

SUSTAINABILITY

Advanced and Innovative Networking with 6G



Deliverable D2.1

Sustainability baseline, Use Cases, and baseline requirements



Co-funded by
the European Union



This work is Co-funded by the European Union under Grant Agreement 101191936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of all SUSTAIN-6G consortium parties nor those of the European Union or the SNS JU (granting authority). Neither the European Union nor the granting authority can be held responsible for them.

This document contains material, which is the copyright of certain SUSTAIN-6G consortium parties and may not be reproduced or copied without permission.

All SUSTAIN-6G consortium parties have agreed to the full publication of this document.

Project reference: 101191936
Start of the project: 2025-01-01

Call: HORIZON-JU-SNS-2024
Duration: 30 months

Document properties	
Document number	D2.1
Document title	Sustainability baseline, UCs and baseline requirements
Work Package	WP2 - Sustainability landscape, needs, and methodologies
Contractual Date of Delivery	2025-07-31
Actual Date of Delivery	2025-07-31
Editor(s)	Sokratis Barmounakis, Panagiotis Demestichas (WINGS)
Reviewers	Luigi Briguglio, Margot Bezzi (CSL), Clare McCarthy, Christoph Schmelz (NOK-DE), Laurent-Walter Goix (NOK-FR), Berna Sayrac (Orange), Spyros Batistatos (P-Net), Nicola Magnani (TIM)
Dissemination Level¹	PU
Type²	R
Version	1.0
Status	Final

Revision history			
Revision	Date	Issued by	Description
0.1	2025-04-16	SUSTAIN-6G WP2	Initial D2.1 version based on the ToC agreed during and after the Munich F2F (March 2025)
0.2	2025-06-24	SUSTAIN-6G WP2	First complete draft of D2.1, released for review.
0.5	2025-06-30	SUSTAIN-6G WP2	Post-review - GA approval version
0.6	2025-07-21	SUSTAIN-6G WP2	GA approval version review complete; pre-final version for Coordinator review
0.7	2025-07-23	SUSTAIN-6G WP2	Minor fixes to v2.0
0.8	2025-07-24	SUSTAIN-6G WP2	Chapter 6, ID2.2 UC3 edits, ready for coordinator review
1.0	2025-07-30	SUSTAIN-6G WP2	Final version submitted

Abstract: This deliverable establishes the baseline framework for embedding sustainability into 6G networks, addressing both "Sustainable 6G" and "6G for Sustainability" aspects. It defines environmental, societal, and economic sustainability pillars and introduces key design principles, trade-offs, and evaluation metrics. A state-of-the-art review of enabling technologies and eco-design strategies is provided. The document also outlines sustainability-driven requirements derived from nine use cases across agriculture, smart grid, and telemedicine sectors. This foundation will guide technical development, system-level integration, and future validation within SUSTAIN-6G.

Keywords: Sustainable 6G, 6G for sustainable applications, Sustainable ICT, ICT for Sustainability, Environmental Impact, Societal Impact, Economic Viability, Eco-Design, Key Value Indicators (KVI), Agriculture, Smart Grid, Telemedicine, e-Health

¹ **PU** = Public, fully open, e.g. web (Deliverables flagged as public will be automatically published in CORDIS project's page), **SEN** = Sensitive, limited under the conditions of the Grant Agreement

² **R** = Document, Report (excluding periodic and final reports), **DEM** = Demonstrator, pilot, prototype, plan designs, **DMP** = Data management plan, **ETHICS** = Deliverables related to ethics issues, **SECURITY** = Deliverables related to security issues, **OTHER** = Other, e.g., Software, technical diagrams, etc.

Executive Summary

Deliverable D2.1 defines the conceptual, technological, and methodological foundation of sustainability within the SUSTAIN-6G project. Its objective is to structure the role of sustainability in future communication systems and guide the integration of sustainability concerns across the design, deployment, and operation of 6G networks.

Sustainability must be prioritised from the earliest stages of 6G development, rather than treated as an afterthought. Every component and system must be shaped by values such as energy efficiency, trust in Artificial Intelligence (AI) -driven functions, climate resilience, and resource-conscious engineering. Life cycle assessment, modular design, and clean production methods are critical enablers, but they must be integrated into a broader, holistic strategy that balances environmental, economic, and societal objectives.

To ensure that sustainability is meaningfully embedded, a multi-dimensional framework of Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) must be established. This framework should capture and balance environmental, economic, and societal priorities alongside technical performance. By making trade-offs transparent and understandable, and by integrating participatory processes, stakeholders can make informed, value-driven decisions that reflect both shared objectives and competing constraints.

While environmental considerations have traditionally been the focus, holistic sustainability encompasses environmental, societal, and economic pillars. Achieving sustainability in 6G requires global coordination and measurable accountability. Industry must proactively contribute to the development of international standards, ensuring that environmental and societal responsibility are built into the specifications of next-generation networks. These efforts should be closely aligned with broader policy frameworks, such as the UN Sustainable Development Goals, the EU Green Deal, and evolving climate regulations. Clear, robust sustainability KVIs and KPIs must be defined, tailored to the needs of society and the specific requirements of 6G infrastructure and services, to provide compelling incentives for vendors and operators.

Mobile Network Operators (MNOs) face complex demands in balancing economic performance, environmental responsibility, and societal inclusion. Holistic decision-support frameworks are needed to assess outcomes across multiple KVIs, enabling smarter, more adaptive planning. Business models should evolve to reward efficient usage and embrace value-driven strategies, such as modular service plans and energy-aware service-level agreements. Collaboration on shared infrastructure can reduce both capital expenditure and environmental impact. Lifecycle-oriented network planning is essential, synchronising equipment lifecycles with decarbonisation targets and ensuring that densification brings societal value without unnecessary environmental impact. Circular economy principles must be embedded from the outset, moving from linear consumption to sustainable, lifecycle-wide network management. MNOs are committed to aligning with key values across the three sustainability pillars supporting UN's Sustainable Development Goal (SDG) targets.

From a technology perspective, 6G networks should leverage intelligent, energy-aware solutions such as AI-driven orchestration, digital twins, and real-time monitoring to optimise operations and resource use. Investments should target low-energy, spectrum-efficient technologies like advanced Wi-Fi, LiFi, Optical Camera Communication (OCC), and Free Space Optics (FSO), as well as energy-efficient Passive Optical Networks (PON) and intelligent Radio Access Networks (RAN). Cloud-native and edge architectures, powered by renewables and supported by advanced cooling, are critical for scalable, low-impact infrastructure. Eco-design principles must be embedded throughout, from raw material sourcing to end-of-life. Systems should be resource-efficient, durable, modular, and easy to recycle, with clean production methods and minimalist, recyclable packaging. Devices must support low-power modes, and clear labelling should enable effective recycling, supporting a circular economy.

The sustainable development of 6G networks is inseparable from their ability to deliver transformative impact in critical sectors such as telemedicine, agriculture, and smart grids: In telemedicine, 6G will enable ultra-reliable, low-latency connections necessary for remote diagnostics, real-time patient monitoring, and advanced medical imaging. By supporting high-quality video, haptic feedback, and AI-driven analytics, 6G can expand access to healthcare in remote and underserved regions, reducing the need for travel and associated emissions. Secure, resilient, and energy-efficient networks are critical for

safeguarding sensitive health data and ensuring continuity of care. In agriculture, 6G will drive the digital transformation of agriculture through precision farming, autonomous machinery, and real-time environmental monitoring. Massive Internet of Things (IoT) connectivity and AI-driven analytics will optimise resource use (water, fertilisers, energy), minimise waste, and enhance crop yields. Through data-driven decision-making, 6G supports sustainable food production, reduces environmental impact, and empowers rural communities with new economic opportunities. 6G will underpin the next generation of smart grids, facilitating real-time monitoring, distributed energy management, and integration of renewable sources. Ultra-low latency and high reliability will enable dynamic balancing of supply and demand, predictive maintenance, and rapid fault detection. These capabilities are essential for decarbonising energy systems, improving grid resilience, and supporting the transition to a sustainable, low-carbon economy.

By embedding sustainability-by-design, leveraging advanced enabling technologies, and aligning with global standards and societal needs, 6G can become a cornerstone of responsible digital transformation and inclusive growth.

List of Authors

Partner	Name
NOK-DE	Clare McCarthy, Ross Staton, E. Poonkizhali, Christoph Schmelz, Dariush Soleymani, Zeljko Stankovic, Jafar Mohammadi
ORA	Berna Sayrac, Louise Renoux, Azzedine Gati, Olivier Bouchet, Marie-Hélène Hamon, Samira Jaber
B-COM	Jean Dion, Patrick Savelli, Guillaume Vercasson
CEA	Mattia Merluzzi, Emma Complido, Serge Bories
CSL	Luigi Briguglio, Margot Bezzi, Lucas Pereira Carwile, Carmela Occhipinti
DTAG	Barbara Gede, Krisztián Fehér, Adrian Gallego Sanchez, Felix Dsouza, Hans Einsiedler
EAB	Ali Balador, Xuejun Cai, Lackis Eleftheriadis, Agne Aberg Larsson, Hannes Larsson, Sepideh Matinfar, Josilo Sladan, Selome Kostentinos Tesfatsion, Gustav Wikström, Ahmed Arif
EDF	Imane Oussakel
EUR	Anastasius Gavras, Alessandro Bassi
JD	Marcus Reutemann, Shaden Baradie
KUL	Chesney Buyle, Thomas Feys, Liesbet Van der Perre, Gilles Callebaut, Jona Cappelle, Emanuele Peschiera, François Rottenberg
MDC	Andrea Novaresio
NOK-FR	Dominique Chiaroni, Laurent-Walter Goix, Chaima Ghribi
OULU	Arturo Basaure, Marja Matinmikko-Blue
PNET	Athanasios Bachoumis, Spyros Batistatos, Christos Tranoris
POLITO	Sandro Moos
QAMPO	Mónica Tristán, Antonio Sainz
QTEK	Tompros Spyridon, Frank Hieromnimon, Kostas Koutsopoulos
RW	Julie Bradford, Osman Hassan
SAG-AT	Daniel Hauer, Anton Steinwendtner, Alfred Einfalt, Konrad Diwold
SAG	Kim Schindhelm
TIM	Mauro Renato Boldi, Nicola Pio Magnani, Bruno Melis, Davide Sorbara
UC3M	Leonardo Lo Schiavo, Albert Banchs
WINGS	Sokratis Barmounakis, Panagiotis Demestichas

Table of Contents

1	Introduction.....	8
2	Sustainability definition and challenges	9
2.1	Sustainability context	9
2.1.1	What is sustainable development?	9
2.1.2	Why is sustainability important?	9
2.1.3	Challenges for 2030	9
2.2	The sustainability pillars.....	11
2.2.1	Environmental pillar.....	11
2.2.2	Societal pillar	12
2.2.3	Economic pillar	14
2.3	Objectives for Sustainable ICT and ICT for Sustainability	14
3	6G sustainability aspects.....	17
3.1	Sustainable 6G.....	17
3.1.1	Sustainability by Design.....	17
3.1.2	Operational sustainability.....	21
3.1.3	Sustainability at end of life.....	21
3.2	6G for Sustainability.....	22
3.2.1	6G's Role in Sustainability and Emission Reduction	22
3.2.2	Economic Impact of ICT and Connectivity Technologies	22
3.2.3	6G and Society	23
4	MNO Perspective on Sustainable 6G Public Networks.....	25
4.1	Description	25
4.1.1	Context	25
4.1.2	Overview	25
4.1.3	Motivation, objective and drivers.....	26
4.1.4	Challenges	26
4.1.5	Values, principles and driving criteria.....	26
4.1.6	Key Values (environmental, economic and societal)	26
4.2	Impact and Sustainability Analysis Framework	28
4.3	Ecosystem and technical aspects	28
5	Overview of 5G technology, state-of-the-art and sustainable 6G enablers.....	30
5.1	Scope of this chapter.....	30
5.2	5G technology and 6G requirements	30
5.2.1	5G technology fundamentals.....	30
5.2.2	6G technology fundamentals.....	32
5.2.3	IMT- 2030 work in ITU-R.....	34
5.2.4	3GPP context.....	35
5.3	State-of-the-art per network segment	36

5.3.1	Access points State-of-the-Art	37
5.3.2	Fixed access network	40
5.3.3	Radio access network.....	42
5.3.4	Metro & core networks	47
5.3.5	Data Centres and service core	47
5.4	State-of-the art per technology	48
5.4.1	Artificial Intelligence	48
5.4.2	Cloud native technologies, cloud/edge continuum, SBA.....	55
5.4.3	Security and Privacy in the Network.....	61
5.5	Eco-design rules and key technology enablers.....	62
5.5.1	Eco-design rules for a sustainable 6G	62
5.5.2	Key technology enablers for 6G.....	63
5.6	Preliminary methodology for the identification of an optimised solution.....	67
5.7	Conclusion.....	68
6	Use Case-driven sustainability needs and technical requirements.....	69
6.1	Broad applicability of 6G for sustainability in vertical sectors	69
6.2	SUSTAIN-6G vertical overview.....	71
6.2.1	Agriculture	71
6.2.2	Smart Grid.....	74
6.2.3	Telemedicine	76
6.3	SUSTAIN-6G Use Cases.....	78
6.3.1	Agriculture UC1: Connectivity on Demand: Temporary Connectivity Solutions in Rural Areas	78
6.3.2	Agriculture UC2: Task Offloading to the Edge for Critical and Resource-Demanding Tasks	81
6.3.3	Agriculture UC3: Agriculture Data vs. Information	85
6.3.4	Smart Grid UC1: 6G enabled grid balancing services from distribution grid assets	93
6.3.5	Smart Grid UC2: Resilient Grid Section Operation.....	96
6.3.6	Smart Grid UC3: Joint Planning of 6G / Smart Grid Infrastructures.....	100
6.3.7	Telemedicine UC1: Concurrent Preoperative Surgical/Engineering Planning.....	105
6.3.8	Telemedicine UC2: Remote Rehabilitation Assessment	107
6.3.9	Telemedicine UC3: Privacy-Aware Medical Data Federation with 6G-Assisted Trust Establishment.....	111
7	Strategic recommendations	115
7.1	Strategic recommendations in the global context.....	115
7.2	Strategic recommendations related to the MNO perspective	116
7.3	Recommendations from a sustainable 6G technology perspective	116
7.4	Recommendations from a 6G for sustainability perspective.....	118
8	Conclusions and future outlook	119
9	References.....	120

10	List of Acronyms and Abbreviations	134
11	Glossary and Definitions.....	137

1 Introduction

The transition to 6G presents a critical opportunity to embed sustainability not as a peripheral goal, but as a foundational design axis. In an era marked by escalating climate challenges, increasing energy demand, digital inequality, and growing trust deficits in technology, future communication infrastructures must respond not only to performance expectations, but also to environmental, societal, and economic imperatives. The SUSTAIN-6G project places sustainability at the centre of this transformation, aiming to define how it can be systematically integrated into the design, development, and deployment of 6G systems.

