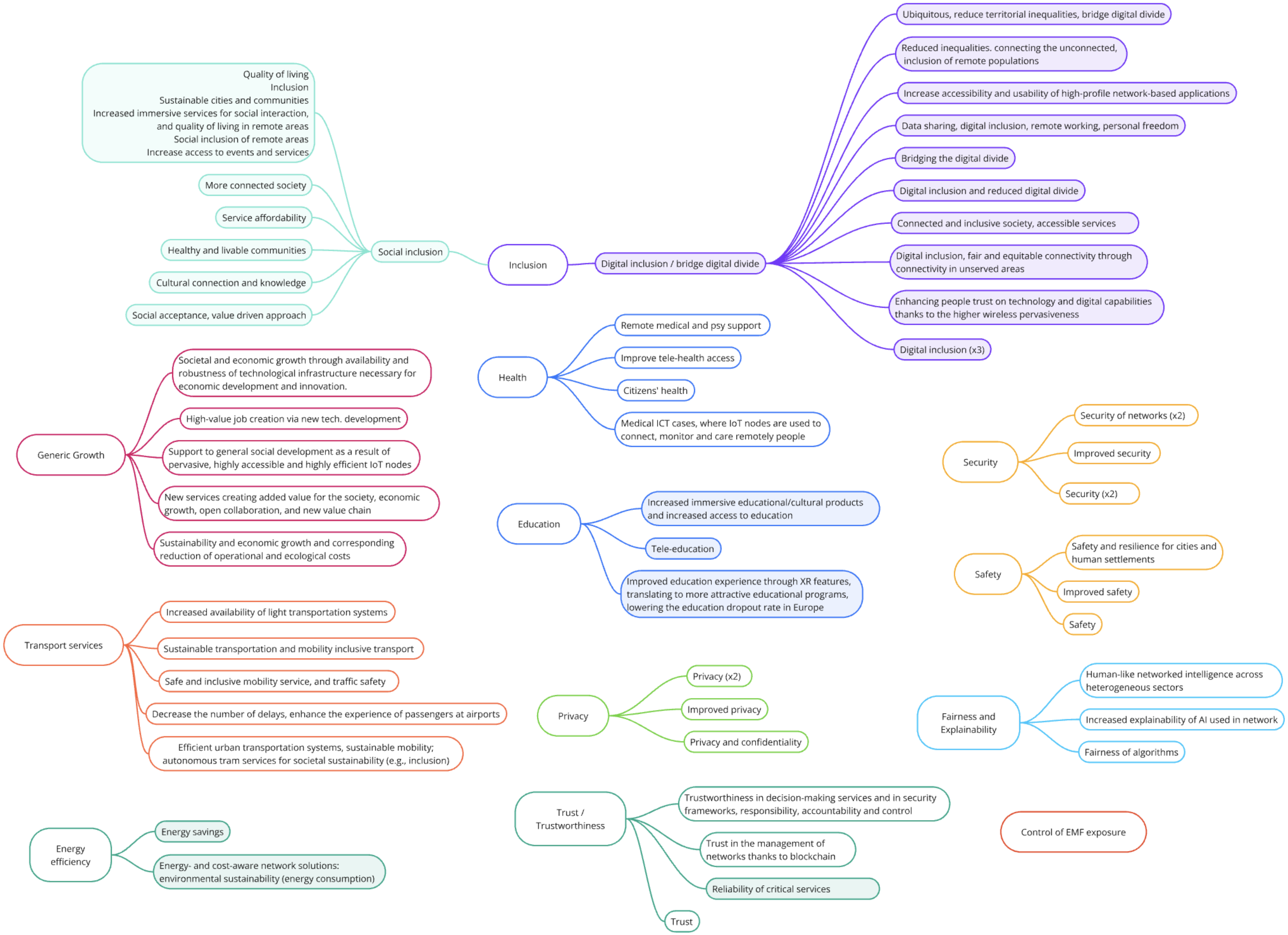

Figure 9: Concept map of social sustainability targets set by SNS JU projects.

Summarising, we can state that Inclusion is a central target for the projects and represents the most shared understanding of what is to be considered within the pillar of social sustainability. Besides this, social sustainability aspects are represented in different ways: either through concepts with an existing tradition in being and translated as technological requirements (e.g. security, privacy, explainability, reliability); or through societal goals, meaning the sectors where value is being created.

This representation of social sustainability also opens the way to a gap analysis, reflecting on additional aspects of the concept of social sustainability that, while relevant for the context of future networks and connectivity, are currently not addressed in the ongoing debate and in existing approaches. These include, for example, nuances of the concept attaining to mental health and well-being, cultural identity and diversity, cultural heritage, autonomy, freedom, or the right to disconnect.

2.5 On policy and regulation

The survey results, as shown in Figure 10, reveal that the engagement of projects analysed with policy and regulatory aspects on sustainability is generally limited. Notably, only one project—a Coordination and Support Action (CSA)—affirmatively declared active involvement in this area. Eight projects expressed a potential or indirect interest, often describing their engagement as “not explicit,” “only indirect,” “potential,” or “not yet addressed.” Among these, three projects specifically noted that any policy-related activities would depend on the work of dedicated groups, particularly mentioning the Sustainability Task Force. Of the remaining 18 projects, thirteen explicitly answered “no” to engaging in policy and regulation, while five provided no answer (N/A). Only sparse indications of thematic focus emerged: one project aims to promote green business models, another emphasizes compliance with existing spectrum and radiation regulations with an intent to influence future updates through dissemination of project results, and a third project, despite not being active in this domain, cited an interest in EU cybersecurity regulations (such as NIS2 and CRA) relevant to critical infrastructure resilience. Overall, the findings highlight a significant gap in the integration of policy and regulatory considerations into project activities, which could be interpreted as in line with the technology feasibility focus of the projects, as demonstrated by their relatively low TRLs.

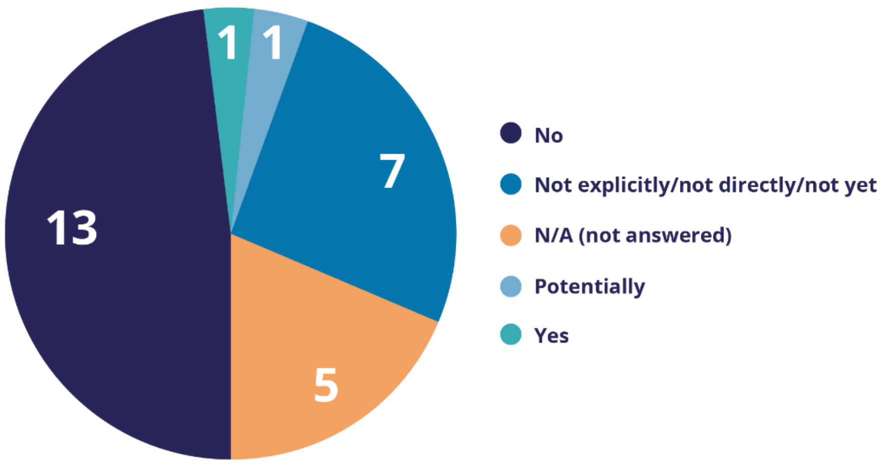

Figure 10: Engagement of SNS JU Projects to in policy and regulatory aspects of sustainability.

2.6 Key Insights

The following insights attempt to capture the way in which the SNS projects have shown to engage with sustainability targets and to societal values across the three pillars of sustainability.

- **Addressing sustainability in the early stages of technology development:** Most of the projects interviewed operate at Low TRL, focusing on technology enabler feasibility in conceptual or lab environments. This is linked to a number of trends observed across projects as to how sustainability targets have been addressed.

  In general, low TRL has shown to limit the ability of projects to engage directly with sustainability goals or to assess real impact. The definition of use-cases, for example, often originated from the need to showcase what a technology can achieve in terms of features and performance, without exploring what the position of users would be as to the need to address a specific societal, individual, economic or environmental challenge, or as to the best way to solve it. As a result, the way projects associate use cases and value outcomes remains limited to requirements generation, while evaluation and observation of impact and outcomes are much harder to realize at this level.

  Similarly, in the early stages of technological development specific challenges arise in defining how KVIs should function and be implemented. Indeed, while KVIs of higher TRL activities could more explicitly be shaped around sustainability outcomes, lower TRL activities require different approaches to folding sustainability into their work.
- **Broadening the scope and nuances of the concept of sustainability:** In general, there is a need for a more nuanced and forward-thinking approach to sustainability, capable not only to duly balance environmental goals with economic viability and societal well-being, but also to capture additional important aspects across all pillars of sustainability.

  As concerns environmental sustainability, targets related to energy and power are predominant, with less attention on other elements of the environment like waste management, circularity, renewable energy, biodiversity, etc, pointing to a potential misalignment between current project priorities and broader public and policy expectations. As concerns economic sustainability, many projects tie their expected impact on sustainability to the improvements they expect to deliver on efficiency and performance – using less energy, less materials or notably costing less. It appears a clear implicit assumption that better performance will lead to cost savings, which in turn creates economic sustainability. Key economic drivers are therefore cost-efficiency, cost savings, and related activities as well as industrial growth. The impact on the economic experience of stakeholders or verticals, beyond cost-savings, was only minimally addressed by the projects.

  Regarding the concept of social sustainability, it is most frequently interpreted as the capacity to create social and digital inclusion or safety. As concerns the other interpretations, they can be reconducted to two main approaches: either projects mention principles that can be reflected into technology requirements (e.g. security, privacy, trustworthiness, resilience), or they refer to the creation of applications in social-relevant sectors (health, education, transport, EE). In general, the concept of social sustainability appears framed under a general positive assumption as to the change that technology will deliver to society. Such a perspective overlooks the existence of a series of possible negative implications on society related to hyperconnectivity, as well as any possible existing concern within different societal groups as to the networks of the future. A proper awareness of such implications and of real stakeholders' needs is necessary, to orient technological development priorities and targets towards future scenarios that truly reflect what is desirable and sustainable from a social sustainability perspective.

Finally, both social and economic sustainability are described in diverse terms, granularities, and natures, and could benefit from greater structure to support analyses. In particular, both aspects of sustainability were interpreted in a very focused way. A wider range of economic and social sustainability values and targets, reflected in policy and industry strategies but currently unexplored by projects, could be considered. To do so, a clearer guidance on navigating across possibly priority values (to understand what they are, why they matter, and how they relate to the projects) would support a better alignment and comparability across efforts.

- **A holistic approach to sustainability requires specific competences:** Sustainability targets are often described conceptually rather than being precisely or uniformly quantified. This may stem from a lack of relevant expertise. Many sustainability metrics require specialized knowledge and data that extend far beyond the domain of telecommunications equipment, systems, and the typical skill set of technologists.

  For example, understanding impacts on biodiversity would likely necessitate the involvement of an ecologist—someone familiar with appropriate methods for assessing such effects, which may be influenced by how equipment is deployed and operated. Similarly, evaluating supply chains or market competition linked to a new technology might call for the expertise of an economist.

  While GHG emissions can be estimated using established methods based on electricity consumption, equivalent methodologies for other sustainability dimensions are largely lacking, particularly in the context of the technologies examined in most SNS projects. This gap in expertise becomes especially significant when explicit sustainability targets are included, which may explain why so few projects define such targets. For similar reasons, indirect sustainability impacts—such as those related to use cases or vertical application areas—are often mentioned but rarely quantified. This may also in part explain the predominance of EE as the primary lens through which sustainability is interpreted and addressed. This can be explained by two main factors.

  First, EE is a quantifiable metric that can be directly linked to hardware technology. It does not require consideration of deployment scenarios, specific use cases, or location-dependent variables. This makes it a convenient and attractive sustainability indicator for many projects. Second, the emphasis on EE may also reflect how sustainability was framed within the funding mechanisms, particularly in the calls for proposals. In the first call, sustainability was largely defined in terms of EE. It was only in the second call that all three pillars of sustainability—environmental, social, and economic—were explicitly introduced.

To conclude, addressing broader aspects of sustainability and circularity typically requires the inclusion of experts from diverse fields such as economics and ecology. However, unless these competencies are explicitly requested in the call documentation, project teams may be reluctant to expand their composition accordingly. As a result, more comprehensive consideration of sustainability across all three pillars is likely to depend on clear prioritization and explicit guidance within future calls.

3 SUSTAINABILITY METHODOLOGIES

This section explores how the 6G SNS JU projects approach sustainability through methodological frameworks based on a structured analysis of responses to the Sustainability Task Force questionnaire. These questions were designed to assess the degree to which projects integrate sustainability principles in a systematic, measurable, and design-oriented manner, from early planning to operational deployment.

Specifically, projects were asked whether they employed recognized definitions such as the UN SDGs or ITU and ISO standards, and whether they applied any formal methodologies to assess sustainability impacts. They were also invited to describe how the use phase of their technologies was taken into account, including user-cantered design processes and representative use cases, and to indicate whether they considered the full lifecycle of their solutions by including Life Cycle Assessments (LCA) or upstream and downstream supply chain sustainability.

Subsequent questions explored the types of metrics and indicators used to monitor progress towards sustainability goals, and whether the projects employed KVIs as defined by the 6G-IA Smart Networks and Services Vision group. Projects were also asked whether circularity principles or eco-design approaches were considered in the development of their technologies and whether they followed a proactive or reactive approach to sustainability, either by embedding it from the start or addressing it at a subsequent stage.