The challenge is not simply to improve efficiency or reduce emissions in isolated parts of the system, but to reimagine networks as sustainability-aware systems — capable of delivering performance and innovation while respecting planetary boundaries, fostering societal inclusion, and supporting long-term economic viability. This requires a cross-cutting approach: one that links design assumptions to lifecycle impacts, system functions to real-world value, and performance trade-offs to stakeholder needs. At the same time, it also demands new frameworks for evaluating sustainability in a multi-dimensional, measurable, and context-aware manner.

This deliverable provides the conceptual and methodological foundation to pursue that objective. It does not treat sustainability as a fixed checklist or single KPI, but as a set of interconnected values and evaluation principles that will shape SUSTAIN-6G's technical development and demonstration work in later stages.

The document is structured as follows:

- **Chapter 2** sets the context for sustainability in Information and Communication Technology (ICT) and 6G, framing the urgency of action, the challenges ahead, and the rationale for treating environmental, societal, and economic pillars as integrated, equally weighted priorities.
- **Chapter 3** defines how sustainability becomes a design driver within the 6G system itself, proposing foundational concepts such as sustainability-by-design, operational sustainability, and sustainability at end-of-life. It also elaborates on the role of 6G as a sustainability enabler and discusses trade-offs across pillars and with traditional performance objectives.
- **Chapter 4** presents a perspective from Mobile Network Operators (MNOs) on the deployment of public 6G networks in a sustainable consumer market. It identifies the operational challenges, stakeholder roles, and key considerations for aligning technical deployment with sustainability targets.
- **Chapter 5** provides a detailed technology-centric view of sustainable design, reviewing 5G and emerging 6G enablers, eco-design rules, and methodological elements for optimising technology selection and architectural choices.
- **Chapter 6** links these enablers and principles to concrete vertical needs, with a structured analysis of use cases in sectors such as agriculture, energy, and health. It includes baseline requirements, impact pathways, and early sustainability indicators, forming a use-case-driven bridge between high-level design values and deployment realities.
- **Chapters 7 and 8** provide strategic guidance for further development phases and outline future perspectives that will steer project evolution and standardisation engagement.

In summary, this deliverable serves as the entry point for engineering sustainability into 6G: defining the pillars, values, trade-offs, and structures that will guide technical and operational decision-making across the project and beyond.

2 Sustainability definition and challenges

This section establishes the foundational understanding of sustainability within the context of 6G. It defines key concepts, explains why sustainability is critical for future ICT systems, and outlines the main environmental, societal, and economic challenges that 6G must address by 2030 and beyond.

2.1 Sustainability context

2.1.1 What is sustainable development?

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [Bru87]. In the SUSTAIN-6G project, sustainability encompasses three interconnected pillars – environmental, societal and economic sustainability. Furthermore, SUSTAIN-6G has identified two aspects of sustainability: “Sustainable 6G” and “6G for sustainability”. The sustainability pillars and aspects result in six sustainability dimensions to be considered throughout the SUSTAIN-6G project. The three sustainability pillars, two sustainability aspects and resulting six sustainability dimensions will be explained in more detail in the following sections.

2.1.2 Why is sustainability important?

Sustainability is one of the global megatrends that will impact all aspects of life over the next decades. Sustainability means that we must commit to treat the world’s limited resources (natural and societal, tangible and intangible) with care, enabling future generations to have the same, if not better, conditions we enjoy nowadays. Currently, this is not the case, just because development has usually focused on addressing complex and challenging technical concerns, without considering also broader societal and environmental aspects. Therefore, linear consumption patterns are depleting natural resources; competition for these resources is causing economic and political volatility. This dynamic disproportionately harms vulnerable populations, deepening inequities, undermining human dignity, and hindering societal inclusion as the gap between affluent and poor communities grows both globally and within nations.

Our climate is changing. Temperatures are rising and extreme weather – floods, droughts, storm force winds - is more prevalent. Higher temperatures are caused by higher levels of greenhouses gases (GHG) emissions in the atmosphere that result from burning carbon-based, fossil fuels, extracting raw materials and industrialised processes. To serve the mass markets, economies rely on industries where operational processes seek the highest return on their investment. Often this leads to the exploitation of their workforce and/or the environment, and sadly a high percentage of goods produced end up as waste in landfill sites. Moreover, after the COVID-19 pandemic, the world is grappling with a relentless cascade of societal, economic, and political threats. To ensure resilience in this volatile landscape, a fundamental mindset shift is needed in the development of products and services, requiring also a thorough assessment of their impact throughout their entire life cycle.

Consequently, sustainability comprises three tightly coupled and interdependent pillars: **environmental, societal, and economic sustainability**. The resilience and adaptability in each of these pillars is required to protect and enhance natural, human, societal, financial and manufactured capitals that together support the modern digital world [Fft20]. Many target areas and actions within the three pillars are identified in the United Nations 17 Sustainable Development Goals (UN SDGs) [Uni15] and ICT is a pervasive enabler that underpins the success of many of the goals.

Sustainability must be factored into the strategies for standards and deployment of new technologies. For 6G, it will ensure that it is *sustainable by design* and implemented in such a way that other industries can become more sustainable.

2.1.3 Challenges for 2030

Reduce the impact to the environment. The European Climate Law [R2021/1119] writes into law the goal set out in the European Green Deal [Eur19a] for Europe’s economy and society to become climate-

neutral by 2050 [Eur19b]. The law also sets the intermediate target of reducing net GHG by at least 55% by 2030, compared to 1990 levels³. This will be achieved by cutting emissions, investing in green technologies and protecting the natural environment. Specifically for ICT, this particularly affects the energy consumption during operation, and to a certain extent the use of (raw) materials. Therefore, a key objective must be to limit the demand by ICT to the worldwide production of energy.

Corresponding statistics and forecasts as outlined, for example, in [WI24], [VKS24] or [Nic18], provide a broad range for the current and expected share of ICT in the worldwide energy consumption, ranging from roughly 2% in 2026 up to a worst case of 21% beyond 2030. This on the one hand reflects an uncertainty with respect to the dynamic development regarding, for example, the adoption of Artificial Intelligence (AI) and Machine Learning (ML) technologies, and on the other hand the variety of definitions which domains ICT actually includes – devices and terminals, network technology (fixed and wireless), service and application platforms, data centres, and (cloud) computing platforms.

In that sense, while the objective (“reducing net GHG by at least 55% by 2030 ...”) as such is simple, the strategy to achieve this target is challenged by how ICT defined and the stakeholders involved, as well as the large number of existing and researched ICT technology enablers, leading to the need for a pragmatic approach and strategy that enables a differentiation along the timeline:

- **The short-term strategy** basically imposes no modification of the hardware already deployed, but the exploitation of easy-to-deploy technologies for reducing the electric energy demand such as micro-grids. Comparable strategies have already started to be implemented in the public domain, for example, by supporting or pushing residential to deploy renewable energy sources such as solar panels.
- **The medium-term strategy** is anticipating a longer-term strategy, by adopting new approaches or technologies that have reached a sufficient degree of maturity and can be implemented with light modifications of the deployed assets, with the objective to better control – and reduce – the electric energy demand. This could be the redesign of systems to support a sleeping mode, optimised operations software, or the adoption of auxiliary technologies such as liquid cooling. Further directions could include the re-optimisation of already installed solutions through technology complementarity.
- **The long-term strategy** consists in identifying new methodologies towards a full eco-design of new products or solutions, reflecting also the responsible innovation paradigm. This long-term strategy – in the context of ICT – therefore applies typically to the design and specification of new network generations, as this is currently the case for 6G mobile networks. However, such long-term strategy is prone to considerable uncertainty, for example in the context of the adoption and implementation of Artificial Intelligence technologies in ICT – here, the share of different ICT domains in the overall energy consumption will strongly depend on the final decisions on a centralised or distributed AI architecture.

The societal challenges must be reflected. A technology is – or becomes – only attractive if the end-users get the feeling that they are receiving the service they need for improving their life at reasonable “cost”. The term “cost” is thereby not to be understood as a purely economic price tag for obtaining the product or service, but includes societal cost for having this service, for example:

- How many persons will lose their job with the scale of this service?
- How many hours the persons will spend for their family after the introduction of this service?
- How much will this service impact the privacy and any other fundamental rights of persons?

In other words, cost includes the three intertwined pillars of sustainability. These are fundamental aspects to maintain a market growth and continue to be attractive. So, besides the Quality of Experience (QoE) of end-users, key values (i.e., principles or qualities that individuals or groups deem important,

³ Note that rather often, Carbon Neutrality, Net Zero CO₂ and Net Zero are used interchangeably, while there should clear differentiation be made: Carbon Neutrality includes **Scope 1 and 2** emissions only (direct and indirect emissions), while Net Zero includes **Scope 3** (supply-chain related) emissions as well. For further information see, for example, [Int18], [Den22] or <https://netzeronow.org/post/net-zero-vs-carbon-neutral-difference>.

desirable, or intrinsically good) must be primarily taken into account in the design of a new solution impacting the end-users and any other stakeholders.

For the telecom operators, these considerations raise a request for change of their business models, and these must consider the acceptance of the end-users and of any other stakeholders, at different levels (i.e., individual, community, societal/systemic). Therefore, societal challenges are to be considered as an opportunity and not a barrier for revisiting the traditional development process and integrating the different perspectives of the stakeholders, through engagement processes: as it is well known from project management theories, only through opportune engagement strategies it is feasible to achieve the maximum impact of a project. Acceptance cannot be achieved through mere communication and awareness campaigns with unaware or resistant groups of stakeholders. For these and other groups, it is important to explore the factors why existing development, technology acceptance and business models fail and understand how these may be improved. Addressing these aspects will be fundamental to mitigate – towards 6G – the concerns that impacted the introduction of 4G and 5G mobile wireless networks, with potential benefits for the whole society, also with respect to economic dimension.

The economic challenges are fundamental and need to be considered in the early phase of the eco-design of any new solutions. The objective is to grow the market by providing solutions adapted to new business models, which are also compatible with previous technologies. Such business models shall thereby reflect the expected ICT traffic growth (consumer and enterprise traffic), the expectations and needs of end-users and stakeholders as outlined above, as well as the energy cost – however, for the latter, country-specific conditions may apply (including market conditions or availability of renewable energy sources, cf. e.g. [RR24]), and the geopolitical situation plays an important role. The SUSTAIN-6G project will analyse in detail the different options to propose a sustainability by design approach that will be successful on the market.

2.2 *The sustainability pillars*

2.2.1 Environmental pillar

The environmental sustainability pillar is foundational within the SUSTAIN-6G vision. This section defines how environmental sustainability becomes operationalised as a design principle in the development of 6G systems. The aim is to move from macro-level targets to a structured understanding of how environmental considerations may shape the system's architecture, evaluation frameworks and system-level priorities.

Environmental sustainability in 6G is considered around the following subdomains:

- Reducing energy consumption and improving energy efficiency
- Reducing GHG emissions and supporting the move to renewables
- Resource circularity – greater resilience, adaptability and reuse to extend product lifecycles
- Reducing pollution and protecting and nurturing biodiversity (land use)

Energy consumption and energy efficiency

Energy consumption is the absolute value that characterises any product. It directly impacts the emission of CO₂, since there is a direct correlation between the required number of Watt hours consumed (Wh) and the amount of emitted CO₂. It is therefore fundamental to target a reduction of energy consumption of any solution.

Energy efficiency is a general target for product design towards the reduction of energy consumption. However, it is a relative value expressed in Joule per bit (J/bit), which means that even if a technology has a high energy efficiency, an increasing number of bits to be processed may lead to an overall increase in energy consumption. This explains why 5G technology overall consumes more than 4G technology despite being more efficient through using, for example, Multiple Input Multiple Output (MIMO) and beam steering technology.

Reducing GHG emissions

With many energy producers integrating renewables sources – solar, wind and hydro – into their energy supply, the ICT industry needs to decarbonise their Scope 1 and 2 emissions, i.e., the (1) direct emissions from owned or controlled sources and the (2) indirect emissions from the generation of purchased

energy consumed by the reporting company [BCB+11]. However, the environmental impact of 6G extends far beyond network use. The lifecycle comprises energy use and emissions across the supply chain, from extraction, manufacturing and transport/deployment and disposal. These are known as the Scope 3 emissions [BCB+11].

Resource circularity

Moving away from a ‘Take, Make, Waste’ key to changing the status quo and ensuring responsible use of finite or non-renewable resources. This can be addressed in two ways:

First, by designing products for resilience and adaptability, especially with regards to their response to environmental or economic shocks. For example: Can a 6G base station function if it is sitting in a meter of flood for one week or in the path of storm force winds that last more than 48 hours? How will it continue to operate if the power supply is cut, either due to lack of power from the grid or malicious intent? By designing to handles these extreme parameters, 6G could be environmentally sustainable.

Second, by adopting a circular approach to production and consumption. The current linear models mean that products are discarded before they reach the end of their natural life because they have obsolescence built in – mobile phones are a prime example. However, if products are designed so they can be refurbished, and so extend their ‘first’ life, or disassembled and recycled to make into a different product, thus giving it a ‘second’ life, then this judicious reuse of energy and materials will also reduce energy demand and GHG emissions.

Reducing pollution and protecting and nurturing biodiversity

Resource depletion and e-waste present additional challenges. Many of the materials used in ICT systems are finite and non-renewable, and their increasing demand risks long-term scarcity. At the other end of the lifecycle, the disposal of digital devices contributes to the growing volume of hazardous electronic waste, which can pollute soil and water if not properly managed.

Many of the raw materials needed to support the digital world are found in remote areas. Every care must be taken not to disrupt communities nor destroy nature when obtaining them. Equally, once the minerals have been extracted, manufacturing and processing should not result in toxic waste destroying neighbouring land and bodies of water.

To evaluate progress in environmental sustainability, 6G systems must be assessed using indicators that cover their full lifecycle. Key performance metrics may include energy consumption per unit of data, carbon emissions per user, the share of renewable energy in infrastructure operation, and the recyclability or reusability of deployed components. These indicators help quantify environmental trade-offs and support design decisions that align with broader sustainability goals.

Crucially, environmental sustainability must become a value system embedded in network and service design. In this way, the environmental dimension of 6G is not merely a set of constraints, but a guiding framework for innovation. It informs the evaluation criteria, system architecture, and service logic that will underpin sustainable digital infrastructure.

2.2.2 Societal pillar

Throughout recent decades, each mobile network generation has achieved progressively wider societal adoption across regions and demographics. This trend has created significant expectations for 6G to address some of the United Nations (UN) Sustainable Development Goals (SDGs), either directly or indirectly, by providing ubiquitous and resilient technologies with broad societal benefit.

The societal pillar of sustainability in 6G refers to the system’s capacity to embed and promote societal values such as inclusion, trust and positive impact across diverse populations. It is not an external benefit or post-design concern, but a core component of network and service sustainability. This dimension takes into account the societal relevance and acceptability of technologies, ensuring that the benefits of connectivity and digitalisation are accessible, fair, and aligned with public interest. Key subdomains identified here include:

- Digital inclusion and accessibility
- Trust, transparency, and resilience
- Social alignment and demographic adaptation

Digital inclusion requires network coverage and service accessibility that spans geographic, economic, and demographic barriers. Nevertheless, increased coverage may impact, among many societal aspects, landscape and architectural constraints, and therefore the acceptance of antennas and other necessary equipment in proximity to buildings of individuals and groups of individuals. If not properly involved in decisions, these stakeholders can raise criticisms, minimising and obscuring the objective of digital inclusion. Therefore, it is essential that 6G systems account for varied user profiles — including the elderly, rural populations, and people with different levels of digital literacy — through accessible interfaces, adaptive services, and resilient infrastructure.

Trust and resilience go hand in hand with system sustainability. As 6G incorporates AI, automation, and pervasive data flows, it must uphold user privacy, enable transparent decision-making, and provide secure channels of interaction. System resilience, especially in the face of failures or cyber threats, is a prerequisite for building long-term trust among users and institutions alike.

Social alignment requires that networked systems be sensitive and responsive to cultural, ethical, and societal values. This includes designing services that are aligned with human expectations, do not impose harm or inequity, and support broader societal goals such as access to healthcare, education, or democratic participation. A structured evaluation of societal impact — through dimensions like user fairness, perceived agency, or societal disruptiveness — helps ensure that sustainability goals are human-centred.

Research suggests a need to also consider how technology integration affects patterns of social interaction across diverse contexts. Prompted connectivity may deepen societal reliance on digital devices, potentially leading to increased screen time, Internet addiction, and related mental health issues, such as anxiety, depression, and attention disorders. Recent studies indicate evolving patterns of technology use; with populations in top mobile markets using smartphones approximately 5 hours per day [Sen24], [Dua25], [Arc25]. Some research suggests associations between certain patterns of technology use and changes in social interaction. For example, the convenience of eCommerce, video on-demand and home-sharing services coincides with changing patterns of people gathering in communities in some regions [DT225]. Other research has highlighted how the use of mobile phones has evolved in some age groups from a communication medium to a modality of reorganising social relationships and interactions. This, in specific socio-cultural contexts, increases the risk of problematic smartphone use and overdependence in fragile adolescents worsening the Fear of Missing Out (FOMO) [NS24]. Yet some studies have established a link between the excessive use of social media and declining fertility rates in both high- and low-income regions due to the lack of strong relationship building [SJR22] [WSS22].

Social connection has been identified as a global public health priority from the World Health Organisation (WHO), particularly in relation to population ageing challenges [CV+25] [Who25]. According to the WHO, social health refers to “the adequate quantity and quality of relationships in a particular context to meet an individual’s need for meaningful connection” – a dimension of health that is interdependent with physical and mental well-being.

Research continues to examine the effectiveness of digital services in supporting meaningful social connections [Who21]. As we move towards the 6G era, with its anticipated integration of AI assistants and expanded services, these considerations take on increased importance.

6G has now an opportunity to contribute constructively to this area through specifications and enablers that, by virtue of their wide interoperability and adoption, could significantly influence how technology integrates with social life. These technical standards would complement efforts by application developers, policymakers, and other stakeholders who also play important roles in this ecosystem.

An objective is to create standards for 6G that can support balanced social connection across digital and physical contexts, by designing an appropriate set of functionalities to help e.g.:

- enhance opportunities for in-person social interaction through technologies that aim to support face-to-face engagement and enrich common digital experiences in proximity in outdoor and indoor spaces,
- support a greater variety of devices that promote “invisible technology”, in order to reduce screen dependency while maintaining connectivity benefits, and

- give users the right level of control, autonomy and governance on the usage of such technologies, applications and services in their daily life.

Societal sustainability in 6G therefore demands not only inclusive access and secure operation, but also systems that resonate with the values of the communities they serve. This pillar supports the long-term legitimacy and adoption of 6G networks, reinforcing both public value and system robustness.

2.2.3 Economic pillar

The economic pillar of 6G sustainability addresses the financial viability, value distribution, and innovation capacity of future communication systems. It considers how 6G infrastructures and services can remain cost-effective, accessible, and economically beneficial to a broad set of stakeholders across their lifecycle. Key identified subdomains in this pillar include:

- Investment and operational cost-efficiency
- Enabling participation and innovation
- Lifecycle value retention and affordability
- Long-term return on sustainability investments

Infrastructure deployment and network upgrades in 6G will require significant capital and operational investments. Sustainability in this context means ensuring that cost per user remains manageable while delivering enhanced performance. Virtualised, modular, and software-defined architectures are particularly valuable in lowering costs and supporting more agile deployment models. Equally important is the system's capacity to support innovation — especially by small and medium-sized enterprises — and to stimulate economic activity across diverse sectors. 6G should offer interfaces and market models that enable third parties to develop applications, operate services, or integrate value-added functions into the ecosystem. Sustainability also implies that 6G systems are designed for long-term value retention. This includes strategies such as modular upgrades, infrastructure reuse, and collaborative service models that reduce waste and increase cost-efficiency. Affordability must not be limited to end-users; it must also apply to operators, developers, and public bodies deploying 6G for societal benefit. Finally, evaluating economic sustainability requires dedicated indicators. These may include total cost of ownership, infrastructure Return on Investment (ROI), innovation uptake rates, or economic value delivered through vertical applications. The goal is to ensure that investments in 6G deliver not only technical performance but also durable economic returns and inclusive growth.

2.3 Objectives for Sustainable ICT and ICT for Sustainability

Traditionally, innovations in mobile network technology have been driven by improving the on-air technical performance of mobile network equipment. This has resulted in focusing network design and innovations on maximising data rates and capacity achievable within a limited envelope of spectrum resources. This approach focuses on the commercial sustainability of mobile services by delivering better user experience to more users more efficiently from a limited set of existing network infrastructure and related upgrade investments.

However, led by global initiatives like the UN SDGs, industries are increasingly being assessed in the context of their wider impact on the economy, society and environment. Specifically, industries are being asked to rethink their ways of working to make a net positive contribution to the future sustainability of each of these three areas. The ICT sector, and the communication industry within this, is one such sector looking to rethink the way it targets and assesses future innovations to be more aligned with this global vision. And within the communication industry, 6G networks as the emerging next generation of mobile communications plays a crucial role.

SUSTAIN-6G is the European Lighthouse Project that has the primary goal to address and integrate sustainability as a central component in the research and development of 6G mobile technologies. In the spirit of the UN SDGs, it aims to consider sustainability across the three pillars of economic, societal and environmental. However, it also acknowledges that 6G can affect sustainability across these pillars in two distinct areas: sustainable 6G and 6G for sustainability.

Firstly, there is a direct or first order effect of deploying the physical ICT equipment and infrastructure required to provide an end-to-end 6G service. Within the technical innovations planned for 6G, there is scope for improving factors such as energy consumption in mobile networks. Within SUSTAIN-6G,

innovations like this related to improving the sustainability of 6G equipment or network deployment models are termed “Sustainable 6G”.

The second area where 6G can affect sustainability is in how it is used. Connectivity underpins many of the devices and software applications which are increasingly being used in the digital transformation of businesses. This can include applications such as the usage of sensors in farming to gather real time data on soil and crop conditions to allow more targeted interventions and improve yields. Using 6G in such a way has the potential to make a positive contribution to environmental sustainability via reduced water usage on farms for example. Innovations in 6G aiming to maximise improvements in economic, societal or environmental sustainability caused by the usage of 6G services are termed “6G for sustainability” in SUSTAIN-6G.

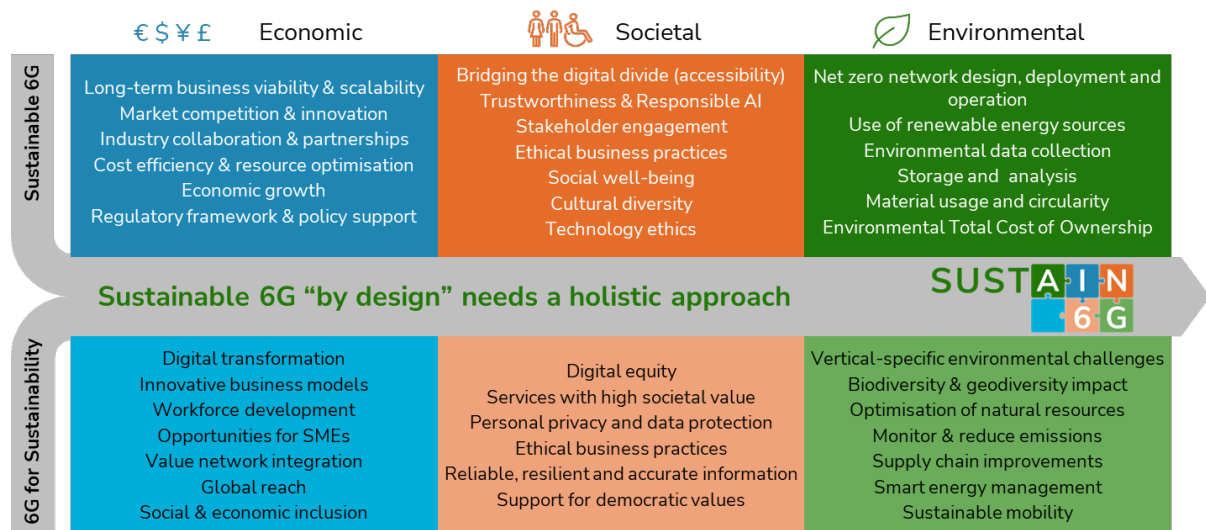


Figure 2-1: Dimensions of sustainability considered in SUSTAIN-6G

Finally, we acknowledge that there is an important interconnection and dynamic between the six dimensions of sustainability explored by SUSTAIN-6G, as shown in Figure 2-1. For example, using 6G infrastructure to provide the connectivity required to monitor and control Smart Grids in the energy sector is an example of 6G for sustainability. The expectation here is that this application would have a positive impact on environmental sustainability in the energy sector, by making the generation and supply of electricity more efficient and with less wastage and GHG emissions. However, this would require a highly reliable and secure, nationwide 6G network that is well beyond the design targets of today’s wide area mobile infrastructure which typically targets consumer-grade services. Supporting such an application of 6G, would require the deployment of additional cell sites and mobile network infrastructure with a negative impact on the environmental sustainability contribution. Additionally, there would be increased costs associated with the enhanced 6G network impacting the economic and specifically the commercial sustainability of the service. Similarly, a wider application of telemedicine would improve and enlarge access to quality healthcare for people living far from large urban centres, but with the potential for negative environmental impact due to the increased deployment of network access equipment.

SUSTAIN-6G aims to create a holistic framework, for defining and assessing sustainability, that takes into consideration these interdependencies.

Sustainability and 6G are key for the evolution of ICT. 6G is required to address the performance needs in terms of Key Performance Indicators (KPIs) by the public as well as by vertical sectors. 6G technology will drive markets to provide concrete solutions for this demand. But 6G needs to be as well designed based on criteria considering environmental, societal and economic Key Values (KVs) from the very beginning (Sustainability by Design – SbD). This set of criteria will facilitate the identification of sustainability requirements for the specific solution design, for technology enablers across all network segments and Use Cases (UCs). A third step will be to determine dedicated quantitative and qualitative identifiers for the KVs, expressed by means of Key Value Indicators (KVIs), that allow for the evaluation and assessment of the developed technologies with respect to their sustainability effects.

This is a mandatory precondition to further exploit sustainability into public and vertical sectors, where 6G will play a key technology enabler role. All these sectors have their dedicated KPIs, sustainability KVs – and KVIs – as well. With the integration of 6G technology enablers into the respective UCs and applications towards a 6G ecosystem, a key challenge will be to optimise the effects on sustainability from an end-to-end perspective (from the device via network and service infrastructure to the vertical application and infrastructure) and furthermore consider the different lifecycles of assets in the different domains. Only thereby it will be possible to enable a systemic view on sustainability, i.e., optimise the sustainability effects across the whole 6G ecosystem. In terms of finding an optimal solution it is obvious that multiple loops with integration, evaluation, and technology improvements will be required.

In summary, we need a sustainable 6G technology that can play a key role in optimising processes towards the desired effects on environmental, societal, and economic sustainability across all sectors.

3 6G sustainability aspects

The ITU-R has recognised the motivation for International Mobile Telecommunications in 2030 (IMT-2030) development as continuing to build an inclusive information society while contributing to the UN SDGs. Sustainability is therefore a foundational aspiration for future IMT systems, helping address the need for increased environmental, societal, and economic responsibility. 6G technology is expected to meet IMT-2030 requirements and demonstrate how it addresses related sustainability challenges and expectations. This includes embracing the principles of “Sustainable ICT” and “ICT for sustainability” across the three sustainability pillars.