The questionnaire further discussed how sustainability-by-design principles were applied and whether projects actively selected components or materials for their sustainability characteristics, even at the expense of performance. Resource-sharing strategies and their architectural implications were examined, along with the degree to which projects promoted flexibility, adaptability, and reconfigurability to support sustainable operation across diverse contexts. Projects were also asked to describe whether their design was modular and scalable, such as “Lego-like” systems. Finally, the questionnaire addressed a critical conceptual distinction: whether a project aimed to reduce the environmental impact of its technologies (so called first order effects) or to enable sustainability in other sectors through its technological outputs (so called second order effects).

Together, these questions provide a comprehensive framework for assessing how deeply and systematically sustainability is embedded in the design, implementation, and evaluation of the next-generation communication technologies. This section synthesizes project responses to draw key insights into current practices, emerging gaps, and opportunities for more harmonized, impactful methodologies across the 6G research landscape.

3.1 Use of Standardized Sustainability Definitions

This subsection assesses whether projects define sustainability in reference to recognized external standards or frameworks. The goal was to identify the extent to which definitions such as those from the United Nations, the International Telecommunication Union (ITU), and the International Organization for Standardization (ISO) are used to ensure coherence, comparability, and methodological consistency in how sustainability is conceptualized and applied across the 6G SNS JU project landscape.

The use of standardized sustainability definitions has been reported in a minority of project responses. Among the 27 projects assessed, approximately 40% of those from Call 1 and 50% from Call 2 indicated that they referred to recognized frameworks or standards when defining sustainability within their scope. Across the research streams, this translated to approximately 60% of Stream A and 40% of Stream B projects. No projects from Streams C or D reported the use of standardized definitions. These distributions are illustrated in Figure 11.

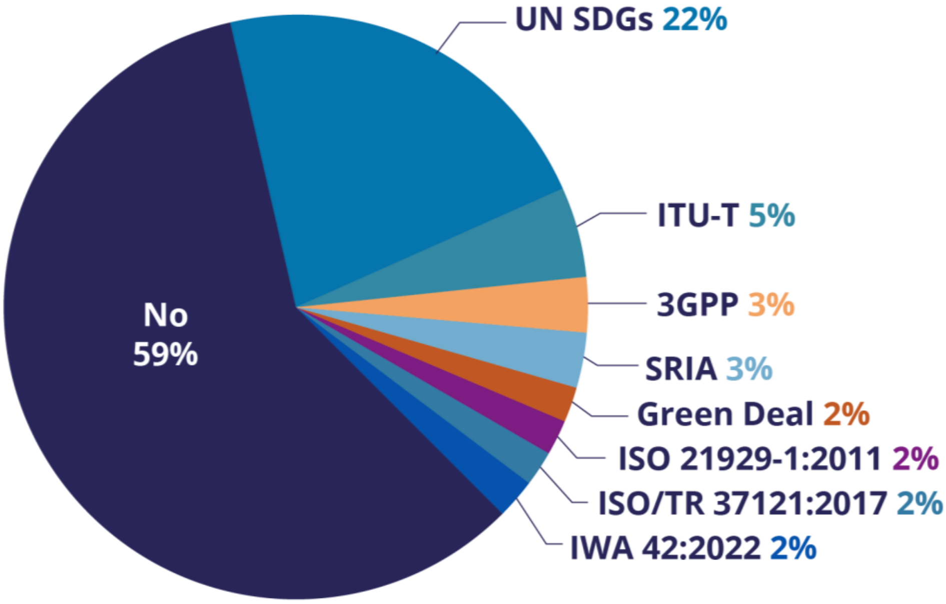

Figure 11: Distribution of Standardized Sustainability Definitions across projects

The most frequently cited sustainability framework was the United Nations Sustainable Development Goals (UN SDGs), which accounts for 22%. Other standards referenced, although less frequently, included ITU-T guidance documents (5%) and selected ISO standards (<3%).

In several responses, the inclusion of sustainability frameworks was mentioned with a relative prominence of the UN SDGs and a more limited spread across other available international standards.

These findings indicate that within the current landscape, sustainability definitions are difficult to standardize across projects, causing a possible lack of convergence in shared terminology or baseline frameworks.

3.2 Methodologies for Sustainability Impact Assessment

This question aimed to assess whether projects apply standardized methodologies to evaluate sustainability impacts throughout their development and deployment cycles. The question focused not only on the presence of such methodologies but also on the nature of their adoption and the perceived challenges associated with implementation.

The analysis indicates that the adoption of standardized sustainability assessment methodologies remains limited across the surveyed projects. Among all the responses, only 11% reported the use of recognized standards, such as those developed by the International Organization for Standardization ISO or the 3rd Generation Partnership Project (3GPP). Specifically, approximately 7% of the projects referenced ISO standards, and 4% mentioned 3GPP-related approaches. The overall distribution is summarized in Figure 12.

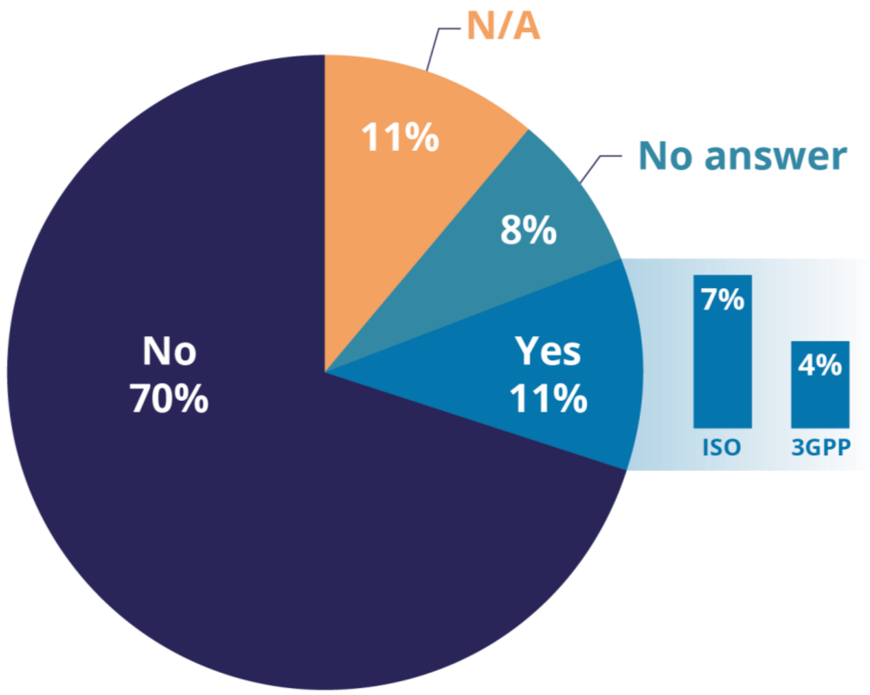

Figure 12: Standardized Methodology Used across Projects

Barriers to adoption were not always explicitly stated, but these included the perceived complexity of existing standards, limited awareness or familiarity with sustainability methodologies, and constraints in terms of project resources or expertise.

The majority of projects (70%) did not report the use of formal methodologies to systematically assess the environmental, social, or economic impacts of their work. Some responses described efforts to embed sustainability objectives from the design phase, whereas others implied that sustainability was evaluated only after technical development had occurred.

There is a growing interest in sustainability-related outcomes, which are often approached through ad hoc mechanisms instead of being guided by established frameworks or quantitative evaluation methods.

3.3 Integration of Use Cases and End-User Perspectives

This question analysed whether projects consider the use phase of their technologies by integrating end-user needs, behaviours, and perspectives into the design and evaluation processes. The objective was to assess the extent to which user-centric methodologies contribute to shaping the sustainability-related outcomes of technological innovations within the 6G SNS JU framework.

Almost 50% of projects provided affirmative responses, indicating that use cases were actively employed to guide technology development. These use cases covered a wide range of sectors, including light transportation, industrial automation, remote healthcare, extended reality (XR), public protection, and smart connectivity for the IoT. However, the level of integration of sustainability concerns among these cases varies. Several projects have reported using structured approaches, such as design thinking, including its core stages: empathizing with users, defining needs, ideating solutions, prototyping, and testing. Other forms of user engagement include targeted surveys, some of which gather data disaggregated by gender or assess perceived impacts on quality of life, connectivity sufficiency, and operational efficiency. In certain cases, user requirements are said to influence system-level reconfiguration mechanisms and performance-related Key Performance Indicators (KPIs), including those related to sustainability.

Almost all responses explicitly connected user needs or feedback to specific sustainability outcomes, such as energy use reduction, accessibility, or social inclusivity. Budget constraints were cited in some responses as a limiting factor for conducting more immersive or long-term user engagement activities, such as ethnographic studies or co-design workshops. Although the inclusion of user perspectives is widely acknowledged as valuable, its implementation is more complex.

3.4 KVIs and SNVC Methodology

This question assessed the extent to which projects incorporate KVIs, as defined by the methodology of the 6G-IA Smart Networks and Services Vision group -Societal Needs and Value Creation subgroup (SNVC), to support sustainability-related evaluation and alignment. The objective was to understand both the prevalence and consistency of KVI use and to evaluate how these indicators are tied to sustainability goals and project impact assessments.

A total of 16 projects reported using KVIs in their work, although there were variations in how KVIs were interpreted and applied. Among the remaining projects, some responded negatively or did not provide an answer.

Among those reporting KVI usage, few have described structured processes for validating the relationship between their KVIs and sustainability objectives.

Not all the projects answered with details on the KVIs framework. However, when details on how KVIs were discussed, projects discussed how they were co-developed with stakeholders or how they evolved over the course of the project. In general, projects have different interpretations of the SNVC framework, which is likely due to differences in project maturity and focus. For some projects, the absence of use cases or the early-stage nature of technical development (i.e., low TRL) may have limited the applicability of a detailed KVI framework.

3.5 Circularity, Eco-Design, and Life Cycle Assessment

These questions were designed to explore whether projects adopted systemic and lifecycle-oriented approaches to address sustainability. These questions examined the extent to which LCA methodologies, full supply chain considerations, and circularity or eco-design principles are integrated into project planning and implementation.

These results indicate that LCA practices have rarely been adopted, mostly because of the R&D nature of the projects. Only two of the 27 projects reported including LCA in their methodology. In these cases, lifecycle thinking is applied either at the technology component level or in the context of networked services. The reported LCA approaches address the design and use phases, with limited consideration of end-of-life impacts or the use of recognized LCA frameworks or tools (e.g., ISO 14040 series). Approaches to LCA include:

- Focus on the design, manufacturing, and use phase of the dual-mode use of optical and radio communications, combined with the exploitation of printed electronics technology.
- LCA at the service level for cloud-native applications, Multi-Access Edge Computing (MEC), and network services across a multidomain edge-cloud continuum.
- AI-powered solutions designed for managing the entire lifecycle of computing, communication, and networking resources.

Supply chain sustainability considerations focused on a narrow subset of the supply chain, typically limited to the immediate scope of their technical contributions. In total, 15 % of projects discussed this topic. In a few cases, material and hardware considerations have been mentioned. In addition, security considerations in the software supply chain were considered.

Regarding circularity and eco-design, only three projects provided explicit responses. Among these, one study described a comprehensive “sustainable-by-design” strategy incorporating principles of sustainable implementation, use, and disposal, related to photonics design for sustainable IoT systems. The remaining responses referenced EE improvements as indirect contributions to circularity.

3.6 Architectural and Design-Level Considerations for Sustainability

This set of questions analysed whether and how architectural and design-level decisions contribute to sustainability objectives in 6G SNS JU projects. The questions covered a broad range of themes, including:

- Proactive versus reactive approaches to sustainability
- Integration of sustainability-by-design principles
- Selection of components based on environmental trade-offs
- Strategies for resource sharing and architectural efficiency
- System-level properties such as flexibility, modularity, and scalability

More than 80% of the projects described themselves as following a proactive sustainability approach, indicating that sustainability considerations were addressed during early design phases rather than retrofitted post-development. Projects are committed to EE or cost-effectiveness, whereas others target predictive design models or AI-driven optimization. However, less than 10% of responses discussed the specific environmental outcomes associated with these early interventions.

In terms of sustainability-by-design implementation, responses showed heterogeneous levels of granularity. Some projects have focused on control-level mechanisms, such as energy-aware resource allocation or virtualization strategies, whereas others have referenced system-level architectural decisions. The majority of sustainability-by-design responses focused on EE.

When analysing the component selection trade-offs, the questionnaire asked whether projects prioritized highly sustainable parts over conventional high-performance options, even if they underperformed technically. 22% of the projects reported actively seeking sustainable components, and a smaller subset (11%) indicated a willingness to use underperforming but more environmentally friendly components.

Again, more than 80% of projects reported resource-sharing strategies and architecture-level optimization. These strategies are often framed in terms of the resource management practices that yield sustainability benefits. Many projects have incorporated dynamic resource allocation or multi-tenant systems, with some explicitly including carbon awareness or renewable energy sourcing in their models. Some responses also indicated that improved resource utilization should go with enhanced scalability, as it might lead to higher overall system use rather than actual environmental savings, indicating the need for more refined impact models. This effect, known as the rebound effect, is targeted by a couple of projects in the landscape.

With respect to flexibility, adaptability, and reconfigurability, 21 projects answered affirmatively. Examples include reconfigurable hardware and software, dual-mode connectivity systems, and self-organizing network architectures. Flexibility has also been linked to intelligent orchestration, an elastic infrastructure, and adaptive routing. Nevertheless, efforts are required to assess whether these characteristics are implemented primarily for functional robustness, economic scalability, or environmental benefits.

Modular and scalable architectures were also reported as a common approach, with 74% of the projects indicating that their systems were designed using composable or "Lego-like" building blocks. These modular architectures are associated with the goals of interoperability, ease of deployment, and reuse across multiple use cases.

3.7 Sustainability Targets: First and Second order effects

This question was designed to assess whether projects aim to reduce the environmental impact of the technologies they develop (referred to here as first-order effects) or to enable sustainability improvements in other sectors through the use of those technologies, referred to as second-order effects. The question also sought to explore how clearly these targets were defined, and how they were incorporated into the sustainability strategy of the project.

Projects reported both orientations, with some focusing primarily on first-order effects, such as reducing the energy consumption of communication networks or improving the material efficiency of the components. Others aimed at second-order effects by enabling more sustainable practices in vertical domains, such as transport, healthcare, manufacturing, and immersive media. Several projects indicated that their work simultaneously contributed to both types of effects.

Examples of first-order effects include the design of energy-efficient radio access networks, power-saving hardware architectures, and carbon-aware system-orchestration techniques. In these cases, the goal is to reduce the direct negative environmental impact of the technology being developed.

Second-order effects have been described in various domains. Use cases have been reported in areas such as remote healthcare, immersive collaboration through extended reality (XR), autonomous public transport systems, smart manufacturing, and environmental monitoring. The common ground was that the enabling technologies developed in these projects could contribute to emissions avoidance, resource optimization, or increased societal resilience in the respective sectors.

These findings suggest that both first-order and second-order effects are pursued across the program, although methodologies to capture, quantify, and compare these impacts have different maturities.

3.8 Key Insights

The analysis of project responses revealed several positive trends along with important methodological and conceptual challenges. Taken together, these findings provide a clearer picture of the current state of sustainability integration within 6G SNS JU projects and indicate areas for both consolidation and improvement. The following key insights can be highlighted.

- **Broad recognition of sustainability as a relevant concern across project portfolios**: Almost all projects addressed sustainability in some form, with many incorporating it in the early stages of design. This reflects a growing alignment with the overall strategic vision of the SNS JU, where sustainability is positioned as a cross-cutting objective.
- **Among the various dimensions of sustainability, EE is the most systematically addressed**: Concrete technical strategies are proposed and, in some cases, integrated into architectural decisions. This indicates a strong foundation from which broader environmental strategies can be developed. Several projects have also reported using flexibility, adaptability, and modularity as design principles; while often developed for performance or scalability, they also contribute to potential sustainability gains.
- **KVIs are used with varying degrees of formality and structure**: While the application of the SNVC methodology has not been fully adopted, widespread interest in defining and tracking value-aligned indicators signals an emerging culture of impact-oriented project management. This provides a promising basis for future standardization and benchmarking efforts.
- **Limited coverage of environmental domains besides EE**: Although EE has been frequently emphasized, coverage of other environmental domains, such as material use, emissions, and end-of-life impacts, remain limited, and social and economic sustainability aspects have not always been addressed systematically.
- **Life cycle and supply chain considerations tend to be underrepresented**: Especially in low-TRL projects, the early-stage focus on technical feasibility may have limited the capacity to engage with full value-chain assessments or long-term environmental impacts. As projects mature, structured support incorporating lifecycle thinking may be beneficial.

4 SUSTAINABILITY TRADE-OFFS

This section explores the trade-offs considerations and choices SNS JU projects face while incorporating sustainability considerations. These approaches are of different nature, and most of them need to be considered up-front, prior to the design of the system under study. Nevertheless, the built-in flexibility that 6G networks are expected to deliver could allow for the accommodation of sustainable approaches even beyond the first system design.

6G offers means to improve EE and to exploit the trade-offs that inherently come from system design decisions and the target use cases in mind. One of the main concerns when operating a 6G infrastructure falls on how and whether to distribute its management and control, this having an impact on EE. Similarly, a trade-off exists when deciding which computing, storage, and networking resources are deployed at any point of the network infrastructure, being the schemes and resource allocation strategies relevant in seeking EE improvement. Another trade-off that is relevant in SNS JU actions is the system modularity or scalability, playing an important role in the development of sustainable products that can adapt to future needs and larger number of users. However, given the existing hardware and the resource and time constraints in the execution of projects, the modular design process usually lies with non-research-oriented projects. Finally, recent advances in cybersecurity practices are brought into the systems by means of different techniques, calling for environmental sustainability considerations, each leading to different resource needs in terms of bandwidth, computing, storage, etc.

All in all, the subsequent sections provide an insight into the degree of consideration of sustainability approaches and the pros/cons they may bring along. This section puts forward the benefits and drawbacks of applying sustainability principles in the research and development processes in the SNS JU projects, extracted from the questionnaire, with the aim of guiding subsequent 6G system design considerations by future SNS actions. Moreover, it synthesizes project responses to draw key insights into current practices, emerging gaps, and opportunities for more harmonized, impactful methodologies across the 6G research landscape.

4.1 From trade-offs to co-optimizations – achieving the critical balance

In a hyper-connected world, it is inevitable that communication network infrastructures will be continually upgraded with new hardware and processes. This ensure the capabilities of networks to face future global challenges and, consequently, an effective long-term management. This challenge will be further exacerbated by the anticipated replacement of existing radio units with newer, more advanced models. However, steps are currently being taken to mitigate this impact, making the networks more flexible, intelligent and sustainable.

One of the key focus areas within the SNS JU community is EE. It is well known that having this KPI in mind implicitly brings about the worsening of other KPIs, as it is not possible to boost all performance metrics simultaneously. Accordingly, in parallel with efficiency optimisation efforts, and with the amount of resources available, a number of different trade-offs arise. For example, an increase of the EE (in bit/J) usually implies decrease of bandwidth efficiency (in bit/s/Hz) and vice versa. Similarly, and to a more generic level, to improve sustainability a trade-off is required between resource consumption and performance.

The questionnaire explored the approaches of the projects towards tackling these and many other trade-offs, with a view to channelizing them towards co-optimization endeavours, rather than the management of competing interests with winning and losing sides. Essentially, the exploration cantered around opportunities to include sustainability parameters alongside performance and functionality related ones so that a balanced equation could be drawn. It is observed that EE and savings are already on a path to achieving such a balanced optimization within many functional and performance-related domains.

4.2 Balancing Performance and Resource Consumption

The quest of top-notch performance has often meant increased power consumption, therefore impacting environmental sustainability. This trade-off had sometimes been overlooked in technical communities, whose main goal had been to reach even higher performance metrics disregarding the power required to satisfy those. With the cost of energy challenges, the trend has reverted towards striking a balance between performance and resource consumption, trying to adapt the performance to that desired and not wasting energy in the process.

The analysis of the responses related to the consideration of the “Performance vs resource use (memory, processor cycles, bandwidth, etc.) trade-off revealed that a substantial, 85% of the surveyed SNS projects (23 out of total 27) focus on balancing performance with resource consumption, emphasizing the need to optimize resource efficiency while maintaining high performance in 6G networks.

As shown in Figure 13, the trade-off “"Bandwidth/Computational resources vs. Coverage / Capacity / Latency" is the most explored trade-off among the surveyed SNS projects, considered by 11 projects. This tendency underscores the major challenge of balancing network performance and resource efficiency in 6G network development. Several projects (8 projects) investigate energy-related trade-offs, including “Energy/Power vs. Bandwidth/Computational resources” and **“**Energy/Power vs. Coverage/Capacity/Latency/Reliability “. This further highlights the growing emphasis on power considerations in future 6G networks.

On the other hand, complexity-related trade-offs seem to receive relatively lower attention; specifically, only 2 projects consider the “Complexity vs. Coverage/Capacity/Reliability” trade-off and 2 projects study "Energy/Power vs. Complexity”. Similarly, only 3 projects examine the “Accuracy vs. Complexity/Memory consumption” trade-off. Such tendency indicates that aspects related to computational complexity and their interplay with network performance may represent areas for further research investigations within the community.

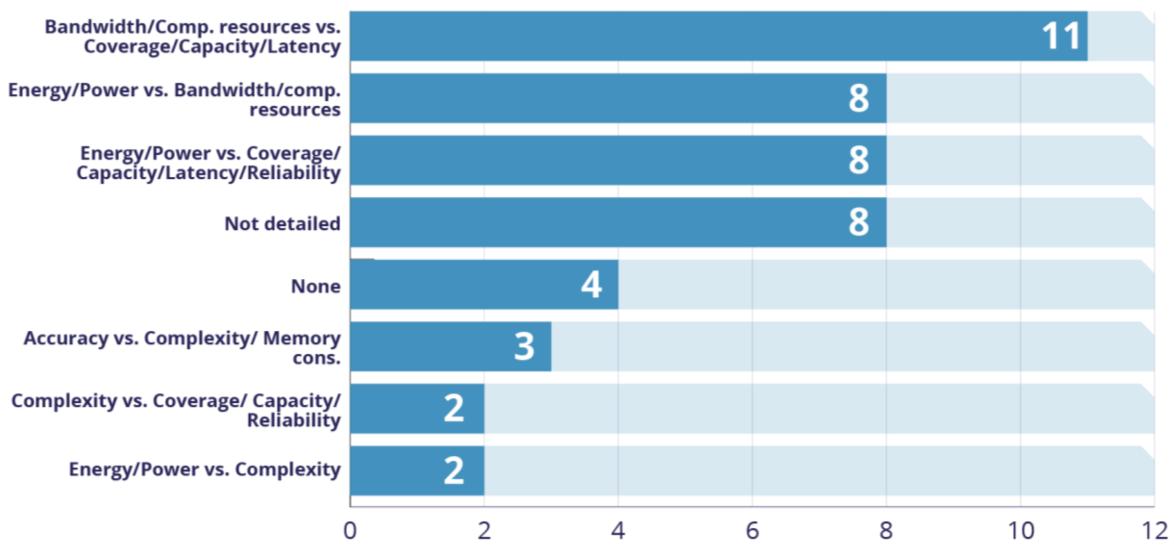

Figure 13: Studied trade-offs in the SNS Projects

4.3 Architectural trade-offs

4.3.1 Centralized versus distributed architectures

When designing 6G network architectures, it is important to define and evaluate the architectural blueprint options within the Proof of Concepts (PoCs) framework. The trade-off between centralized and distributed architectures is one of the considerations, with analyses carried out as part of the project activities.

Centralised architectures are frequently mentioned for their ability to simplify network management by centralizing control, while distributed architectures are highly valued for their scalability, fault tolerance, and suitability for decentralised operations. Hybrid approaches are occasionally referenced in the surveyed SNS projects, combining centralised control with distributed elements to adapt to specific use cases. It is noted that hybrid architectures are less common compared to purely centralised or distributed setups.

As illustrated in Figure 14, several cutting-edge technologies were identified in the projects' responses as enablers for these architectures. In particular,

- **Edge computing**: Allows shifting processing from centralized data centres to nodes closer to the end users, enhancing system responsiveness and resilience of services by enabling local decision-making.
- **Software-defined networking (SDN)**: Enables centralized and flexible control of distributed network elements, allowing operators to dynamically configure, manage, and optimize network behaviour through software applications.
- **AI-based orchestration**: Dynamically manages and optimizes workloads across centralized and distributed infrastructure. By analysing network conditions, and application requirements, AI-driven orchestrators can intelligently balance resource allocation, predict potential bottlenecks, and adapt processing strategies in real time.

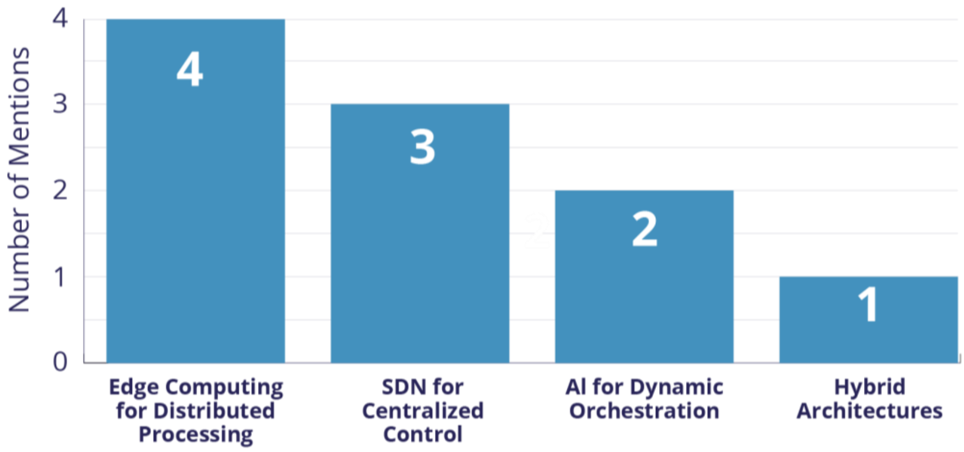

Figure 14: Specific Technologies for architecture options

In summary, the responses collected and the variety of evaluations - mostly preliminary comparisons of different architectural options - suggest that the envisioned 6G system's ability to flexibly run specific functions either centrally or in a distributed way, using AI/ML techniques to improve EE, could justify higher initial investment costs (CAPEX), with the expectation of reduced operational costs (OPEX) in the long term.