3.1 Sustainable 6G

Sustainability in 6G must begin at the system level — not only as a set of external constraints or evaluation metrics, but as a technical principle embedded in the network’s architecture, components, and operating logic. In [HEXII25-D14], sustainable 6G actually refers to the ambition to minimise the negative effects of the 6G system and its deployment in the three sustainability pillars. Besides minimising the negative effects of the 6G system and its deployment in the three sustainability pillars, also it is also possible to imply positive effects in the societal and economic domains, but in any case not in the environmental one, where the direct impact of the technology, also referred to precisely as first order effect, is considered always negative in [L.1480], which, by the way, indeed only addresses the GHG emissions. The reason behind this outcome stems from the fact that the production of any new technology always implies an increase of GHG emissions compared to the status quo, even though the GHG emissions due to the production of new technology are reduced when compared to the ones produced by the legacy ones.

The above-mentioned KVs are assessed via KVis which, in case of Sustainable 6G, are referred to as quantitative or qualitative indicators to assess the impact of the technical enablers, i.e., the technology applied to a UC. Moreover, any technical enabler is assigned not only one or more KVis, but also one or more KPIs, i.e. quantitative indicators for measuring the technical key performance, namely the technical value / capability needed to deliver a UC. As highlighted in [HEXII25-D14], it is therefore straightforward that in turn the KVis may be mapped to existing KPIs, or to new KPIs, or cannot be mapped to any KPI and therefore they are kept as KVis.

This section focuses on the internal dimension of sustainability: how 6G technologies, functions, and design processes can be shaped to reduce negative impacts across their lifecycle while actively supporting sustainability goals. The subsections that follow consider sustainability at three key levels: design time, runtime, and end-of-life — each representing a critical stage for embedding eco-efficiency, societal responsibility, and economic viability into the network itself.

3.1.1 Sustainability by Design

6G will need to be Sustainable by Design (SbD), i.e., it should be intentionally embedded into the design process - not added as an afterthought. This will ensure that 6G is a sustainable technology that enables other industries to become more sustainable. There are five SbD principles for consideration:

- Energy efficiency and GHG reduction – design enablers net reductions across the lifecycle of networks and UE
- AI sustainability – design enablers for trustworthiness and compliance readiness of AI processes, resources and datasets.
- Hardware efficiency – materials resources should be designed to use as little hardware as possible, extend hardware lifetime and enable higher utilisation and sharing of resources.
- Resilience and climate change adaptation – design allows adaption to more extreme climate conditions and variability in the energy supply, but equally it ensures that infrastructure can adapt in times of economic or social crisis and minimise market volatility and social exclusion.
- Value-oriented design and operations – deliver technology enablers that support UCs that benefit industries, people and planet. Requirements from key industries, such as agriculture,

energy and healthcare should be considered to maximum the positive impacts that these industries can have on the economy, society and the environment.

Each sustainable design principle should be considered at each stage of the product lifecycle. As per ITU-T Recommendation L.1410 [L.1410], there are *four high-level lifecycle stages that apply to ICT goods, networks and services*. The stages are (see Figure 3-1):

- Raw materials
- Production
- Use
- End of Life

Note that production waste is allocated to the production stage and impacts from transport and energy supplies are included in all lifecycle stages.

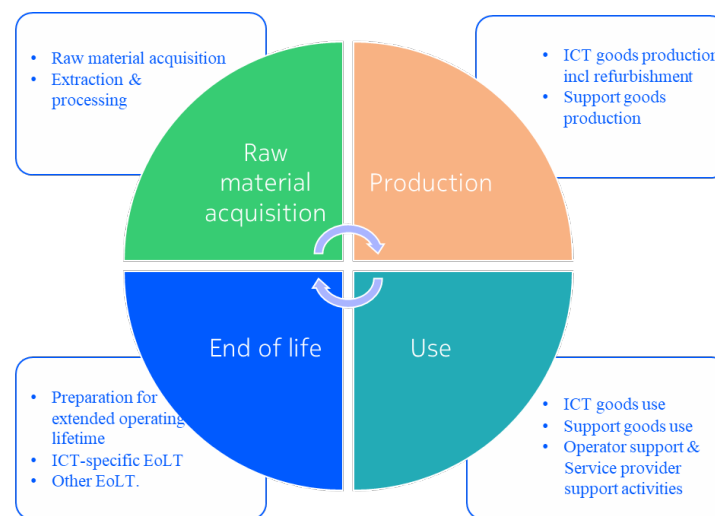


Figure 3-1: High-level lifecycle stages that apply to ICT goods (source: Recommendation ITU-T L.1410)

3.1.1.1 Interactions and trade-offs across sustainability pillars

Sustainability in 6G is a dynamic, multi-dimensional framework. While the environmental, societal, and economic pillars offer structure for identifying core sustainability objectives, these pillars are not always mutually reinforcing. Moreover, sustainability goals often intersect, and sometimes compete, with system performance objectives such as latency, coverage, reliability, throughput, and scalability. Designing sustainable 6G systems therefore requires navigating two types of trade-offs:

- Among sustainability pillars (e.g., reducing emissions vs. maintaining affordability)
- Between sustainability and performance goals (e.g., energy savings vs. latency)

A typical example of the former is the potential conflict between reducing environmental impact and maintaining economic accessibility. Improving energy efficiency may reduce emissions and operating costs in the long term but require high initial capital investment or specialised hardware, which may increase financial barriers, especially for Small and Medium Enterprises (SMEs). Similarly, increasing service reliability for societal benefit — such as in health or safety applications — may raise energy demand and operational complexity.

In terms of the latter category, core 6G performance targets such as ultra-low latency, high throughput, and dense connectivity often imply increased hardware density, frequent transmission, or intensive data processing — all of which carry environmental and energy costs. In short, meeting extreme performance KPIs may undermine sustainability goals unless energy-aware or circular approaches are tightly embedded from the start.

To support structured decision-making in light of these trade-offs, SUSTAIN-6G introduces the concept of multi-dimensional KPI/KVI frameworks. These frameworks include:

- Environmental metrics (e.g., energy-per-bit, CO₂ per user, renewable integration ratio)

- Societal indicators (e.g., access equity, user-perceived trust)
- Economic parameters (e.g., infrastructure ROI, cost per beneficiary)
- Performance anchors (e.g., latency, coverage, data rates)

This evaluation logic enables transparent visualisation of tensions — for instance, plotting a UC's improvement in inclusion versus its increase in energy cost — and allows stakeholders to weigh priorities based on deployment context.

Another key consideration is the divergence in stakeholder perspectives. What constitutes an acceptable trade-off for a national operator (e.g., investing in modular infrastructure to reduce lifecycle cost) might be unsustainable for a local authority managing short-term budgets. Therefore, evaluating trade-offs must account for actor-specific constraints and priorities.

Ultimately, the sustainability of 6G will depend not only on achieving high individual scores across metrics, but on the ability to navigate interdependencies across dimensions and layers. Design priorities must emerge from this understanding, supported by flexible system architectures and adaptive resource management.

3.1.1.2 *Eco-design challenges and rules for converging towards the optimal solution*

In this paragraph we will address a sustainability by design approach to go beyond the environmental criteria and include also the societal and the economic criteria.

For the identification of an optimised solution, we need to adopt eco-design rules, and key technology enablers. The eco-design rules are quite well known and can be summarised as follows:

Eco-design rules

- *Life Cycle Thinking*: This rule considers the entire life cycle of a product: Raw materials, Production, Distribution, Use, End of life (recycling, disposal). The goal is to reduce the total environmental footprint at every stage.
- *Minimise Resource Use*: This rule indicates that we need to use fewer materials and less energy. One direction that can be adopted is the simplification of the system as much as we can while maintaining the performance expected. We need then to prioritise renewable, recycled, or recyclable materials. Design for material efficiency (lightweighting, reducing waste). We need to adopt also zero-energy materials, or components optimised in terms of energy consumption.
- *Design for Durability*: This rule indicates that we need to adopt products that have a long lifetime. The promotion of modular design is key to be replaced or upgraded easily. Encourage repairability and serviceability.
- *Design for Disassembly*: This rule ensures that the product can be easily taken apart for repair, reuse, or recycling. Avoid permanent bonding of dissimilar materials (like gluing plastic to metal).
- *Use Clean Production Techniques*: This rule indicates that we need to choose low-impact manufacturing processes: Less energy, Fewer emissions, Less water or chemical use. Reduce toxicity in materials and processes.
- *Optimise Packaging*: This rule indicates that we need to pay attention to the packaging. The packaging should be in line with a demand but not more. When there is no need for a smart packaging, the objective is then to minimise the packaging material. Use recyclable, biodegradable, or minimalist packaging. Design packaging to protect efficiently while reducing waste.
- *Design for Energy Efficiency*: This rule is a central rule since it will identify the key technology enablers for an absolute energy efficient design. It includes also a minimisation of the energy used during the product operation (its energy consumption). It must support low-power modes or energy-saving features (like sleeping mode operations). For electronics: use energy-efficient components (e.g., low-power processors) and use massively optical technologies when possible as a complementarity technology to avoid physical limits of a specific technology.
- *Plan for End-of-Life*: Ensure that the product or its parts can be: Reused. Recycled. Safely disposed. Clearly label materials to aid recycling. This rule is quite important since it will drive

a circular economy for the sovereignty of an industry. Comply with directives and standards like Waste Electrical and Electronic Equipment (WEEE) [D2012/19] or ISO 14006 [14006].

- **Avoid Hazardous Substances:** Reduce or eliminate use of toxic, rare, or hazardous materials (like lead, mercury, or per- and polyfluoroalkyl substances, PFAS). Comply with standards like RoHS (Restriction of Hazardous Substances) [D2002/95]. This rule is important to anticipate blocking situations due to the use of regulated materials. It can be extended also to the respect of regulation rules in term of EM emissions.
- **Comply with Environmental Standards:** Follow eco-design regulations like: EU Eco-Design Directive (2009/125/EC). ISO 14006 (Environmental management systems – Guidelines for eco-design). Incorporate Environmental Product Declarations (EPDs) or Eco-Labels. This rule is fundamental and needs to be adopted at the beginning of the design process of any product to be in line with a certification imposed by governments or standards.

Key enabling technologies:

To achieve a greener ICT (Information and Communications Technology) sector, several key technology enablers are driving sustainability. These technologies are aimed at reducing energy consumption, improving efficiency, and minimising environmental impact.

Table 1 gives an example of some key technologies that need to be envisaged for the future design of solutions. This is not an exhaustive list, but simply an extraction from a long list of key technology enablers.

Table 3-1: List of key enabling technologies for a greener ICT

Technology enabler	Remarks	UC targeted	Environmental impact	Societal impact	Economic impact
Microgrids for 5G Cell sites	Covers all local production of electricity	Cell sites; Base stations	Contribute to reduce the emissions of CO ₂ of a country through the use of renewable energies	Not visible	Reduction of the electricity bill of operators.
Bit Interleaving for energy savings	Technique used to reduce the frequency at the reception level	Can be implemented in all synchronous transmission system	Reduces the electricity consumption of electronic systems	Can be visible when it impacts the boxes at home	Gain in CAPEX and OPEX
Integrated systems	Develop more chipsets for low price devices.	Can be efficient for in-door networks where the cost is an issue	Reduction of the size of systems	Technology less visible	Can contribute to a massive market
Quantum Signal Processing (QPS)	Envisage new processing technologies	Can be deployed everywhere	Photonic interactions less energy consuming than electron interactions.	Not visible	Can offer new possibilities to the AI technology.
Ultra-low Latency Networks for sustainability	Looking for low latency networks pushes for new low power consuming techniques	All UC requiring ultralow latency	Can contribute to design simple systems less energy consuming	Create opportunities for new critical services	Can be mandatory for some UCs

In summary, we need to build a methodology for the sustainable design of new solutions, and in particular for the 6G. The objective of this method is to converge rapidly towards the absolute optimal solution. But to do this there is a need to list all the key technology enablers to be able to use some of them in the design process.

3.1.2 Operational sustainability

In the same manner as the design, 6G networks and infrastructures must be deployed and operated in a sustainable manner. In particular, those sustainable aspects of 6G *by design* need to be put in place (e.g. activated) in actual networks. This means that during deployment and operation of 6G networks and infrastructures, the following sustainability principles and practices should be adopted:

Deployment Phase means installation and rollout of network infrastructure, including base stations, fiber optics, antennas, and supporting systems.	Operational Phase means the ongoing management, monitoring, and optimisation of network infrastructure and services to ensure reliable, efficient, and secure connectivity.
Environmental Sustainability: - Low-impact site selection - Sustainable construction practices - Energy-efficient equipment installation - Minimising transportation footprint - Environmental compliance and permitting	Environmental Sustainability: - Energy efficiency in active equipment - Renewable energy integration - Cooling and climate control optimisation - Real-time environmental monitoring - Software-driven optimisation
Economic Sustainability: - Cost-efficient rollout strategies - Infrastructure sharing - Future-proofing investments - Local sourcing and labor - Digital tools for planning	Economic Sustainability: - Operational cost reduction - Resource optimisation - Energy cost management - Service reliability and uptime - Scalable operations
Societal Sustainability: - Community engagement and transparency - Job creation and skills development - Equitable network expansion - Respect of health and safety standards - Respect to of cultural and social sensitivity	Societal Sustainability: - Network availability and resilience - Digital inclusion through operational excellence - Data privacy and cybersecurity operations - Workforce wellbeing and skills development - Transparent reporting and accountability

3.1.3 Sustainability at end of life

End-of-life management is a critical component of the sustainable 6G lifecycle, requiring proactive planning from the earliest design stages to ensure minimal environmental impact and maximum resource recovery. Sustainable end-of-life strategies for 6G infrastructure and devices must prioritise the principles of circular economy: designing for disassembly, promoting modularity, and enabling the reuse, refurbishment, and recycling of components wherever possible. This approach reduces waste and resource depletion as well as supports compliance with international environmental directives and standards such as RoHS [D2002/95], WEEE [D2012/19] or ISO 14006 [14006], in addition to local regulations. Material labelling and traceability are essential to facilitate efficient sorting and recycling, while partnerships with certified recycling organisations help ensure responsible disposal of materials that cannot be recovered. Additionally, end-of-life considerations should be integrated with broader sustainability goals by assessing trade-offs between environmental, societal, and economic impacts—such as balancing the costs of advanced recycling technologies against the benefits of reduced pollution and increased resource efficiency. Ultimately, a robust end-of-life framework for 6G will contribute to the overall sustainability of the ICT sector, aligning with the United Nations Sustainable Development Goals and reinforcing the role of 6G as a driver of positive change for industry, society, and the environment.