4.3.2 Dedicated hardware versus virtualized resources

This trade-off stems from the consideration of the best suited purpose-built hardware platform to perform a task, which is in most of the cases more efficient than opting for a general purpose one. Virtualization brings along adaptability for implementations to general purpose hardware at the cost of not being optimized, therefore entailing additional power consumption. However, in the latter case, a flexible enough hardware can support multiple implementations, thus being more sustainable as can be "reused" over time.

As shown in Figure 15, a significant amount of surveyed SNS projects (18 out of 27) did not explicitly engage with the trade-off between dedicated hardware and cloudification/virtualization, as a driver in architectural decisions. This limited consideration indicates that a strong majority of the projects relies either on dedicated hardware or virtual resources without an explicit comparison of sustainability aspects. While a direct trade-off analysis might be lacking, certain projects have highlighted in their responses the distinct advantages of both approaches. Dedicated hardware can be associated with potential "performance advantages" (e.g., for energy-critical tasks) while cloudification offers "scalability and flexibility." This suggests that projects might be implicitly choosing one over the other in their architectural decisions based on their primary needs (performance vs. scalability/flexibility) and specificities of the addressed use cases, rather than relying on a thorough comparative analysis.

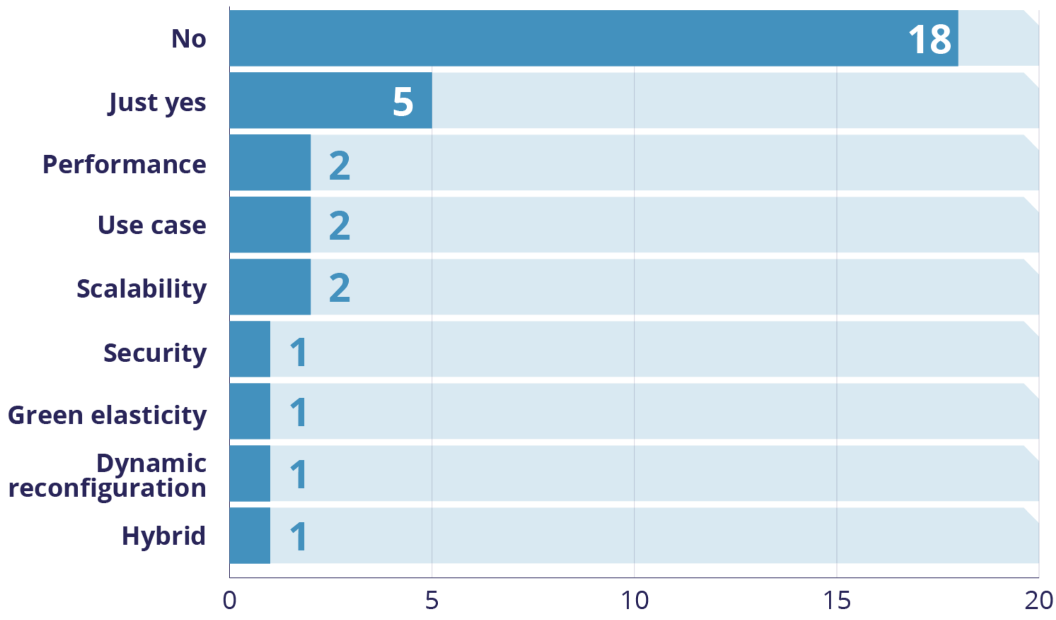

Figure 15: Dedicated hardware vs. cloudification/virtualization

4.4 Energy Efficiency strategies

To achieve sustainability, several key approaches and strategies may be applied to specific components of the 6G system. These strategies depend on the use cases and scenarios being considered, and the solutions must be tailored according to balance requirements such as performance, EE, and cost, while satisfying all of them to a reasonable extent.

The projects have emphasized that there is no solution that is being considered overall, but there are approaches that stem from the use of certain technologies to reap EE. The approaches that are mostly considered in the community are related to the optimization of the system (and parts of it). These are classified into the following groups:

4.4.1 Network Infrastructure Management

Optimized IT network infrastructure management goes beyond the technical requirement, enabling cost savings, scalability, improved security, and increased productivity. In recent years, various tools have been developed and promoted to support this, including:

- AI-driven triggers for switching off carriers or terrestrial cells when traffic is offloaded to satellites.
- Infrastructure-level power management complementing network-level mechanisms and exploration of virtualized RANs with dynamic power management.
- Dynamic resource provisioning where orchestrators create and release resources based on demand.
- Use of programmable switches and SmartNICs that can be powered off.

4.4.2 Energy-Aware Routing

Energy-aware routing protocols can be classified into two categories, energy savers and energy balancers. Energy saving protocols are used to minimize the overall energy consumed, while energy balancing protocols attempt to efficiently distribute the consumption of energy throughout the network. Some strategies being addressed in SNS JU projects are:

- Algorithms (using heuristics or AI/ML) prioritize routing through already-active devices. The algorithms try (as far as they can) to route incoming connectivity services throughout active devices rather than activating/powering up those being in sleep mode.
- Attempt to maximise use of powered-on equipment before activating sleeping components.
- Traffic aggregation at the optical layer using digital sub-carrier multiplexing to reduce energy requirements.

4.4.3 Radio Unit (RU) Optimization

The Radio Unit (RU) is a major power consumer, depending on various factors such as the specific technologies in use, network configuration, and the operating environment. In 5G networks, the complexity and power demands increase due to technologies like massive MIMO (mMIMO) and due to the use of higher frequency bands (such as mmWave). The RUs not only process and transmit signals to and from user devices but also handle real-time tasks such as beamforming, which are energy intensive. Therefore, network operators and technology developers continuously focus on optimizing the EE of RUs. This includes advancements in Power Amplifier (PA) technology, more efficient cooling solutions, and intelligent software algorithms that optimize signal processing and transmission to reduce power usage. We present some of the approaches investigated by SNS JU project that can substantially reduce the energy consumption of the RU:

- Energy-proportional service delivery when RUs must remain operational.
- Advanced management of power amplifiers, e.g. keep RF power amplifier operating with high efficiency without losing linearity.
- Granular control of digital signal processing functions.
- Use of RU metrics and sensor data to inform decisions.
- RAN intelligence algorithms analyse traffic and KPIs to optimize RU functions.

4.4.4 IoT and Sensor Networks

Sensor networks are increasingly recognized as a valuable tool for advancing sustainability efforts across various sectors. This type of networks enforces decision-making based on the real-time data they can provide based on environmental conditions, resource consumption, and operational efficiency. The means to achieve sustainability in sensor networks in SNS JU projects are the following:

- Zero energy IoT nodes implement sleep modes
- Devices wake only for specific tasks (communication, sensing, actuating, processing)
- Trade-offs between computation and communication time to maximize sleep periods
- Consideration for distributed, heterogeneous sensor networks.

4.5 Energy-aware network design

Energy-aware networking can be defined as the set of techniques that exploit energy-related information to assist not only design and implementation of the network infrastructure, but also the process of the data transmission over the network, such as the route computation or the traffic forwarding processes. In the context of designing 6G networks, careful decisions on issues such as modularity and resilience of the design, or backwards compatibility would be of prime importance with respect to reusability of the infrastructure, efficient maintenance and monitoring of the network, and low cost (in terms of resources) upgradability. In the following three subsections, SNS projects responses to these design-related trade-offs are presented and analysed.

4.5.1 Backwards compatibility versus complexity/clean slate approach

This trade-off revolves around the complexity that is required to implement a solution that is able to persist over time being compatible with an older version and yet featuring the latest upgrades to be future proof. Naturally, bringing in clean slate solutions make an overall network replacement necessary, contradicting any sustainability goals.

Some projects answered by saying they are taking a clean slate approach but were not clear on whether the sustainability relative to backwards compatibility is addressed — these were noted as 'yes'.

4.5.2 Resilience versus redundancy (stand-by resources)

Another important element would be how to design a resilient network while redundancy is kept at its minimum, since ensuring 'resiliency through redundancy' would require, in general, to take a wasteful (non-sustainable) approach.

This aspect is being addressed in 13 out of 27 projects, each incorporating it into their agendas in various ways, commonly through the use of redundancy. The remaining 13 projects either did not include this item in their agenda or did not provide a response, while for one of the projects, the question was not clear, and so no information was provided. Among the 13 projects providing answers, 3 projects provided a generic response, and so the relevance is not very clear. Another project seems to address the resiliency, although the redundancy factor is not clear from their answer. There are 4 projects working on the resiliency but with other means than redundancy. The remaining 6 projects work out resiliency, and certainly through redundancy by following means:

- Use of idle satellite sharing of computational capabilities, or 3D network (2 projects).
- Redundancy with additional equipment or transmission channel (3 projects).
- Through tackling online energy aware restoration mechanism (1 project).

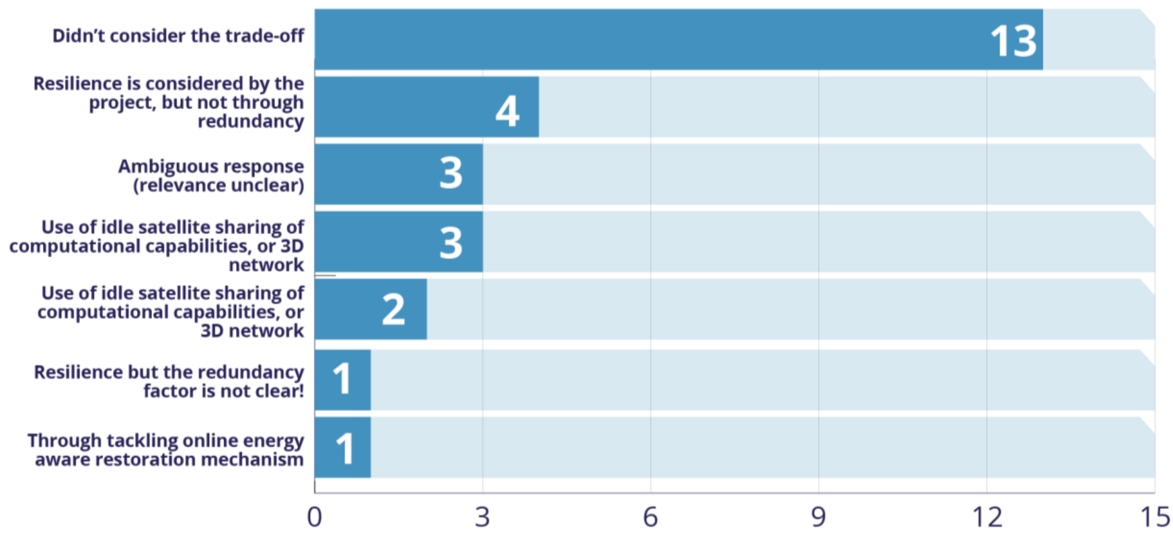

Figure 16: How the projects address Resilience vs Redundancy (as stand-by resources) trade-off

4.5.3 Time to deliver versus modular/reusable design

Conceiving a solution for a certain purpose always entails effort, and yet additional effort (and normally time) is required to provide a multi-purpose modular solution that can tolerate an extended lifetime. This trade-off is being assessed here, since projects being limited in time, usually leads to quick decisions that target faster development, which is mainly addressed by using multi-purpose hardware and software-based solutions.

This aspect is addressed by 4 projects out of 27. The approaches considered include:

- Balancing the trade-off between time-to-deliver and modular/reusable design through incremental development, enabling early results while building scalable frameworks.
- Adoption of microservices for its service-based architecture, with most of the network functions being open-source.
- Usage of compute continuum layers, reusable and adaptable ML modules, and modular and reusable global service-based architecture to manage heterogeneous, modular, computing resources.

These technological choices are aimed at facilitating deployment and enabling adaptable implementations, which simplify management while ensuring cost-effectiveness and environmental sustainability through longevity of deployed infrastructure. In essence, if only software modifications are needed, this would enable the existing computing elements to remain fit for purpose under changing circumstances.

4.6 Security versus Energy Savings/Efficiency

Security and trust are crucial for future communication systems, especially as the network connects the physical and digital worlds more tightly. Security in 6G involves ensuring data confidentiality and integrity, often achieved through encryption and secure authentication, and trust is ensured with mechanisms such as trusted hardware, platform, and foundation. Achieving security and trust targets requires a multi-faceted approach, encompassing technological advancements, policy frameworks, and collaborative efforts. Processes and strategies are recommended, that include techniques such as robust authentication and access control, leveraging AI and machine learning for threat detection, employing distributed ledger technologies for secure data management, establishing federated trust relationships, and so on. All of these would require extra network (and compute) resources and so are prone to more consumption and material usage, making energy consumption and EE a relevant issue.

Regarding the trade-off between security and EE, 8 SNS projects provided responses, out of which only 2 projects indicated that they work on Security as a main solution in their agenda. Yet it is not clear if security vs EE is addressed. The rest do not have security as a topic in their agenda, although three projects indicate implicit or indirect related works.

It seems projects that are directly dealing with security issues, do not have any agenda on EE of the solutions or the network. This might reflect their original focus, when the project was defined at the time of the proposal preparation.

4.7 Key Insights

Several trade-offs emerge from SNS projects' considerations when seeking sustainable solutions to be developed in the 6G context. Based on the analysis presented in this section the following key insights can be extracted.

- **EE emerges as the main common objective of SNS projects, although considering different trade-offs**: Trade-offs considered are at the architectural level, how flexible and modular the solution is conceived, where the functions are computed and particular solutions for improving EE. It is widely accepted that energy optimizations need to go hand in hand with other functional or performance related requirements. Accordingly, it can be said that this is a co-optimization, reaching beyond a trade-off consideration.
- **Technology improvements and architectural considerations will significantly affect EE and power consumption**: 6G is expected to feature new applications and features that, in many cases, could bring along additional power consumption. On the other hand, 6G solutions and technological improvements will be provided with increased flexibility and adaptability to changes in the RAN and usage patterns that could potentially revert the expected trend making the system more energy efficient.

  The technology improvements towards EE optimization can be present in many elements of the network, and in the network design as a whole, ranging from overall architecture decisions to mechanisms that optimize EE in single elements. It is clear from the answers considered, that in the course of the 6G network architecture definition, many projects do separately foresee architectural solutions that allow balancing the different trade-offs putting emphasis on those of particular interest.
- **Early design decisions & EE trade-off analysis may significantly impact performance**: No overall analysis of the devised 6G solution tackling the above-mentioned trade-offs was initially conceived in any of the projects. Energy-related trade-offs are of main interest for the projects, examples are many and varied in seeking EE at network/component level, while aspects related to computational complexity and their interplay with network performance may represent areas for further research investigations within the community. Regarding the

architectural decisions, many variants are still subject to study in current SNS projects, as still there is not a single solution that fully satisfies everyone. Decisions on design features that can be taken early enough such as distributed vs centralized architectures, provision of backwards compatibility, and choices on redundancy and modularity are still being assessed and many results will be stemming from these analyses.

- **EE trade-offs to be considered at the conceptual stages of R&I work**: The variety of technological choices to be incorporated in the 6G network design and their trade-offs provide, on one hand, insightful conclusions to the SNS community on the capabilities of the projects to address future demands. On the other hand, how these ideas are conceived also reflects the change of mindset required to inherently adopt all these options when positioning future project proposals. To date, projects carry out studies oriented towards their primary needs to satisfy use cases' needs rather than relying on a thorough comparative analysis. Accordingly, in the complex system 6G represents, the management of the above-mentioned trade-offs, and the achievement of focused optimisations in some of the relevant dimensions, might not necessarily translate into a full system level optimisation.
- **Sustainability by design**: Sustainability by design approaches will have a better chance of addressing the above-mentioned trade-offs and of finding co-optimizations that address future needs with a holistic, systems perspective. This calls for an interdisciplinary and holistic analysis of the system, with the objective of reaping the highest possible benefits from every dimension that tailor and contribute to system sustainability, finding the most appropriate blend among variables, in each given specific context. This process opens a window for a critical reflection regarding what criteria are to be used to define what is optimal. Choices need to be made, prioritising achievements and targets, setting thresholds and limits.

Overall, the sense of priority – when navigating trade-offs and conflicts to find the right balance – depends on a system of values through which importance to achievements and impact are assigned. Based on this value system, objectives are prioritised, and thresholds are set, distinguishing what is acceptable from what is not.

These criteria for prioritisation vary across stakeholders, therefore, a full understanding of trade-offs and co-optimisation management, cannot leave aside a critical reflection on whose priorities are influencing the decisional process and priority setting.

5 IMPLEMENTATION CONSIDERATIONS

This section presents a synthesis of project views on a set of implementation-oriented challenges cantered on sustainability, efficiency, and long-term impact. The questions have been organized into four thematic areas to reflect the multifaceted nature of sustainable design in digital technologies. The first theme, Implementation efficiency, explores how design decisions affect energy and resource consumption, as well as the compromises for achieving optimal performance. The second, Scalability, Maintainability, and Modularity, addresses how systems are built to accommodate growth, facilitate maintenance, and support modular evolution. The third theme, Sustainability and Circular Design, highlights efforts to reduce environmental impact through recycled components, energy limits, and lifecycle planning. Finally, the fourth theme, Societal, Ethical, and Infrastructural Considerations, focuses on the broader implications of technical choices, including user transparency, privacy, social outcomes, and the reuse of existing infrastructure. Together, these themes offer a comprehensive overview of how projects are integrating sustainability and responsibility into their design and deployment strategies.

5.1 Implementation efficiency

This section focuses on how design choices made in the projects impact energy/resource usage and efficiency. It summarizes the responses collected from multiple projects regarding key implementation challenges and strategies in this regard. The questions focused on three main areas: efficiency at the end-user and application levels, system-wide and infrastructure-related resource management, and forward-looking approaches such as the adoption of energy-autonomous devices. Projects were asked whether they had encountered specific challenges—such as increased resource use, added complexity, or inefficient design choices—and how they addressed them. The insights gathered provide a snapshot of current practices, gaps, and innovative directions in sustainable system and application design.

5.1.1 End-User and Application-Level Efficiency

System design decisions can impact resource consumption and performance at the user devices and application layers.

EE in end user devices has been a relevant research area within the SNS projects. The identified approaches include:

- Energy-aware protocols, designed to minimize resource consumption at the end-user devices.
- Optimized handover mechanisms between network components to avoid unnecessary energy usage by devices. Specifically, these mechanisms enable efficient transitions between network components to avoid energy spikes.
- Dynamic power management strategies in devices, influenced by network conditions. Such strategies adapt device power usage based on network demands.
- Addressing network-user device interdependencies, focusing on how network efficiency impacts device energy consumption. Research effort is being spent into how networks and user devices influence each other’s efficiency.

Figure 17 shows statistics on the number of projects dealing with these aspects.

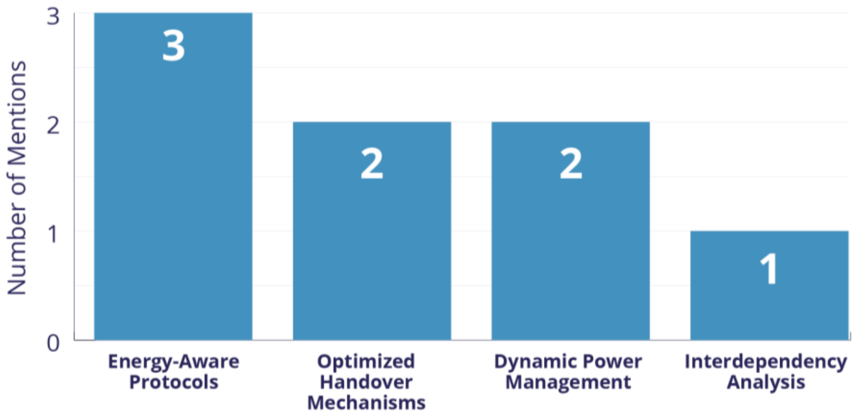

Figure 17: Specific Technologies for End-User device efficiency

With respect to application efficiency, only 6 projects reported encountering challenges related to the creation of APIs or data models that led to heavy resource consumption at the application layer.

In these cases, the focus was largely on specific use cases, where resource usage was tied to particular functional or performance demands. Moreover, projects emphasized security-related mechanisms or intent-based functionalities—both of which can require more complex data models or continuous interactions that may increase load at the application level.

To manage these challenges, projects developed KPIs tailored to their specific contexts. These KPIs helped them monitor and understand resource use more precisely, guiding optimization efforts where possible.

Moreover, most of the projects focused on must-have features. The implementation of nice-to-have features, generally considered as over-engineering, is only considered by a minority of the projects. 7 projects draw attention to specific nice-to-have features and potential developments related to non-Terrestrial Network and backhauling, or energy-aware technologies. 13 projects explicitly indicate no plans to introduce nice-to-have features.

5.1.2 System level and infrastructure efficiency

Efficiency, complexity, or capacity of systems and networks can be influenced by the backend infrastructure, including data centres.

Most of the projects do not consider introducing complexity or more capacity in data centre operations. However, 6 projects consider potentially additional complexity due to the implementation of distributed deployments, or for enabling AI/ML techniques, or virtualized operations.

Also, most projects did not actively prioritize the introduction of new parameters that would affect the data path or significantly extend the length of existing ones, such as increasing encryption key sizes.

In general, there is a reliance on existing security standards and protocols, with limited uptake of newer or more advanced security enhancements. Several factors seem to contribute to this trend. For instance, some projects cited technical complexity and integration challenges as barriers to implementing such changes. Others felt there was no immediate operational need, especially if current measures were already deemed sufficient for their risk profile.

Additionally, the use of emerging security paradigms, such as quantum key distribution, post-quantum cryptography, and homomorphic encryption, was reported by 16% of the projects and may require further research and targeted incentives to drive adoption at the architectural level. Statistics are shown in Figure 18.

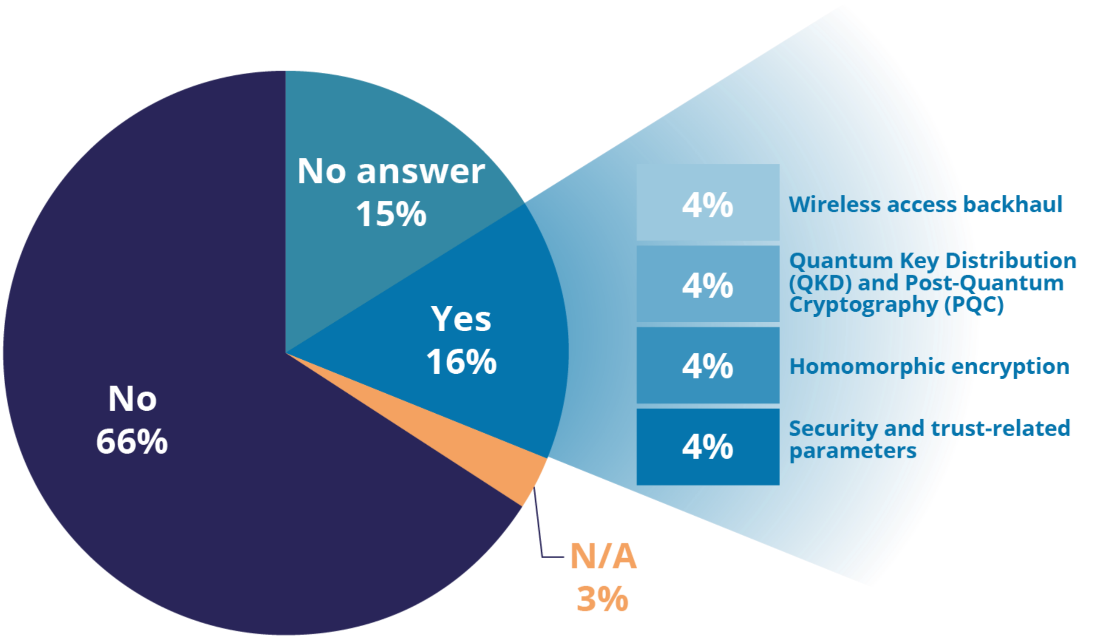

Figure 18: New parameters affecting data path or extension of the length of existing ones

A significant portion of the projects is positive regarding the deployment of resource-sharing mechanisms to optimize hardware, spectrum, and overall resource utilization, as shown in Figure 19. However, while there is increased awareness and research activities targeting resource optimization, practical deployment across projects is still under development and requires further emphasis to achieve widespread efficiency gains.

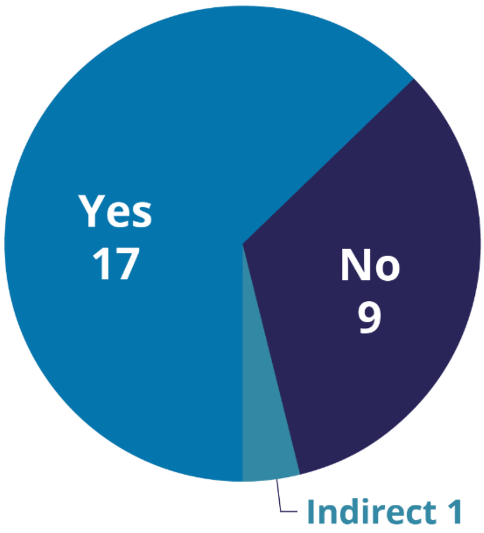

Figure 19: Projects applying resource sharing to optimize hardware/spectrum resources

5.1.3 Innovative and Forward-Looking Sustainability Approaches

More advanced or experimental sustainability strategies in technology design are also of interest to SNS projects.

Roughly one third of the responding projects (27) consider zero-energy devices. Typically, zero-energy devices represent energy autonomous IoT devices, and in general, SNS projects tend to focus on cellular systems. A few projects specifically highlighted their involvement in zero-energy IoT devices, while other projects mentioned RIS as energy autonomous devices being considered in their research.

5.2 Scalability, Maintainability, Modularity & Circular Design

This section discusses how scalability, maintainability, modularity, and circular design are approached in various SNS JU projects. Scalability is a key priority for 59% of projects, emphasizing the need for scalable solutions without full-node upgrades. Maintainability is supported by only a few projects, with approaches like running protocol stacks as applications and implementing AI/ML micro-orchestration. Modularity is widely adopted, with projects focusing on modular and scalable designs at both architectural and functionality levels. Circular design is less emphasized, with limited use of recycled components and a gap in end-of-life planning. Projects are exploring sustainable design techniques and reusing existing infrastructure to improve sustainability.