3.2 6G for Sustainability

3.2.1 6G's Role in Sustainability and Emission Reduction

It is well known from literature [MAA+20] [HEX21-D12] that 6G will be both an infrastructure that supports a multitude of services to help the achievement of the individual targets in the UN SDG framework, as well as a tool to help authorities and other stakeholders to collect various data, thus enabling the monitoring of relevant indicators.

More generally, digital technologies create new opportunities to cut emissions and fight climate change across sectors [Wor23] as outlined in various studies on the so-called enablement effect [HEX22-D13]. In June 2022 the Body of European Regulators for Electronic Communications (BEREC) [Ber22] referring to a previous Global e-Sustainability Initiative Report [Ges15], reported that according to certain estimations from ICT industry players the digital solutions could allow reducing around 15–20% of global GHG emissions from other sectors [Eri24]. Furthermore, based on a macro analysis of 181 countries for the period 2002–2020, there is a correlation between connectivity and decarbonisation, with a 10% increase in mobile broadband penetration found to cause a 7% reduction in CO₂-emissions per capita [EB24].

While it is hard to predict what 6G will be, it is anticipated that enhanced communication capabilities in addition to other capabilities such as sensing or Artificial Intelligence and Machine Learning (AI/ML) could potentially be leveraged to enable sustainability in a variety of different sectors.

However, as outlined in [HEXII23-D11] while ICT in general, and specifically 6G, can be an important enabler, literature highlights that technology itself is not sufficient to unleash the enablement effect: suitable strategies, policies and regulations have to be implemented in order to drive cultural change and new personal behaviours toward sustainability goals.

In fact, as noted in [Wor23] “digitalisation does not by default shrink the carbon footprint of any sector. Some solutions may reduce unit-level emissions while boosting overall usage, producing a rebound effect. For example, although 5G technology—which can be used for Internet of Things solutions—is more energy efficient per unit of data, increases in data volume and in use of the underlying network infrastructure can result in higher total emissions. Because these effects are not always foreseeable at the outset, constant attention should be paid to measuring and balancing the climate-friendly effects of an innovation and its possible rebound effects”.

Rebound effects are one of the aspects that make the assessment of the “6G for sustainability” quite complicated. As outlined in [HEXII23-D11], a common basis for research in this area is the definition of a baseline scenario, a definition of a scenario with a solution that reduces GHG emissions applied and a comparison between the two. This is by necessity a hypothetical setup since the two scenarios cannot exist at the same time.

At the end of 2022, ITU-T proposed a well-grounded approach with Recommendation L.1480 [L.1480], which brings transparency, consistency, and comprehensiveness to enablement assessments of ICT solutions [HEX23-D14]. As acknowledged in [HEXII23-D11], this methodology could also be applicable to new technologies to some extent; however, it cannot be properly applied to 6G at the moment for two reasons: firstly, no data exists on 6G yet, and secondly, the definition of a baseline scenario would be difficult as well, since 5G is still under deployment.

3.2.2 Economic Impact of ICT and Connectivity Technologies

Beyond impacting environmental sustainability, ICT is seen as a key sector for powering economic growth with connectivity related technologies being amongst the World Economic Forum’s 2024 top ten list of technologies poised to significantly influence societies and economies in the next three to five years [Wor24]. This high importance attached to connectivity is largely related to its underpinning role in the digital transformation of organisations and businesses across the world. The World Economic Forum estimates that by 2025, digital transformation had already added \$100 trillion to the world’s economy [Wor24]. More specifically, the McKinsey Global Institute [Mck20] has carried out analysis of the economic impact of UCs requiring advanced connectivity in the mobility, healthcare, manufacturing and retail sectors. They forecast that the identified UCs in these four sectors alone could increase global Gross Domestic Product (GDP) by \$1.2 trillion to \$2 trillion by 2030. This is an increase

of approximately 1.1% to 1.8% against global GDP for 2024. The same report estimates a further increase to global GDP by 2030 of \$1.5 trillion to \$2 trillion from uses of connectivity beyond industry and instead from its usage in wider society.

It is forecasts like this that have raised the importance of connectivity amongst governments and policy makers. This is reflected in initiatives such as the European Commission's Digital Decade policy program [EC21], which sets out targets and priorities for boosting Europe's digital transformation by 2030. Notably this policy includes targets for gigabit fixed and high-speed mobile networks, acknowledging the underpinning role of connectivity in the digitisation of Europe's businesses and wider society.

3.2.3 6G and Society

The deployment of 6G networks in the coming decade will likely result in a further dramatic increase in network performance and availability, with AI being deeply embedded in network architecture and operation [Chi24] [Hnr24].

The improvement of connectivity speed, quality, network resilience, and security – combined with AI – will reshape infrastructure, services, and applications across sectors. Increased automation and smart control will drive higher production outputs while reducing costs and delivery times. This efficiency boost, however, will create significant workforce challenges, potentially reducing traditional employment unless widespread reskilling initiatives are implemented to develop emerging ICT competencies [Alp25]. At the same time, 6G capabilities will elevate service expectations across sectors, accelerate smart city technology adoption, and increase network reliance for personal and vehicle safety. People in remote or difficult-to-access areas will experience significantly improved access to essential services (e.g., banking, healthcare, goods delivery), provided that privacy and security concerns are adequately addressed. Despite these potential benefits, risks of widening existing inequalities persist due to infrastructure disparities, cost barriers, cultural factors, and varying levels of digital literacy. Addressing these challenges will be critical to ensuring equitable participation in the digital economy and promoting equality of rights and opportunities.

The expansion of work-from-home practices will reduce the need for centralised office resources while creating new challenges for employee oversight and workplace relationship development. The boundaries between professional and private life will continue to blur, affecting both time and space management for individuals. Meanwhile, the network's ultra-low latency and very high bandwidth will enable immersive Virtual Reality (VR) or Augmented Reality (AR) experience, transforming both entertainment and practical applications. Educational and healthcare applications will offer experiential learning environments and therapeutic interventions. When properly designed, applications in these domains have demonstrated benefits in terms of anxiety reduction, management of behavioural disorders, and cognitive skill development [Dav25]. However, potential negative impacts include harassment in virtual environments, addictive behaviours, and difficulty distinguishing between virtual and real-life experiences [MUA+23]. VR environments and their design will significantly influence self-identity formation and representation, raising important questions about diversity, inclusion, and stereotyping in virtual spaces.

In an increasingly hyperconnected environment, individuals must navigate multiple communication streams simultaneously, leading to attention fragmentation and cognitive overload. This can diminish available cognitive resources, impede concentration, and potentially contribute to stress, decreased productivity, and learning difficulties. Digital interactions increasingly shape our communication patterns, sometimes with concerning implications. Constant connectivity can lead to decision fatigue from frequent micro-choices. Increased device dependence may contribute to excessive screen time and associated mental health challenges, including anxiety and attention disorders. The immediacy of information can intensify "fear of missing out" (FOMO), potentially weakening community bonds and increasing social isolation.

The integration of AI in network structure and function, while necessary for successful 6G deployment, raises significant concerns regarding controllability and accountability [RSR24]. These technological shifts will also reshape power dynamics, as the data economy concentrates influence among dominant corporations that leverage vast data reserves to influence consumer choices and even public opinion. As social theorist Rogers Brubaker observes, hyperconnectivity has significantly empowered

organisations more than individuals, fostering recentralisation and reconcentration of power that reverses the decentralisation seen in the internet's early years. His analysis highlights how hyperconnectivity has enhanced "technologies of control, technologies of distraction, and technologies of manipulation," all built on data extraction and surveillance [Bru23]. The COVID-19 pandemic further accelerated digital mediation across all aspects of life in ways that appear permanent, demonstrating how rapidly technological adoption can transform when necessity demands.

The deep embedding of AI in network structure and function is a necessary requirement for successful deployment of 6G networks, but comes with its own set of concerns, such as controllability and accountability of the AI agents in the network.

All of the above developments are expected to increase both acceptance and resistance/scepticism for ICT. While faster, easier, more affordable and more widespread services are universally perceived as a beneficial outcome of ICT evolution, mistrust towards technology due to the perceived increased scope for abuse, either at the individual level or at the corporate level, will also be present unless it is effectively addressed. This will require cooperation of technology/service providers with national and international regulatory and legislative bodies. Research on the long-term societal trends fostered by ICT evolution will also be required as a guide to regulation and as a means of conceptualising and expressing what is found on societal trends. It is imperative that self-regulation in the form of technological support and regulatory/legislative pressure keeps up with any negative impact of the ever-accelerating pace of technological progress in order to avoid degeneration of the open society into techno-feudalism and a widespread sense of alienation or dispossession [Kar25]. Eventually, people and businesses will have to feel that they can trust and relate positively to ICT, by being supplied with technology-based assurances on data provenance and privacy/security, in addition to well-proportioned public control and oversight [SS23].

4 MNO Perspective on Sustainable 6G Public Networks

4.1 Description

4.1.1 Context

MNOs as one of the main ICT stakeholders, are faced with several conflicting sustainability objectives concerning the networks and infrastructures in all lifecycle phases (design, deploy, run and end-of-life). A typical example is the objective to reduce the network GHG emissions and the objective to have a sustainable business. These objectives are not easily reconciled with each other using the solutions that exist separately for each one of them: solutions like network performance optimisation can target both objectives since they reduce resource usage as well as costs, but other solutions for reducing network GHG emissions such as extension of equipment lifetime, or less ambitious deployment plans may not fit the current MNO business viability relying also on technical performance excellence and differentiation that depends on equipment renewal and aggressive deployment strategies in a competitive market.

This situation is the simplest example case where we can have conflicting sustainability objectives for a single stakeholder and yet the solution is not easy to identify. Extension to the other sustainability pillars and KVs renders the problem even more difficult to solve. For example, let's consider the KV on digital inclusion within the societal sustainability pillar which encompasses different factors such as network coverage, affordability, digital literacy etc. From the coverage perspective, a possible existing solution is Non-Terrestrial Networks (NTN) that however imply high negative environmental impacts (GHG emissions, space waste, among others). This adds another dimension of conflict to the problem and renders it extremely challenging to solve. Furthermore, adding the perspective of another stakeholder, in this example the NTN operator, will render the problem even more complex.

Therefore, we propose to dive into this problem by introducing it in detail and paving the way to have insights on a possible methodology to solve it.

4.1.2 Overview

As discussed above, each sustainability pillar, i.e., environmental, societal, and economic, encompasses a number of different subdomains and associated goals that sometimes compete among themselves as well as with performance objectives. GHG emissions are certainly an important subdomain of the environmental sustainability pillar: currently, the ICT sector accounts for almost 4% of the global CO₂ emissions, with an extremely rapid annual increase of 6% per year [The24]. Most of the major industry players have set themselves CO₂ emission reduction targets through the Science Based Target initiative (SBTi) [Sci25], typically Net Zero⁴ CO₂ commitments for the 2040-time horizon where 6G will have been deployed. Networks and infrastructures account for 25% of the total ICT sector emissions. Therefore, 6G has a considerable impact on the CO₂ emissions and need to support the industry players in meeting their CO₂ reduction commitments across the network infrastructures.

In addition to this CO₂ reduction, also the other subdomains of the environmental sustainability pillars should be addressed, and at the same time the economic viability of the ICT sector should also be kept, bringing sustainable economic and societal value to the society through employment and investment while accommodating the traffic growth at acceptable financial costs and favourable economic conditions for all the stakeholders.

⁴ Note that rather often, Carbon Neutrality, Net Zero CO₂ and Net Zero are used interchangeably, while there should clear differentiation be made: Carbon Neutrality includes Scope 1 and 2 emissions only (direct and indirect emissions), while Net Zero includes Scope 3 (supply-chain related) emissions as well. For further reference see, for example, [Int18], [Den22] or <https://netzeronow.org/post/net-zero-vs-carbon-neutral-difference>.

4.1.3 Motivation, objective and drivers

With specific reference to the GHG emissions, the objective is to reach the Net Zero Carbon neutrality by 2040, through a healthy ICT business (revenues, investments, employment, etc.) for all the stakeholders, providing welfare to society and thus creating economic sustainable value for society through employment and investment.

This objective is valid and important both for the consumer market and for the vertical market. Although the market share of the vertical sector has increased thanks to 5G private networks, the consumer market is still the prevalent market in 5G [Gsm25]. It is plausible to assume that 6G will have the same trend, with an impact on the consumer market at least as important as the vertical market. Furthermore, in 6G, as in 5G, some (if not most) of the vertical UCs will rely on the nation-wide operator networks and infrastructures. Therefore, it is important to consider the consumer market (Business-to-Customer, B2C) 6G together with the vertical market (Business-to-Business, B2B) 6G.

4.1.4 Challenges

The two endeavours, i.e., achieving (1) the environmental targets of the MNOs and (2) sustainable economic growth for the stakeholders should be achieved simultaneously. Thus, the particular challenge for the MNO is to keep the business healthy (sustainable economic growth) while reducing the CO₂ emissions of its nation-wide networks and infrastructures. This challenge incurs environmental, societal and economic values in a sustainable manner. The 6G technology design, deployment and operation should be driven by these values. However, according to the current business models that rely on volume growth, these objectives are often conflicting.

Apart from the conflicting objectives, there is another very important challenge on traceability and access to reliable and sufficient sustainability data throughout the whole value chain. In order to evaluate/assess the sustainability metrics and take actions, there is a need to have reliable and sufficient data from all the stakeholders down the supply chain. This is related to a structured and reliable reporting of the stakeholders. This challenge is also acknowledged by the European Commission, through their attempts towards a standardised sustainability reporting of the European industry such as the Corporate Sustainability Reporting⁵ and the EU Code of Conduct (CoC) for the sustainability of telecommunication networks⁶.

4.1.5 Values, principles and driving criteria

The future solution/scenario we aim at which is described above is desirable for society, since the sustainable growth of the ICT sector (Sustainable 6G) will bring welfare and healthy economic conditions for the needs and well-being of its members, for example through job offers, investment on sustainable innovation, provision of decent work conditions for the ICT workers etc.

In addition, in the envisaged scenario the use of ICT, and 6G in particular, has the potential to positively contribute to the achievement of the sustainability goals of other industry sectors (6G for Sustainability) through emerging or upgraded services that would help other sectors in getting more environmentally, societally and economically sustainable [HEXII25-D14].

4.1.6 Key Values (environmental, economic and societal)

MNOs have the ambition to align their businesses with values for the planet and the humans/society. To this end, they have a comprehensive list of Key Values to address.

Environmentally sustainable 6G networks & infrastructures	6G for economical sustainability	6G for societal sustainability
Typical Key Values:	Typical Key Values:	Typical Key Values:

⁵ Corporate Sustainability Reporting, https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en

⁶ EU Code of Conduct (CoC) for the sustainability of telecommunication networks, https://joint-research-centre.ec.europa.eu/projects-and-activities/green-and-sustainable-telecom-networks_en

• <i>Reduction of GHG emissions of the MNO networks & infrastructures (scopes 1,2 & 3).</i> • Limiting energy consumption. • Preservation of biodiversity (protection of species, land use, ...). • Preservation of natural resources (i.e. limiting the use of mines/metals, water, land, ...). • Minimising e-waste. • Respecting landscape and architectural constraints (e.g., deployment of antennas and other necessary equipment in proximity to protected areas) • Reduction of pollution (water, land, air, space, ...).	• <i>Sustainable economic viability of the telecommunications sector, including all the stakeholders (i.e. creating sustainable economic value for all the stakeholders)</i> • Affordability of the ICT solutions. • Reducing OPEX/CAPEX. • Protecting economic value of properties based on deployment of equipment (e.g., NIMBYism - Not In My Backyard – is a societal phenomenon where residents support the idea of necessary infrastructure, such as antennas, but oppose its placement near their homes due to concerns about property values, aesthetics, health, or quality of life).	• The capacity of technology to respect fundamental rights such as privacy, transparency, dignity (UN SDG #16). • Digital inclusion • Meaningful social interaction and quality of relationships • Trust • Confidentiality • Resilience • <i>Sustainable employment capacity of the ICT sector</i> • Dignity and respect of any other human rights across the entire value chain (e.g. child labour, working ethics/conditions during extraction/mining) • Protecting vulnerable groups • Ensuring the public concerns on Electromagnetic Field (EMF) exposure
---	---	---

It is noted that the key values listed in the table above, while therein referring to Sustainable 6G, can also be applicable to 6G for Sustainability. As far as Sustainable 6G is concerned, it is referred to as a selection of technical enablers needed to produce 6G technology that can address the 3 sustainability pillars, namely the environmental, societal and economic ones.

As a matter of fact, sustainability in 6G is a complex framework with multi-dimensional intertwined aspects that can hardly be addressed separately. However, as a pragmatic way forward, a step-by-step approach can be proposed, focusing at a first instance to a single key value per each sustainability pillar, as per the example in the following table:

Environmentally sustainable 6G networks & infrastructures	6G for economical sustainability	6G for societal sustainability
<i>Reduction of the GHG emissions of the MNO networks & infrastructures (scopes 1,2 & 3), with identified target values for different milestones.</i> • The environmental Key Value (KV) is reduction of GHG emissions which is associated with the UN SDG #13 Climate Action. • Possible levers/solutions are circular economy principles, infrastructure mutualisation, reduction of energy consumption, lifetime extension of equipment, decoupling of	<i>Sustainable economic viability of the telecommunications sector, including all the stakeholders.</i> • The economical KV is the economical/business viability of the telecommunications sector which is associated with the UN SDG #8 Decent Work and Economic Growth & UN SDG #9 Industry, Innovation and Infrastructure. • Possible levers/solutions are innovative business models, marketing	<i>Sustainable employment for the society.</i> • The societal KV is the sustainable employment capacity of the telecommunications sector which is associated with the UN SDG #8 Decent Work and Economic Growth & UN SDG #9 Industry, Innovation and Infrastructure. • Possible levers are similar to those of the economical sustainability pillar.

hardware-software, energy efficiency etc.	strategies, affordability, cost reduction, new revenue sources etc.	
--	---	--

4.2 Impact and Sustainability Analysis Framework

The following table depicts the 1st and 2nd order effects on the 3 sustainability pillars, that are linked to the Key Values indicated in previous tables, where the black items reflect the comprehensive/holistic perspective (first table above) and the red items reflect the limited/pragmatic approach (the second table above).

Table 4-1: First and second order effects on the 3 sustainability pillars

	Environmental	Economic	Societal
1st order effects	Climate change through GHG emissions. Energy consumption. Contribution to non-renewable natural resource depletion through consumption (rare metals, materials, water, land...). Contribution to pollution (water, land, air, space...). Preservation on biodiversity and species (land use...).	ICT solution CAPEX, OPEX, Total Cost of Ownership (TCO). Job opportunities throughout the whole value chain of the ICT solution.	Work ethics throughout the whole value chain of the ICT solution (e.g. ethical sourcing of materials). Job opportunities throughout the whole value chain of the ICT solution. Value-based design to embed societal values into technology
2nd order effects	Reduction of GHG emissions thanks to the use of the ICT solution (e.g. increase in home office work and decrease in home-work commute)	Mobile subscription charges. Job opportunities due to the use of the ICT solution (e.g.	Feeling of security thanks to the trusted and resilient ICT solution (driven by values-based design). Automation and the related gains in terms of process efficiency may enable in theory a more efficient way of doing daily tasks with a possible increase of free-time; however, if not properly managed within management processes, in line with human rights, this capability will translate in an acceleration of the “tempo” of life and in a “rebound effect” related to cognitive resources and time pressure, with an exponential growing number of activities supposed to be attended. Changes in the nature of social interaction and human relationships, and related risks (e.g. screen addiction; social isolation)

4.3 Ecosystem and technical aspects

The ecosystem surrounding the development and deployment of public 6G networks and infrastructures is multifaceted, involving a diverse array of stakeholders, each playing a crucial role in shaping the future of connectivity. At the core are the provisioning actors, who are responsible for building and

maintaining the infrastructure. This group includes MNOs, equipment suppliers, integrators, industry associations, and research centres. Within this category, we find several specialised sub-groups: manufacturers of hardware and components, software and IT platform providers, network management service providers, technical consulting companies and advanced telecom service developers. Additionally, cloud and digital infrastructure services, as well as providers of testing and measurement facilities, contribute significantly to the ecosystem.

Complementing these are European and international associations that guide industry alignment, alongside corporate and academic research institutions that drive innovation. The telecom industry itself—comprising communication service providers, network operators, and solution vendors—forms the backbone of 6G provisioning in terms of networks and infrastructures.

On the user side, the landscape is equally varied. It includes not only individual customers but also sectors within the public domain such as cybersecurity, Internet of Things (IoT), robotics, and cloud services. These users leverage 6G capabilities to enhance their own services and applications, creating a dynamic interplay between technology and societal needs.

Supporting both the providers and users is a third layer of stakeholders: the facilitators and enablers. These include political entities, standardisation bodies, funding agencies, and innovation platforms. Their contributions span from organising conferences and fairs to shaping policy and regulation at national and international levels. Consultants, marketplaces, and enabling platforms also play a role, as do standardisation and open-source organisations. Intellectual property offices and digitalisation facilitators ensure that innovation is protected and disseminated effectively.

From a technical standpoint, the deployment of 6G networks is guided by the ITU-R IMT-2030 framework, which outlines performance capabilities, requirements, and spectrum considerations. While the primary deployment setting is nationwide mobile networks, evaluations may focus on sub-regions to better understand localised impacts. The expected user volume aligns with typical MNO subscription levels, and deployment environments range from dense urban areas to rural regions.

For our evaluation purposes, the MNO 6G public mobile network will be considered to consist primarily of macro base stations with varying antenna configurations, tailored to different geographic and demographic needs. Beyond the physical and technical aspects, a critical requirement is the traceability and accessibility of sustainability data across the entire value chain. This data is essential for assessing the broader impacts of 6G technologies, particularly in relation to key societal and environmental values.

5 Overview of 5G technology, state-of-the-art and sustainable 6G enablers

5.1 Scope of this chapter

This chapter gives an overview of available 5G technology and on 6G technology enablers currently researched. The SotA thereby focuses on public mobile as well as on fixed networks and data centres. Furthermore, a baseline set of eco-design rules for 6G implementation is provided. The identified technology enablers are assessed at a high level with respect to their expected effect on environmental, societal and economic sustainability. The SotA together with the design rules and the initial assessment are fundamental towards creating reference scenarios for evaluating the technology enablers when applied to the UCs outlined in Chapter 6, in terms of being able to quantify the sustainability gain and benefits in an E2E manner.

5.2 5G technology and 6G requirements

5.2.1 5G technology fundamentals

The wireless technology had to cross several generations before reaching the 5G technology. Figure 5-1 shows the wireless technology evolution and Figure 5-2 shows the user equipment evolution.

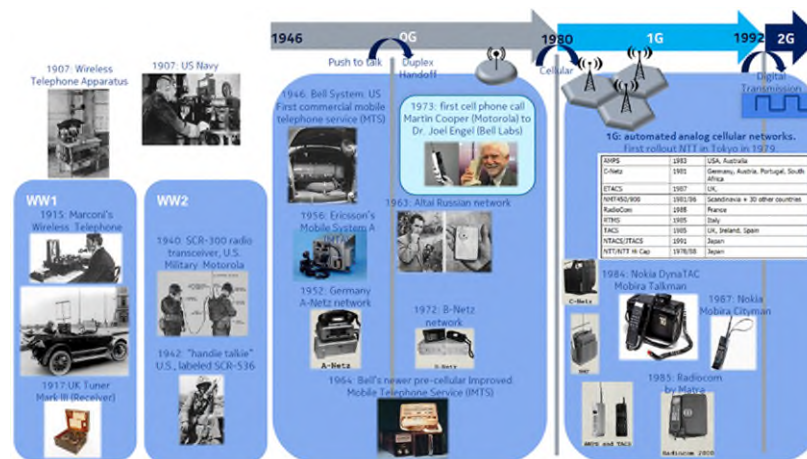


Figure 5-1: Evolution of the wireless technology



Figure 5-2: Evolution of phones through the different generations

But the specificity of each wireless technology is a progressive transformation of the technology from analogue to digital, from a circuit to a packet transfer mode, and from a phone service to a wide range of services offered today by the 5G technology. Figure 5-3 shows this evolution to offer a Quality of Experience in line with the expectations of the end-users.

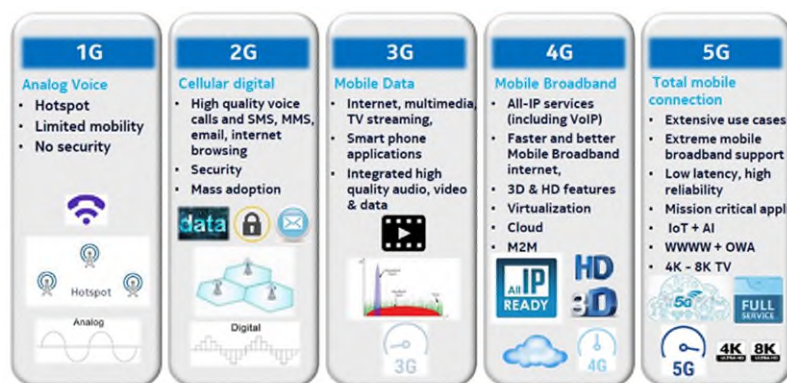


Figure 5-3: Evolution of the wireless technology from 1G to 5G

Concerning the spectrum exploited, we have the RF spectrum and in some advanced technologies, the optical spectrum from the close infra-red to the visible light. Figure 5-4 shows the band of frequencies used by the 5G technology.

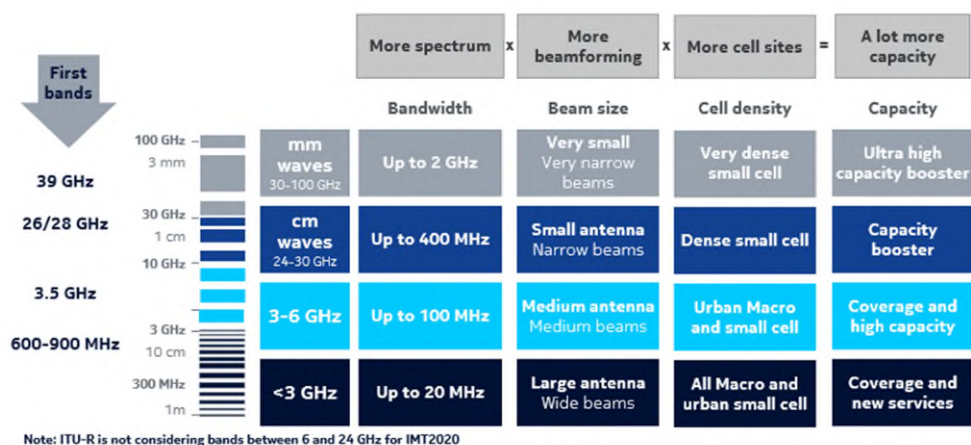


Figure 5-4: Bands of frequencies of the 5G technology

One specificity of the 5G technology is the cloud infrastructure to deliver high performance. The objective is to provide efficient, real-time, low latency, centralised and distributed services. Figure 5-5 shows how the capacity and the latency reduction are managed.