5.2.1 Scalability

The analysis of responses revealed that scalability is a key priority for the majority of the surveyed projects, with 59% of projects recognizing the importance of implementing scalable solutions. This highlights a general trend toward avoiding approaches that necessitate full-node upgrades across an entire domain. However, a significant part of the projects (41%) may place greater emphasis on other considerations such as the integration of cutting-edge features, enhanced security measures, or performance optimization, potentially at the expense of backward compatibility and seamless scalability. In this context, ensuring alignment on key interoperability and upgradeability standards becomes essential for the development of truly global and sustainable 6G networks.

5.2.2 Maintainability

Regarding the support for maintainability, e.g., serviceability and upgradeability, only 7 (out of 27) projects confirmed that they do support these capabilities, although 2 of them did not elaborate further. Among the more detailed responses, approaches include running the protocol stack as an application to enable upgrades, implementing intra-node AI/ML micro-orchestration, developing scalable and efficient infrastructures, and allowing dynamic configuration of network functions and services. Despite these promising examples, a significant number (19) of projects either responded negatively or did not provide a clear answer. This suggests that while some consideration is given to serviceability and upgradeability, these aspects are not yet widely integrated or clearly addressed across the surveyed projects, highlighting an area needing further attention.

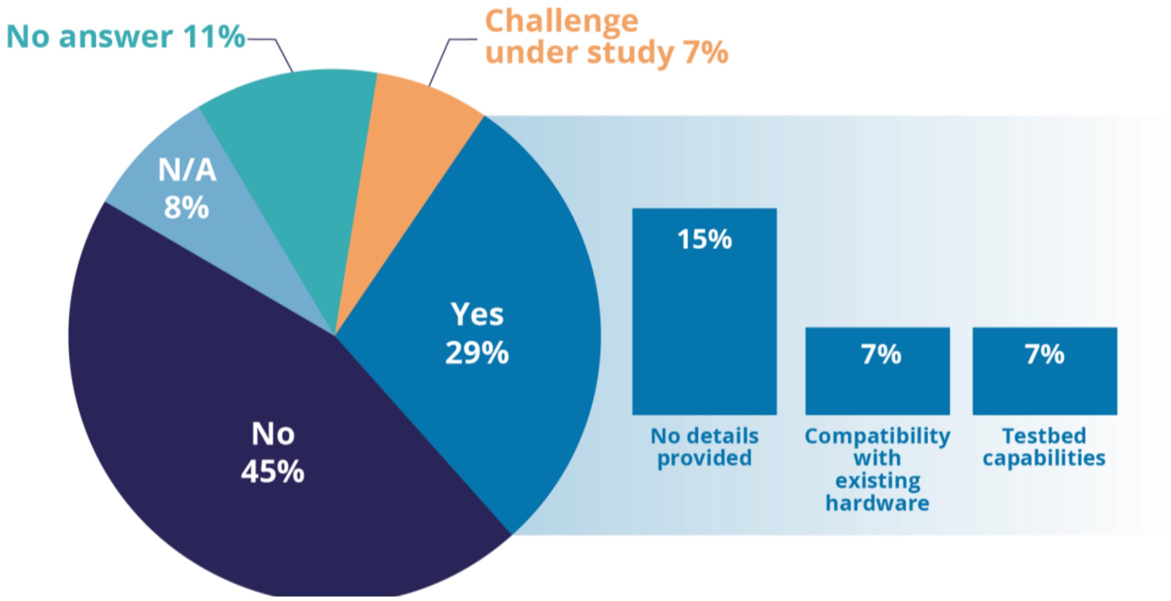

Figure 20: Projects considering minimum system requirements, to avoid hardware upgrades.

The compilation of responses indicates that 45% of the surveyed projects do not consider modest minimum system requirements, suggesting that those projects either do not prioritize minimizing system demands or are open to hardware upgrades or enhancements. On the other hand, a considerable number of projects (29%) work towards reducing hardware dependencies, driven by testbed compatibility concerns or cost-saving strategies. In particular, those projects either aim to ensure that their solutions are tested under realistic hardware constraints or prioritize compatibility with existing hardware to reduce upgrade expenses. Notably, 11% of projects did not provide a response, potentially reflecting a lack of relevant information or a lower priority assigned to this consideration. Furthermore, 7% of projects classify this as a challenge under study, meaning they are still assessing the feasibility of minimizing hardware requirements. A detailed breakdown of the responses is provided in Figure 20.

5.2.3 Modularity

Concerning architecture and functionalities based on modular and scalable designs, most of the projects (21 out of 27) reported adopting these approaches. However, there is a wide and eclectic use of modular and scalable designs across the projects. The thinking of designing architectures based on basic building blocks is prevalent in several projects. Key elements of the system are designed to be modular and scalable, including the service-based architecture, the zero-trust exposure layer and the compute-continuum layer supporting the edge cloud continuum. Other dimensions of modularity and scalability include reusing payload building blocks across different satellite designs, O-RAN compatibility, modular RAN solutions for basebands and RF front ends, as well as modularity scalability at RIS and, and more generically, at circuit level. In general, there is a clear indication that projects are paying attention to modularity and scalability at both architectural and functionality levels.

5.2.4 Circular Design

Several aspects of circular design are investigated by the projects. A small number of projects directly addressed the issue of increasing the level of recycled, refurbished, or repurposed components. Across the projects, limited emphasis on using recycled, refurbished, or repurposed hardware is observed. However, some projects develop modular network architectures, which can be seen as an enabler for refurbishing parts of the system in place; thus, providing a potential solution for upholding maintainability and circularity. Moreover, some projects are considering software reuse, yet there is not sufficient focus on the material lifecycle of the network infrastructure itself. The limited number of responses highlights that circular economy is not a core principle of many initiatives; only 3 projects out of 27 are addressing the aspect of increasing the level of recycled, refurbished, and repurposed components.

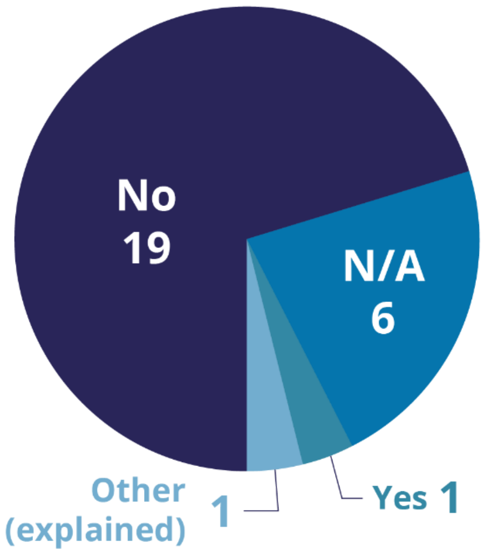

Figure 21: Statistics of projects planning the end-of-life treatment of products and solutions.

As far as end-of-life treatment of products and solutions are concerned, a clear majority of projects are not considering these sustainable approaches, as indicated in Figure 21. Only one project explicitly mentioned such planning and was focused on the durability of transmission components. This reveals a gap in the consideration of the circular economy principles. Proactive planning for the reuse, recycling, or responsible disposal of products and solutions, is essential for avoiding electronic waste generation and resource depletion.

The factors considered by projects achieve sustainable design and implementation are discussed next. The majority of the initiatives are considering the modification of system design and implementation parameters to improve sustainability. Quite a few projects indicated they were setting limits on energy usage, with some also considering GHG emissions and resource use. EE is a noticeable key aspect, with various techniques being explored to maximize it, which highlights its importance for both environmental impact and the practical scalability of future networks. Some examples include AI-driven resource allocation, energy-efficient architectures that prioritize computational tasks over storage requirements, minimizing data transmission via smart, energy-efficient designs, and using self-harvesting energy schemes for ground-based satellites. The exploration of various technical approaches indicates a multi-faceted strategy towards achieving these limits. A summary of the factors considered by projects towards a sustainable design implementation is shown in Figure 22.

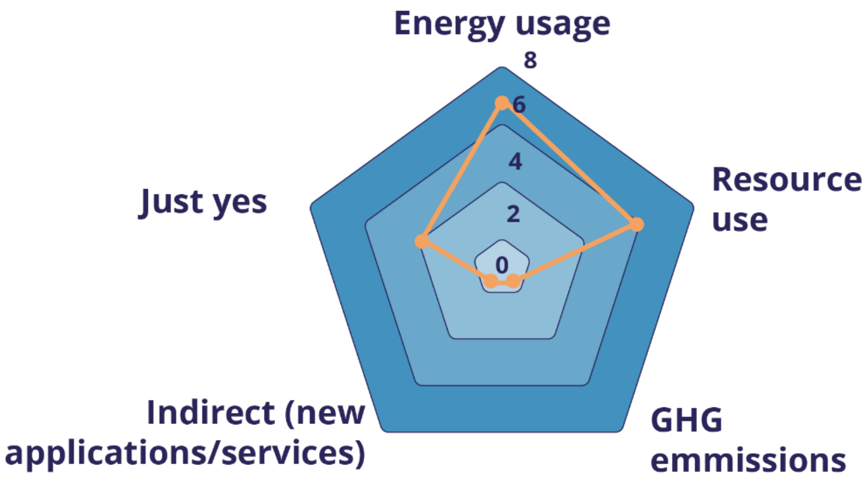

Figure 22: Factors considered towards a sustainable design implementation.

Related to the sustainability of the implementations, projects also consider reusing the existing infrastructure. In fact, two thirds of the 27-respondent project reuse the existing infrastructure. This is a significant figure as infrastructure reuse is part of the holistic sustainability equation. It is noted that projects interpreted differently the original question asking how infrastructure reused was considered. In fact, reuse was understood either as reusing existing experimental facilities, or designs exploiting existing infrastructures as a part of the overall design rather than creating new infrastructure solutions. Probably the second interpretation was the intended one. Considering the cases where the existing physical infrastructure is exploited, different approaches are studied by the projects. Projects consider a) the extension of the service-based architecture to the RAN, allowing reuse of existing core network functionalities; b) sharing computing resources at RAN level; c) reuse of 5G core and ORAN architecture components; d) reuse of lighting infrastructure to provide optical wireless access; and e) reuse of 5G non-terrestrial networks space infrastructure.

As a whole, no clear focus on how reusing the existing infrastructure is considered by the projects, as diverse infrastructure reusing approaches are applied. Still, infrastructure reuse appears to be an emerging trend in SNS projects.

Finally, the use of sustainable components and parts as a part of the overall implementation was also in some initiatives. In fact, 6 out of 27 projects are considering the use of sustainable components and parts in their designs. The projects approach this issue in very diverse ways, and no particular trends on the use of sustainable components and parts can be observed. The highlighted components and parts being considered by the involved projects are a) use of printed electronics- based components (e.g., thin-film transistors, organic photovoltaic cells, supercapacitors and diodes), b) use of sustainable implementation technologies (e.g., sustainable substrates and conductive inks); c) opportunistic use of low processing power and low power processors, analog beamformers and RIS solutions: and d) use of signal processing techniques at electromagnetic level, without using power-hungry analog-to-digital and digital to analog converter (ADC/DAC) and digital processing.

Even though a widespread use of sustainable components and parts is not observed, there are clear signs that sustainable implementation is a topic of growing importance, and fundamental to achieving sustainability in a wide sense.

Developing measurable and assessable sustainability metrics or other indicators are important aspects of sustainability, when considering and comparing different possible implementation approaches. As shown in Figure 23, most SNS JU initiatives state that they are in the process of developing concrete indicators to measure sustainability. The complexity and diversity of each project makes the assessment of sustainability implications via existing metrics difficult. To this end, the projects are actively exploring existing and developing new ways to assess how sustainable the solutions they are developing are. Moreover, the initiatives indicated that new metrics are needed to assess how sustainable the designed technologies can be when scaled. A strong commitment to developing ways to measure and assess sustainability is visible by most of the projects. This highlights the need for evidence-based evaluation of the sustainability aspects of developed technologies, which is imperative for enabling comparison with current state-of-the-art and demonstrating progress. The metrics/indicators that stem from the effort put forth by the SNS JU initiatives could be proven instrumental for sustainability assessment methodologies in next generation networks.

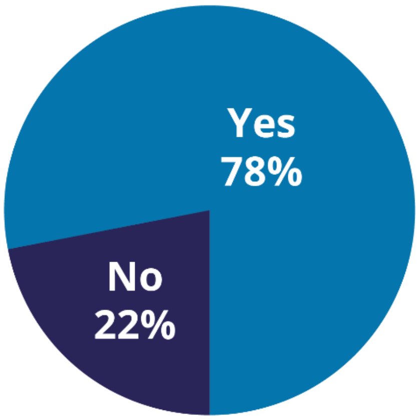

Figure 23: Projects developing measurable/assessable sustainability metrics/indicators.

5.3 Societal & Ethical Considerations

In this section, the focus is societal and ethical considerations. Broader impacts include privacy, explainability, and social implications.

Around 40% of the surveyed projects, specifically 11 out of 27, have made an effort for investing in statistics, explainability, and transparency. These projects have adopted a range of strategies to enhance the trustworthiness and interpretability of their systems, particularly in AI/ML-driven environments. A key focus has been on explainability within the AI and machine learning components. Projects aimed to develop models that are not only accurate but also interpretable, allowing end users or stakeholders to understand the reasoning behind automated decisions or actions. This is especially critical for building trust and ensuring accountability in data-driven systems. In parallel, some projects have worked on implementing network-level components capable of collecting, analysing, and exposing key network statistics. These insights are often made accessible to external modules or services, facilitating real-time monitoring, troubleshooting, and optimization, while also contributing to transparency. One notable approach reported was the definition of a Key Value Indicator (KVI) related to transparency. This metric aimed to assess how effectively users can engage with the system—specifically, their ability to understand how their context or activity influences system behaviour, and how decisions are made in response.