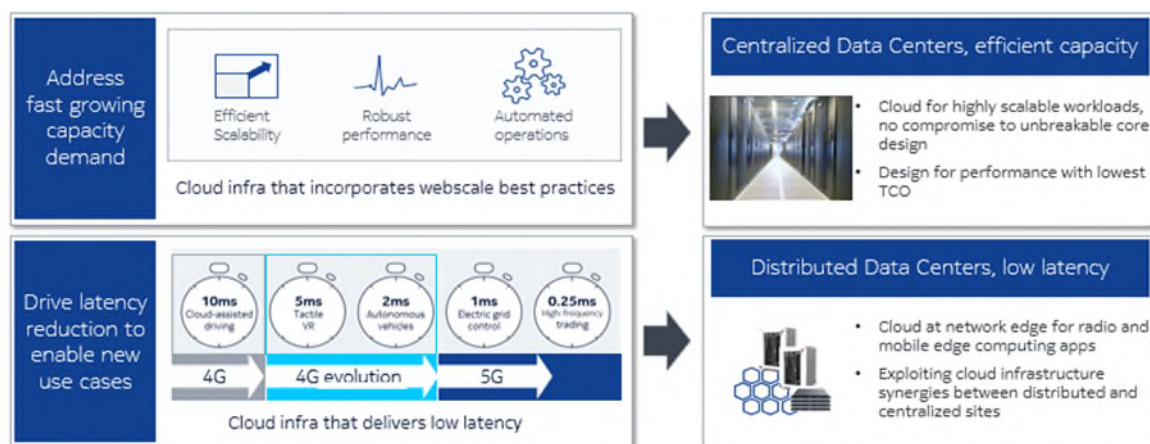


Figure 5-5: Towards a cloud infrastructure for capacity and low latency

Another key differentiator of the 5G with respect to the 4G technology is the network slicing, a foundation for a value creation. Figure 5-6 shows the implication of the service request, on the resource allocation, the orchestration of the network and of the cloud, for a service delivery.

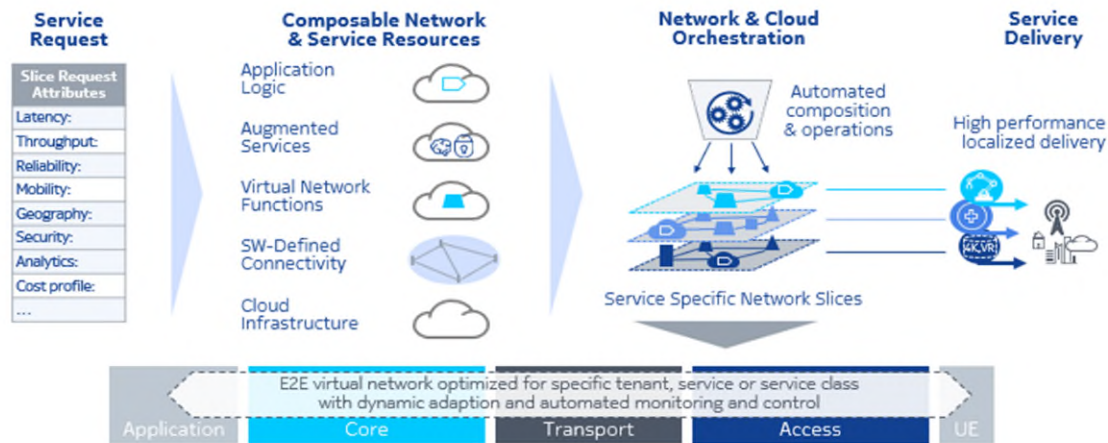


Figure 5-6: Network slicing for a high-performance localised service delivery

If we compare the 4G to the 5G, we can list the following key performance evolutions:

- Data volume 1000x: from 10Gbit/s/km² to 10Tbit/s/km²
- Peak rates 100x: from 100 Mbit/s to 10 Gbit/s
- IoT density 1000x: from 1k/km² to 1 M/km²
- Energy efficiency -90%
- Service intro -93%: from 90 days to 90 minutes
- Latency -80%: from 25 to 5ms and in some cases to 1ms.
- Reliability +90%
- Mobility supported up to 500km/h

5G can be described around 5 key pillars:

1. New spectrum options to offer massive capacity and throughput
2. Flexible radio design, dynamic optimisation for all UCs -also mission critical, high capacity, flexibility, new revenue streams
3. Massive MIMO and beam forming for massive connectivity, improved end-user experience, cell edge throughput.
4. Multi-connectivity and aggregation for end-user experience, extreme mobility, robustness and ultra reliability.
5. Cloud native for a flexible architecture.

5.2.2 6G technology fundamentals

If the 5G technology was proposing a technology able to provide a concrete solution to new UCs the 6G technology can be considered as an incremental evolution of the 5G technology to provide higher performance. The 6G technology is targeting a “super IoT” to connect anything and data for Artificial intelligence. Without claiming completeness, a list of application scenarios can include, for example:

- Personalised human services
- Data Artificial Intelligence – Machine Learning
- Projection interface – holograms – gamification interface
- Sensor fusion – scanning health
- Smart clothing and environment
- Cyber security – Block chain
- Terabit range throughputs
- Huge memory capacity
- Stream fast analytical decision Input Output Operations per Second

- Ultra-Low latency and real time
- Ultra-fast edge
- Printed electronics products
- Bio cybernetic identification
- Autonomous robots

The communications in the 6G era could be focused on [Vis20]:

- Augmenting our intelligence through learning from/with machines, automatic security and in-body monitoring
- Creating new digital worlds through mixed reality & telepresence, high resolution mapping and mixed reality co-design.
- Controlling the automations through domestic robots, remote & self-driving, drone/robot swarms.

The enabling foundations of the 6G for that future is built around three pillars in real time:

- Physical world
- Digital World
- Biological World

The 6G technology aims to unify the experience across physical, digital and biological worlds. The new requirements for this 6G technology are illustrated in Figure 5-7.

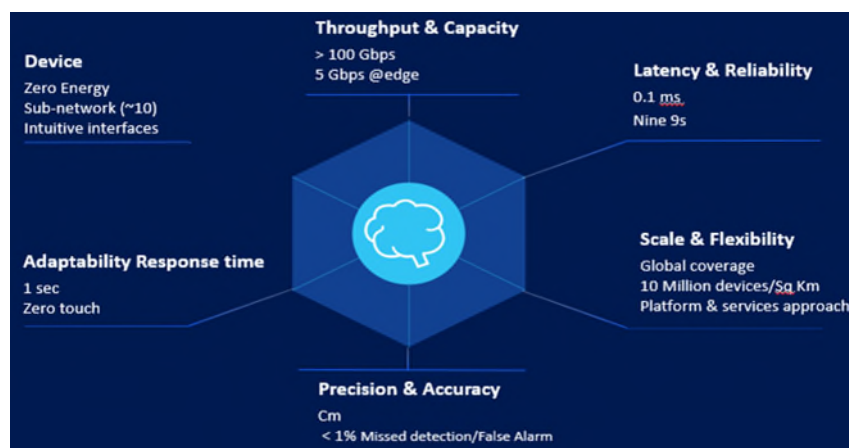


Figure 5-7: New requirements of the 6G technology

As outlined in Figure 5-7, 6 key requirements can be listed:

- Throughput & capacity: > 100 Gbit/s
- Latency and Reliability: 0.1 ms
- Scale & Flexibility: Global coverage, 10 million devices/Sq km, Platform & services approach
- Precision & Accuracy: cm, <1% missed detection/False alarms
- Adaptability Response time: 1 sec; Zero touch
- Device: Towards “Zero energy”, subnetwork and intuitive interfaces.

6G technology proposes therefore three critical dimensions for wireless networks:

- For capacity: more spectrum, spatial reuse and a more spectral efficiency
- For reliability: channel redundancy, multipath adoption and robust modulation/coding
- For latency: faster channel access, shorter paths and shorter symbols and frames.

The 6G era is likely to add three additional dimensions on the top of these three initial dimensions (spectrum, space and efficiency):

- On data: network and sensor data will become fundamental resources to be exploited to improve the performance of the 6G systems

- On compute: Leveraging computing that is available in the local area but separate from the devices could be a new theme.
- On energy: Energy consumption of both networks and devices will be highly scrutinised.

In summary the 6G will require 6 key sustainable technologies: AI/ML-based air interface, new spectrum technologies, network as a sensor, radio access and core network convergence & specialisation, extreme connectivity and security & trust.

5.2.3 IMT- 2030 work in ITU-R

Capabilities of 6G as defined in the global framework for IMT-2030 at the ITU-R include the following targets for research [M.2160]:

- Peak data rate: Maximum achievable data rate under ideal conditions per device. Example research target values include 50, 100 and 200 Gbit/s.
- User experienced data rate: Achievable data rate that is available ubiquitously across the coverage area to a mobile device. Example research target values include 300 and 500 Mbit/s.
- Spectrum efficiency: Spectrum efficiency refers to average data throughput per unit of spectrum resource and per cell.
- Area traffic capacity: Total traffic throughput served per geographic area. Example research target values include 30 and 50 Mbit/s/m².
- Connection density: Total number of connected and/or accessible devices per unit area. Example research target values include 10^6 - 10^8 devices/km².
- Mobility: Maximum speed, at which a defined Quality of Service (QoS) and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies (multi-layer/multi-RAT) can be achieved. Example research target values include 500-1000 km/h.
- Latency: Latency over the air interface refers to the contribution by the radio network to the time from when the source sends a packet of a certain size to when the destination receives it. Example research target values include 0.1 – 1 ms.
- Reliability: Reliability over the air interface relates to the capability of transmitting successfully a predefined amount of data within a predetermined time duration with a given probability. Example research target values include $1 \cdot 10^{-5}$ to $1 \cdot 10^{-7}$.
- Coverage: Coverage refers to the ability to provide access to communication services for users in a desired service area.
- Positioning: Positioning is the ability to calculate the approximate position of connected devices. Positioning accuracy is defined as the difference between the calculated horizontal/vertical position and the actual horizontal/vertical position of a device. Example research target values include 1-10 cm.
- Sensing related capabilities: Sensing-related capabilities refer to the ability to provide functionalities in the radio interface including range/velocity/angle estimation, object detection, localisation, imaging, mapping, etc. These capabilities could be measured in terms of accuracy, resolution, detection rate, false alarm rate, etc.
- Applicable AI-related capabilities: Applicable AI-related capabilities refer to the ability to provide certain functionalities throughout IMT-2030 to support AI enabled applications.
- Security and resilience: Security refers to preservation of confidentiality, integrity, and availability of information, such as user data and signalling, and protection of networks, devices and systems against cyberattacks such as hacking, distributed denial of service, man in the middle attacks, etc. Resilience refers to capabilities of the networks and systems to continue operating correctly during and after a natural or man-made disturbance, such as the loss of primary source of power, etc.
- Sustainability: Sustainability, or more specifically environmental sustainability, refers to ability of both the network and devices to minimise greenhouse gas emissions and other environmental impacts throughout their life cycle. Important factors include improving energy efficiency,

minimising energy consumption and the use of resources, for example by optimising for equipment longevity, repair, reuse and recycling.

- Interoperability: Interoperability refers to the radio interface being based on member-inclusivity and transparency, so as to enable functionality(ies) between different entities of the system.

Table of comparison 5G – 6G

Table 5-1 gives the main capabilities of both, 5G technology and 6G technology. It exhibits the main differences, and the added values proposed by the 6G technology. We notice that one of the key requirements of the 6G technology is a sustainable technology offering a massive connectivity, more reliable and offering ultrahigh bit rate and ultra-low latencies.

Table 5-1: Comparison 5G and 6G technology features

Category	5G	6G
Peak data rate	Up to 20 Gbit/s	Up to 1 Tbit/s (50x faster)
User Data Rate	~ 100 Mbit/s – 1 Gbit/s	1-10 Gbit/s average per user
Latency	~1 ms	~0.1 ms (ultra-low latency)
Frequency bands	Sub-6GHz, mmWave (24 – 150 GHz)	Sub-THz to THz (100 GHz – 1 THz+)
Coverage	Urban, rural, partial global	3D global: land, air, sea space
Device Density	Up to 1 million/km ²	10+ million/km ²
Energy Efficiency	Improved comparing to 4G	Sustainable technology
Mobility Support	Up to 500 km/h	1,000 km/h (e.g., hypersonic)
Reliability	99.999% (URLLC)	Near 100%, even in extrem conditions
AI integration	Limited	Native and pervasive (self-learning)
Security	Enhanced encryption & slicing	Quantum-safe, AI-driven trust
Use Cases	IoT, Smart Cities, AR/VR, Autonomous Vehicles	Hologram, Extended Reality, Digital Twins, Quantic-Computer interface
Network Slicing	Yes (multi-slice support)	Hyper-personalised, context-aware
Commercial Launch	2019- 2023 (ongoing rollout)	Expected around 2030

5.2.4 3GPP context

The 3rd Generation Partnership Project (3GPP) is currently working on 6G design to meet IMT-2030 requirements. As part of this work, 3GPP working group System Architecture 1 (SA1) is defining UCs and requirements in the following areas of interest, documented in TR 22.870 [22.870]:

- System and operations
- AI
- Integrated sensing and communication
- Ubiquitous connectivity
- Immersive communication
- Massive communication
- Industry & Verticals

Furthermore, in June 2025, the 3GPP Radio Access Network (RAN) plenary has issued a liaison statement to ITU-R (RP-251825), in particular about the proposed TPRs from IMT-2030 proposal (Table 5-1). For example, the proposal for latency bound is not below 1ms, connection density not more than 1M devices/km² and reliability up to 5 “9”s, thus in line with 5G requirements but not 10x better.

5.3 *State-of-the-art per network segment*

As 5G networks evolve, energy-aware network architecture design is becoming increasingly important. Studies [Ber17] highlight the necessity of balancing high data rates, low latency, and massive connectivity with sustainable energy consumption. Advanced network planning methodologies consider factors such as network densification, dynamic time-division duplexing, and intelligent traffic steering to optimise power efficiency while meeting growing service demands.

The major part of the current work on network sustainability focuses on energy efficiency and energy consumption. The Radio Access Network (RAN) is the largest energy consumer in a mobile network, consuming about 73% of the total energy of a typical operator network. Separating the power consumption among the different elements that make up the mobile communication network, the Radio Unit including Radio-Frequency Power Amplifier, Digital Front End, analogue-to-digital converters and power supply accounts for about 29%, while the power amplifier alone weighs for about 17% of the total mobile network consumption, according to the breakdown worked out in [VWD+23].

Waveform is a key design element of wireless communication systems, directly influencing the performance, energy efficiency, and resilience of networks. 3GPP conducted a detailed study on suitable waveforms during the standardisation of the first Release of 5G New Radio (NR) (i.e., the Release 15) and selected the Cyclic Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM) with a scalable numerology for downlink and uplink transmissions, while specifying also as optional waveform only for the uplink the Discrete Fourier Transform-spread-OFDM.