In terms of privacy, the issue of collecting personal data also respecting privacy constraints is considered by the SNS JU initiative. The responses of the projects have been classified into three distinct categories depending on the level of detail that was provided.

- Projects with explicit privacy protection measures are identified in the document: Five projects provide detailed approaches to privacy protection, outlining specific methods such as anonymization, encryption, compliance with GDPR, and ethical review processes. For example, one project mentions using "anonymization and encryption to protect user data" while employing "edge processing to retain sensitive information locally." Another project describes removing "personal identifiers to prevent the data from being traced back to individuals." A third project emphasizes the importance of designing "AI/ML algorithms and models" that are "socially robust" by considering "privacy and security aspects of users' data."
- Projects that broadly acknowledge compliance with privacy are also noted down: Three projects confirm that they adhere to privacy requirements but give little information about their specific methods. For example, one project states simply, 'Yes, ongoing,' without any further information, while another says that 'data protection is a legal requirement,' referring to a 'KVI that aims to match privacy concerns with the capacities of a service.
- Another approach is to avoid collecting personal data altogether: This strategy is adopted by two projects that have unambiguously stated that they do not collect personal data and hence have no privacy concerns to address. Some projects have set up protocols to use in case it becomes necessary to collect personal data.

All in all, projects with dedicated strategies take the most thorough approach to protecting privacy. They give very particular details about how things are implemented and about the ethical considerations that were taken into account during their decisions. On the other hand, responses from projects that give only general acknowledgments of compliance do not provide many insights other than that the ethical and privacy issues were considered at some stage.

Projects' opinions on linking social and economic outcomes to technology enablers and creating causality between them are seen in Figure 24. Among the 8 projects (33%) answering yes, 56% leveraged the KVI approach while 44% considered other methods including a) significantly reducing energy consumption and electromagnetic exposure levels per transmitted data bits; b) integrating terrestrial and non-terrestrial network architectures to bridge the digital divide; c) developing Green Business Models aiming at OPEX reduction; and d) moving the Blockchain Radio Access Network (B-RAN) closer to the market.

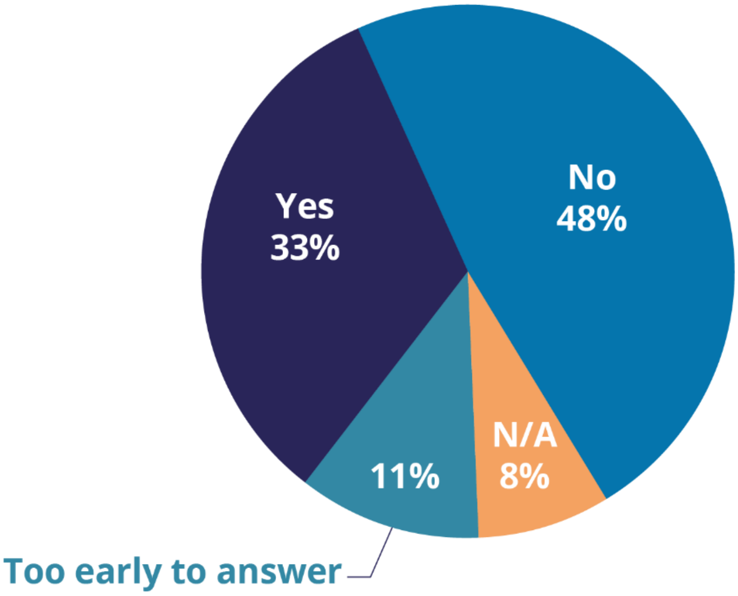

Figure 24: Statistics of projects linking social and economic outcomes to technology enablers.

The view of the SNS JU projects on digital sobriety, that is, the consumption of digital services with moderation, was also consulted. The responses highlight that digital sobriety is not a widespread priority or lacks sufficient focus in the surveyed projects. A significant 66% of projects reported not prioritizing or integrating mechanisms for reducing service consumption, while only 19% confirmed active initiatives in this area. This limited focus can be attributed to factors such as lack of awareness, technical complexity, business priorities that favour performance, and insufficient regulatory incentives. Among the minority of projects that do address digital sobriety, strategies include orchestration and radio resource management (7%), smart selection or routing of access technologies (4%), and semantic reasoning or knowledge-based AI systems (4%). A detailed breakdown of the projects' responses is shown in Figure 25.

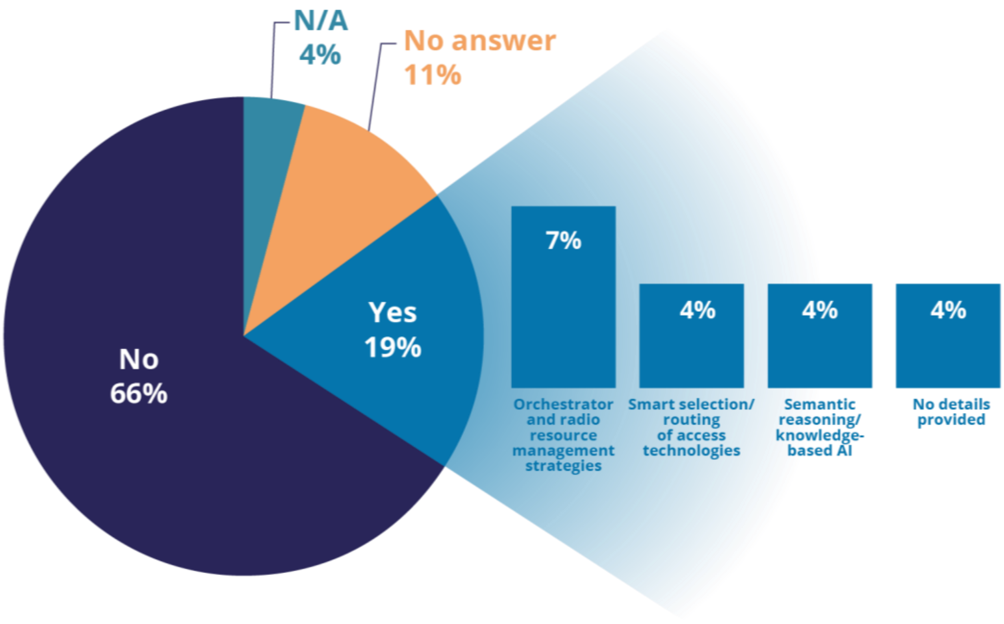

Figure 25: Projects addressing digital sobriety.

5.4 Key Insights

The following key insights can be extracted regarding the SNS projects' considerations on the implementation of sustainability approaches.

- **At the end-user and application level, EE has emerged as a key concern**: Many projects have implemented energy-aware protocols, optimized handover mechanisms, and dynamic power management strategies that respond to network conditions. These measures aim to reduce the energy consumption of user devices while maintaining satisfactory performance. Additionally, some projects are investigating the interdependence between network and device efficiency, recognizing that improvements in one can positively affect the other.
- **Challenges at the application layer appear less common**: Only a small number of projects report inefficiencies due to complex APIs or data models. These issues are typically tied to specific functional requirements, such as security or intent-based features, which can increase resource consumption. To address this, projects often employ custom KPIs that help monitor and guide resource optimization efforts. Notably, most projects focus on implementing only essential features, with only a minority exploring optional or experimental features such as non-terrestrial networking or energy-aware technologies.
- **At the system and infrastructure level, projects generally avoid introducing unnecessary complexity, particularly in data centre operations**: While some complexity arises from distributed architectures and the use of AI/ML or virtualized operations, most projects rely on established security standards and protocols, citing integration challenges and a lack of pressing need for more advanced measures. Cutting-edge security technologies like quantum

cryptography and homomorphic encryption are being explored by a limited number of projects.

- **Forward-looking approaches to sustainability are beginning to gain traction**: About one-third of the projects are investigating zero-energy devices, particularly energy-autonomous IoT systems and reconfigurable intelligent surfaces. Although interest in innovative resource-sharing and energy-saving strategies is growing, practical deployment is still in early stages and would benefit from further research and incentives.

The analysis of SNS JU projects also reveals several key insights into how next-generation networks are addressing scalability, maintainability, modularity, and circular design.

- **Different prioritization of Scalability, Maintainability and Modularity:** Scalability is a prominent priority for most projects with nearly 60% of the SNS JU projects aiming to implement scalable solutions that avoid disruptive full-node upgrades. In contrast, maintainability is less universally integrated, with only a minority of projects exploring dynamic and AI-driven approaches to support system upgrades and serviceability. Modularity emerges as a widely embraced design philosophy, with a majority adopting flexible, scalable architectures across various system layers, including RAN and compute continuum.
- **Circular design receives limited attention overall**: While some projects explore hardware reuse, modularity as a proxy for refurbishment, and low-energy or sustainable components, few consider the end-of-life treatment of systems or implement a structured approach to the circular economy. Notably, infrastructure reuse and sustainable component integration are gaining momentum, suggesting an emerging awareness of environmental impact.
- **KVIs on the rise**: Although concrete sustainability metrics are still under development, there is a strong commitment across projects to establish robust indicators for assessing environmental performance and enabling scalability with sustainability in mind.
- **Trustworthiness emerging as a key concern, but still not globally adopted**: The key findings from the analysis of societal and ethical considerations in the surveyed projects highlight a growing, yet uneven, commitment to privacy, transparency, and responsible AI. Around 40% of the projects actively worked on explainability and trustworthiness, particularly in AI/ML systems, often using KVIs to measure user understanding and system transparency. Privacy protection strategies varied widely: while some projects implemented detailed, concrete methods (e.g., anonymization, edge processing, GDPR compliance), others offered only vague acknowledgments or avoided collecting personal data altogether.
- **Additional aspects**: Only a third of projects attempted to link technological advances to social or economic outcomes, with some leveraging KVIs and others pursuing goals like energy efficiency and digital inclusion. On the other hand, digital sobriety — reducing the environmental and societal impact of digital services through moderation of their usage — received limited attention, with most projects lacking mechanisms to moderate digital service consumption, underscoring the need for greater awareness and incentives in this area.

6 CONCLUSIONS AND WAY FORWARD

The collective work of the 27 SNS JU projects that was presented in this white paper demonstrates that sustainability has been firmly embedded into Europe's 6G research agenda. Despite being a relatively new and evolving area for many technical domains, the projects show clear progress across all three pillars of sustainability—environmental, economic, and societal. There is strong alignment with the strategic vision of the Smart Networks and Services Joint Undertaking (SNS JU), which positions sustainability as a cross-cutting and guiding principle for next-generation networks.

One of the most significant achievements across the portfolio is the widespread and sophisticated treatment of EE and savings. Nearly all projects have implemented dedicated technical strategies—such as AI-based resource orchestration, edge computing, dynamic spectrum management, and localized processing—to reduce energy consumption. These are not isolated efforts; they are being pursued systematically at multiple architectural layers. The projects are not only building on past 5G progress but are taking more holistic and proactive energy-aware design approaches, contributing to more environmentally sustainable communication infrastructures.

An encouraging insight from the analysis is that many projects incorporate sustainability considerations from the very beginning of their system design. This proactive mindset is evident in the adoption of modular, scalable, and reconfigurable architectures, which are crucial for long-term maintainability and adaptability. Over 70% of projects reported using modular "Lego-like" systems, supporting easier upgrades, reuse, and more sustainable deployment models—an important requirement for circularity in Information and Communication Technology (ICT).

Social sustainability has been primarily addressed under the form of digital and social inclusion, which have emerged as central priorities. Projects are addressing these through a variety of means—from targeting accessibility in remote education and healthcare use cases, to embedding principles like fairness, trustworthiness, and privacy in system design. Economic sustainability is also actively pursued, with a large number of projects targeting cost efficiency, scalability, and new business models that foster innovation and resilience in European industry. These efforts highlight an evolving understanding that sustainability must be grounded in human and economic contexts, not just environmental ones.

Although most projects are at low TRLs (average ≈ TRL 4), many are already actively reflecting on how their innovations could enable sustainability in vertical sectors like healthcare, logistics, and manufacturing. There is a clear aspiration to move beyond reducing the negative environmental impact of technology, towards also creating positive sustainability impacts —i.e., technologies that empower others to be more sustainable. Systems-thinking approaches that take into account lifecycle and supply chain considerations are particularly valuable in anticipating the role and impact of 6G in Europe's green and digital transitions.

A majority of projects are adopting Key Value Indicators (KVIs), building on the SNVC methodology, and exploring how they can assess the sustainability value their technologies create. While not yet standardized across the board, this signals a promising shift toward value-centric research and development. With further refinement and adoption, combined with a multi-stakeholder, interdisciplinary collaboration, along with policy and regulatory incentives, this approach could evolve into a harmonized, actionable framework to benchmark impact and guide future innovation.

6.1 Lessons learned

The analysis presented in this paper, focuses on the approach followed by the 27 SNS JU projects that responded to the survey of the SNS JU Technology Board. In addition to the insights that have already been shared in the sections above, several key lessons emerge from this collective body of work, namely:

- **Energy Efficiency Dominates the Agenda**: Energy and power consumption metrics are widely used due to their measurability and alignment with technological feasibility at low TRLs. However, this leads to an underappreciation of other environmental dimensions such as emissions, waste, biodiversity loss and circularity.
- **Low TRLs Limit Systemic Impact Evaluation**: Many projects are unable to demonstrate or validate real-world sustainability impacts due to their focus on lab-based, component-level innovation. Future support structures should help projects anticipate broader impacts.
- **Sustainability-by-Design is Gaining Traction**: Encouragingly, many projects consider modularity, scalability, and resource sharing as pathways to improve sustainability, though often in service of performance rather than explicit environmental or social goals.
- **KVIs Are a Useful but Under-Structured Tool**: KVIs are often adopted but lack rigorous linkage to sustainability outcomes. There's a need for consistent definitions, baseline and target setting, validation processes, and alignment with broader societal values.
- **Sustainability Requires Interdisciplinary Expertise**: Several dimensions of sustainability (e.g., GHG emissions, biodiversity, supply chain ethics) are under-addressed due to a lack of relevant domain expertise within technical consortia. A broader inclusion of relevant vertical and sustainability experts should be considered.

6.2 Research gaps

SNS JU projects have been making significant advances, showcasing impressive progress in their research areas. At the same time, there remain valuable opportunities to further refine and expand efforts, ensuring greater impact in key sustainability areas.

While EE and the reduction of energy consumption are at the forefront of sustainability efforts, the ***use of renewable energy*** is infrequently targeted. Few projects explicitly aim to integrate or optimize for renewable energy, contrasting with global sustainability benchmarks, such as Japan's Green 6G vision or South Korea's emphasis on carbon-neutral ICT.

Policy and regulatory considerations may also be named as under-represented components of SNS JU research as only one project directly addressed regulatory considerations, and few routes have been suggested to influence or align with EU policy. This limits the ability of research outputs to scale into societal impact.

Additionally, there is a general ***limitation regarding second-order effects in sustainability evaluation***. While many projects highlight enablement in verticals (e.g., transport, health), few assess or quantify these second-order effects, despite their relevance for holistic sustainability goals. Admittedly, such an investigation is better fitting for more mature sustainability solutions and may be investigated in future SNS JU projects, with higher TRL solutions that may be directly applied in vertical sectors' environments.

The focus on circularity and lifecycle impacts is evolving, with promising opportunities for expansion. While only a minority of projects currently integrate ***Life Cycle Assessments (LCA) or circular economy principles***, increasing engagement in these areas can drive more sustainable and resource-efficient practices across industries. End-of-life impacts, modular upgrades, and recyclability are largely unexplored.

There is a valuable opportunity to enhance engagement with societal and ethical dimensions in the development of 6G networks. Strengthening the focus on well-being, cultural inclusion, autonomy, and ethical considerations can contribute to a more responsible and inclusive technological evolution and remain to be further explored, with a view to creating associated linkages with technology enablers. By integrating these elements, ***6G can drive positive societal impact*** while ensuring ethical advancements in communications. . These issues are increasingly central in international sustainability frameworks (e.g., UN SDGs).

6.3 Recommendations for stakeholders

The results of the presented survey may have multiple interpretations depending on the type of stakeholder and their position in the future smart networks and services supply chain. Based on the presented insights a few key recommendations can be extracted for key stakeholders in the telecommunications domain:

- **Telecom Equipment Vendors:**
    - Adopt sustainability-by-design frameworks, prioritizing modular, energy-efficient, carbon-aware, adaptable and recyclable hardware, targeting socio-ecological impact as well as economic growth.
    - Co-develop metrics and methodologies for circularity, including standardized material impact indicators.
    - Collaborate with academia to pilot eco-design approaches and validate through real-world demonstrators.
- **Telecom Operators**
    - Push for architectures enabling energy-aware orchestration and dynamic scaling, balancing user QoE with sustainability.
    - Partner with projects to test and benchmark renewable energy integration strategies.
    - Invest in transparent energy monitoring systems for end-to-end tracking of emissions and energy savings.
- **Academia**
    - Integrate environmental and systems science, ethics, and economics into 6G research programs to broaden sustainability perspectives.
    - Lead in developing and refining KVIs and SNVC-aligned methodologies.
    - Expand focus on societal sustainability impacts (e.g., equity, inclusion, health) and develop corresponding metrics, through interdisciplinary collaboration
- **SMEs and Startups**

- Serve as agile innovators piloting modular, interoperable solutions focused on circularity and renewable integration.
- Collaborate with verticals to tailor use cases addressing specific sectoral sustainability challenges.
- Embrace open-source sustainability frameworks to accelerate adoption and interoperability.

- **Policymakers and the European Commission**
    - Require all future calls to explicitly define expectations for all three sustainability pillars (environmental, social, economic).
    - Fund interdisciplinary support teams for SNS projects to embed lifecycle, regulatory, and ethical expertise.
    - Incentivize testbeds and field pilots to evaluate second-order effects in verticals, using real-world KPIs and KVIs.
    - Facilitate the determination of social, economic and ecological requirements, use cases and value indicators for the technology research projects to target and to develop technology enablers for.

6.4 Way forward

To ensure that 6G systems genuinely contribute to Europe's green and digital transitions, future sustainability research must evolve both in the direction of 6G for sustainability as well as sustainability of 6G. Several future research directions may be considered to ensure Europe remains in the driver's seat regarding sustainability technologies.

In terms of Key Research Areas**,** the following could be considered*.* ***Lifecycle Sustainability Assessment (LCSA)*** and ***circular design*** should be systematically embedded into 6G R&D, covering supply chain to disposal, taking into account not only environmental but also social and economic sustainability aspects. Moreover, *Social Impact Modelling* techniques, including anticipatory methods grounded in SSH (Social Sciences and Humanities) methods and insights, should be pursued*.* This would allow to better consider the broader implications of digital solutions on social justice, equity, autonomy, well-being and culture, influencing decisions around 6G design and deployments. *Rebound Effect Analysis* should be included in R&I projects in order to study unintended consequences of efficiency gains, including usage surges and net-negative sustainability outcomes. *Sufficiency strategy development* in support of relevant policy and regulatory frameworks needs to be investigated to ensure long-term sustainability outcomes.

In terms of **Implementation and Network Design** the following aspects should be considered. *Design for Modularity and Reusability* should be promoted to encourage service-based, microservice, and Lego-like architectures that support upgrades without total replacement. *Resilience without Redundancy* should be pursued to advance lightweight failover mechanisms and shared infrastructure models to reduce resource duplication. *Carbon-Aware Orchestration* should also be investigated by implementing AI-powered systems that optimize workloads based on carbon intensity of regional power grids. Finally, a *Security-Sustainability Synergy* could be investigated through research into lightweight, energy-efficient security frameworks to minimize conflict between trustworthiness and energy goals.

Besides the above aspects, several **Supporting Mechanisms** should also be investigated, to further promote advancements in sustainability solutions and the development of sustainable networks. The establishment of *a pan-European sustainability observatory* for 6G to collect, benchmark, and share sustainability-related KPIs, KVIs, methodologies, and use case outcomes, could significantly assist in that direction. Moreover, a *6G Circular Economy Lab* could be launched to validate, among others, recyclable hardware, modular software, and energy harvesting devices in real-world testbeds. Finally, *certification and labelling schemes* could be developed for sustainable 6G technologies, in collaboration with ETSI, ITU, and ISO.

The findings presented in this paper show that the SNS JU projects are laying a strong, credible, and forward-looking foundation for sustainable 6G networks. The current work signals a clear cultural shift—from performance-first to purpose and value-driven research. There is real momentum in the community, and a growing maturity in how sustainability is understood, designed for, and measured. This trajectory holds great promise for the role of European 6G technologies in supporting a more inclusive, climate-resilient, and economically vibrant digital future.

ABBREVIATIONS AND ACRONYMS

Acronym	Description
3GPP	3rd Generation Partnership Project
ADC	Analog to Digital Converter
AI	Artificial Intelligence
API	Application Programming interface
CAPEX	Capital Expenditure
CSA	Coordination and Support Action
DAC	Digital to Analog Converter
EC	European Commission
EE	Energy Efficiency
EMF	Electromagnetic Field
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
ICT	Information and Communication Technology
IoT	Internet of Things
ISAC	Integrated Sensing and Communication
ISO	International Organization for Standardization
ITU	International Telecommunication Union
KPI	Key Performance Indicator
KVI	Key Value Indicators
LCA	Life Cycle Assessments
LCSA	Lifecycle Sustainability Assessment
MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
NTN	Non-Terrestrial Networks
OPEX	Operational Expenditure
O-RAN	Open RAN

PA	Power Amplifier
PoC	Proof of Concept
RAN	Radio Access Network
RIS	Reconfigurable Intelligent Surfaces
RU	Radio Unit
SDG	Sustainable Development Goal
SDN	Software-defined networking
SNS JU	Smart Networks & Services Joint Undertaking
SNVC	Smart Networks and Services Vision
SRIA	Strategic Research and Innovation Agenda
SSH	Social Sciences and Humanities
TB	Technology Board
TF	Task Force
TRL	Technology Readiness Level
UN	United Nations
XR	Extended Reality

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5G-STARDUST	6Green	Origami
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6G-EXCEL	Eco-eNet	SUNRISE-6G
6G-GOALS	ETHER	SUPERIOT
6G-NTN	FIDAL	TeraGreen
6G-Reference	Hexa-X-II	TERRAMETA
6G-SENSES	HORSE	TrialsNet
6G-SHINE	iTrust6G	VERGE
6G-XR	NANCY	

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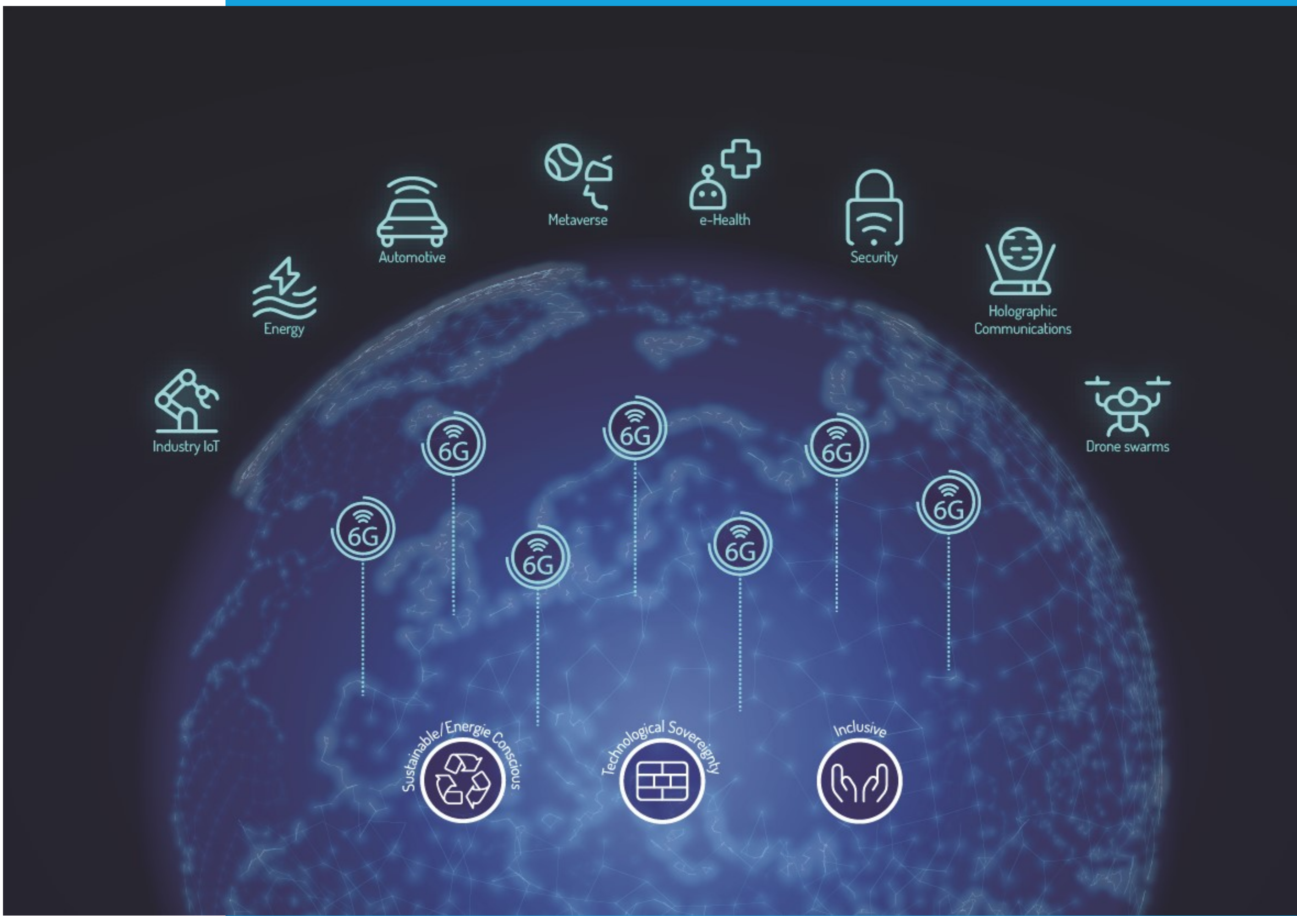

Website: https://smart-networks.europa.eu/sns-ju-working-groups/

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