CP-OFDM was selected for NR due to an efficient implementation using the discrete Fast Fourier Transformation, robustness to time dispersion that causes frequency selectivity in the radio channel and ease of exploiting both the time and frequency domains when defining the structure for different channels and signals. Besides the integration of multi-antenna processing (i.e., MIMO) is rather easy with CP-OFDM because the channel equalisation and multi-antenna processing operations can be executed separately and in sequence (i.e., not jointly), thus significantly reducing the processing complexity at the receiver

The main drawback of CP-OFDM, however, is its high Peak-to-Average Power Ratio (PAPR) resulting from the multi-carrier modulation. A high PAPR necessitates significant power amplifier backoff to reduce nonlinear distortions, as to meet the out-of-band emission and the modulation quality requirements.

The power backoff becomes a disadvantage because it reduces the energy efficiency of the transmitter and limits the transmit power, affecting throughput and coverage. The PAPR disadvantage of CP-OFDM has been considered acceptable for NR operating at frequencies below 52.6 GHz and traded-off with the advantages of CP-OFDM previously discussed. However new UCs with power-limited links such as Non-Terrestrial Networks (NTN) and for higher frequency operations this trade-off could not even represent the optimal solution.

The foreseen usage of the upper millimetre waves range (100 – 300 GHz) by the upcoming 6G standard will require a careful design of the waveform and choice of slot structure. Power amplifier limitations may lead to a choice of waveform with small envelope variation, while phase noise requires receiver compensation algorithms and a waveform intrinsically resilient to such impairment. Besides, operation at extreme channel bandwidths requires waveforms that enable the use of analogue-digital-converters with smaller sampling rate or smaller resolution [STP+23].

One of the primary challenges in achieving energy-aware network planning lies in its multi-layered architecture, spanning access points, RAN, metro/core networks, backhaul, and data centres. Each layer contributes differently to the total energy consumption of the network. Access points are highly dynamic and require real-time adaptation to fluctuating traffic, while data centres and core networks demand more stable yet scalable solutions that incorporate intelligent resource allocation and virtualisation strategies.

Towards sustainable network management strategies, promising approaches involve federated learning and reinforcement learning frameworks [AMO+25] that dynamically optimise base station operation based on traffic patterns, leading to substantial energy savings while maintaining service quality. These AI-driven solutions can reduce energy consumption by up to 77% compared to conventional methods. Another key area of research focuses on leveraging traffic-aware base station sleep control mechanisms

to align network energy consumption with real-time traffic variations [WCZ+21]. Advanced predictive models utilising spatial-temporal traffic forecasting have demonstrated effectiveness in determining optimal base station activation states, significantly reducing unnecessary power consumption during off-peak hours. Reinforcement learning methods further enhance these strategies by improving decision-making in dynamic network conditions.

Smart grids can provide real-time insights into energy generation, consumption, and storage, allowing telecom operators to dynamically adjust 5G network power allocation based on energy supply conditions [SDK23]. For instance, machine learning (ML)-based forecasting models can predict periods of high renewable energy availability, enabling networks to shift workloads to base stations powered by solar or wind energy, thereby reducing dependence on fossil fuels. In the same direction, energy harvesting techniques are being explored to supplement traditional power sources, particularly in heterogeneous cellular networks (HetNets) [ZZG+15]. By dynamically shaping traffic distribution in response to renewable energy availability, these techniques can balance energy supply and demand at the cell level. This results in more efficient utilisation of harvested energy while minimising reliance on the electrical grid, demonstrating an effective way to integrate sustainable energy sources into 5G network infrastructure. Especially in the Ultra-Dense Heterogeneous Networks case [AYY+17] which poses further challenges, various approaches have been applied to cope with rising traffic demand while ensuring energy efficiency. The deployment of small cells closer to users increases spectral efficiency but also introduces new challenges in power consumption. Research suggests that optimising resource allocation and developing hybrid random access schemes can significantly improve both spectral and energy efficiency, ensuring sustainable network operation. Moreover, grid-aware energy management mechanisms can align network activity with the grid's energy status. During times of surplus renewable energy production, 5G infrastructure can operate at higher capacity, ensuring optimal network performance while minimising emissions. Conversely, when renewable energy generation is low, network components can enter low-power states, implementing advanced sleep modes or dynamic cell on/off strategies to conserve energy.

Data-driven optimisation is another line of research, particularly leveraging AI and deep learning to enhance energy efficiency while maintaining QoS. AI-based approaches have revolutionised network management by introducing real-time adaptability in response to fluctuating traffic conditions. The integration of Deep Reinforcement Learning (DRL) and supervised learning models enables mobile networks to predict traffic loads and adjust network configurations dynamically. This method contrasts with conventional approaches that rely on static power-saving techniques, which often result in either excessive energy consumption or dropped connections due to over-aggressive power reduction [MLZ+24].

In the evolving landscape of 5G and beyond, energy-aware network planning must be approached holistically, encompassing all layers of infrastructure—from access points to data centres. The adoption of AI-based predictive models, traffic-aware base station control, renewable energy integration, and energy-efficient network slicing has shown significant potential in minimising energy consumption without sacrificing network performance. Future research will focus on multi-layer AI coordination, ensuring that energy-aware decisions are made collectively across RAN, core, and cloud environments. Additionally, the rise of 6G will further emphasise sustainable, intelligent networks, where quantum computing, green AI models, and ultra-low-power hardware will define the next-generation communication paradigm.

5.3.1 Access points State-of-the-Art

5.3.1.1 *Product status*

Wi-Fi technology

Definition: The Wi-Fi technology connects wireless computer networking devices to communicate with each other and connects them to Internet. Wi-Fi uses therefore radio signals sent from a wireless router to nearby devices, to be translated into data.

Current version: Wi-Fi technology is a computing solution that includes a set of standards for wireless networks based on IEEE 802.11 specifications, which ensures compatibility and interoperability in equipment certified under this name. The latest version commonly used is Wi-Fi 6.

Next versions: Wi-Fi 7 takes over from Wi-Fi 6 [Wat25] (Figure 5-11) and Wi-Fi 6E protocols. This evolution promises an explosion of speeds, lower latency, as well as better network management in case where several devices are connected to it. Channel size, next-generation OFDMA, 4096-QAM modulation, 16-stream MU-MIMO, and a never-before-seen Multi-Link Operations feature are the main changes with Wi-Fi 7. Wi-Fi 7 is designed with tri-band operation and 6 GHz in mind at outdoor operation with Automated Frequency Coordination.

Remarks and comments: Wi-Fi 7 is IEEE 802.11be in the old naming convention, where Wi-Fi 6 was IEEE 802.11ax. The energy consumption issue of Wi-Fi 7 is a central topic. For instance, applying the IEEE 802.3az, Energy Efficient Ethernet standard, in essence allows an access point to reduce its power when traffic is low.

Point d'accès pour l'intérieur

	AP130	AP330	AP432
Études de cas recommandées	Faible densité pour les environnements intérieurs : petits bureaux, télétravail et salles de réunion	Densité moyenne pour la vente au détail et les points de vente (PoS), les écoles primaires et secondaires et les bureaux	Environnements intérieurs à haute densité, y compris les vastes espaces de bureau et les grands campus universitaires ou d'entreprise
Radios et flux	Wi-Fi 6 2x2	Wi-Fi 6 2x2 avec radio de sécurité de balayage dédié 2x2	Wi-Fi 6 4x4
Nombre d'antennes	4 antennes internes omnidirectionnelles	6 antennes internes omnidirectionnelles	8 antennes internes omnidirectionnelles
Débit de données maximal*	1 201 Mbits/s / 574 Mbits/s	1 201 Mbits/s / 574 Mbits/s	2 402 Mbits/s / 1 148 Mbits/s
Ports	1 x 1 Gbits/s (PoE+)	1 x 2,5 Gbits/s (PoE+)	1 x 2,5 Gbits/s (PoE+)
Consommation électrique	Pointe : 10,9W Moyenne : 10,5W	Pointe : 15,9W Moyenne : 15,5W	Pointe : 19,5W Moyenne : 11,65W
Supports de montage (inclus)	Plafond en T-Bar Montage sur surface plane Matériel et guide de montage	Plafond en T-Bar Montage sur surface plane Matériel et guide de montage	Plafond en T-Bar Montage sur surface plane Matériel et guide de montage
Accessoires en option (vendus séparément)	Support vertical universel Injecteur 802.3at PoE+	Support vertical universel Injecteur 802.3at PoE+	Support vertical universel Injecteur 802.3at PoE+
Fiche technique	AP130	AP330	AP432

Figure 5-8: Key performance indicators of the wi-Fi technology according to [Wat25]

Light Fidelity (LiFi) technology

Definition: LiFi is a high-speed, bidirectional and networked wireless communication technology using light, offering a substantially similar user experiences as Wi-Fi except using light instead of RF.

Directions adopted: Beyond the strong potential of the technology, the LiFi technology had to face several challenges that has created paths that need to be analysed. The two major challenges were the bit rate offered and the surface of connectivity (to share a maximum of subscribers). Recent studies show that the Multiple Input Multiple Output concept has been adopted by the optical community to offer a large bit rate with a reasonable surface of connectivity.

The bitrate race has also created a modification of the type of source. If initially the source was envisaged with Light Emitting Diodes (LEDs) emitting in the visible domain, recently a dynamic has been created to adopt infrared (IR) laser diodes instead of LEDs, in particular, Vertical-Cavity Surface-Emitting Laser (VCSEL) operating in the IR bands. This technology direction is justified when a high bit rate connection is required, but it creates trouble in the motivations for a massive deployment. For Visible Light (VL) LEDs the main argument was to exploit an existing lighting for more than a simple illumination of a space. The objective was then to modulate directly the LEDs to offer in a simple and sustainable way a data communication for free (since the added energy consumption to modulate a LED is negligible in front of the energy consumption of a LED). If higher bit rates are required, then there is a need to jump from VL LEDs to IR lasers. The question for which UCs and applications this technology shift is advantageous – also with respect to sustainability values – is a topic for further studies.

For the surface of connectivity, it is also important to identify the different needs: full mobility versus Fixed Wireless Access (FWA). Once again for some UCs, the FWA could be preferred with an optical technology that will then justify a need for a technology complementarity (Wi-Fi for a mobility at a reasonable bit rate, and LiFi for FWA with high KPIs).

Remarks and comments: There is then a need to analyse the comparison: VL LED versus IR lasers and full coverage (for LiFi mobility) vs FWA.

Optical Camera Communication (OCC) technology

Definition of the OCC technology: The OCC technology is a broadcast technology that uses a modified LED lighting driver to modulate the light emitted from the luminaire to transmit data that can be demodulated through the use of a smartphone camera.

Directions adopted: This technology exploits the capabilities of the optical cameras of our smart phones. And smart phones are today, in their majority, compatible with OCC. So, the question was: what service can be offered to subscribers, exploiting only this low bit rate, unidirectional data communication system?

Products of today are offering in-door positioning with a good accuracy (in the cm range) and a reception of broadcasted contents for advertising or information [You22].

Perspectives: The perspective of this system is quite large since this service could be deployed massively in complementarity, for example with a LiFi technology for FWA and a Wi-fi technology for mobility for in-building UCs.

Remarks and comments: OCC brings all the elements needed to demonstrate the positive impact in terms of Energy Savings and Energy Efficiency

Adoption of LED light:

- Ecological: no mercury or polluting gases. No battery since the OCC modem is powered by the lamp Consumption: 8 to 10 times lower than a conventional bulb
- Very long service life: From 25,000 to 50,000 hours, or 25 to 50 times more than a conventional incandescent bulb,
- Reduction of maintenance operations and their costs.
- No heat felt: The outside temperature of an LED bulb (or LED spotlight) is about 35°C. There is therefore no risk of burns, especially during installation

Promote an electromagnetic signature close to zero without interference

- The Light visible doesn't produce radio frequencies
- Interference free 1,000x data density and physically contained and immune to interference.

Favour an Unlicensed spectrum

OCC operates in spectrums which are not subject to licensing in any country.

Depending on the UC, substantial savings can also be noted since the map and information are now pushed and available on smartphone

Free Space Optics (FSO) technology

Definition: The FSO technology is a point-to-point communication system that is typically deployed in outdoor environments as a replacement for cables. Used for the backhauling, in outdoor or indoor applications, to reduce the cost of installation and increase security (the beams are pointing a direction and are enough small to minimise the risk of any interception). It can further be used also for submarine communication systems.

Directions adopted: For FSO generally IR lasers are used to reach distances in the air, close to 1km, and underwater close to few 10's of meters. Since this system is generally used in outdoor, some other systems are required to guarantee the stability of the sources.

Perspectives: The perspectives are large also for in-door application to realise for example a backbone of interconnection for access points.

Remarks and comments: This technology will not be analysed in this project, but a dedicated study is required.

5.3.1.2 *Research status*

Wi-Fi technology

Wi-Fi 8 is the next generation to follow Wi-Fi 7, with the expected features:

- Multi Access Point coordination (moved from IEEE 802.11be)

- Distributed Multi-link Operations
- Physical and Medium Access Control layer enhancements
- AP power savings

Complementary functionalities beyond Wi-Fi 8:

- Combine < 7GHz and mm Wave
- AI/ML functionalities
- Multi AP coordination: Discussed for 802.11be
- Multiple nearby APs coordinate their TX over the air: avoid channel contention and improve resource sharing.

Pros: Higher throughput & improved worst-case latency

Cons: Extra overheads / complexity

LiFi technology

Nowadays, more than 20 providers [Lif25] are proposing Li-Fi solutions, following proprietary or IEEE 802.11bb standardised in 2023. Solutions go from 54 to 220 Mbit/s in cells, with IR technologies. Currently, the Access Point is a LED transmitting in IR spectrum, usually powered by Power over Ethernet standard IEEE 802.3at. Access Point are requiring from 8 to 10 W. Dongles are linked with Laptop thanks to USB connectors and demand around 3 W.

The research on the LiFi technology is still going on. Many challenges are tackled. Beyond the IEEE 802.11b standard, research activities are targeting high bit rates to anticipate the needs of the 6G. If today the LiFi technology can find a market for Fixed Wireless Access applications, it is envisaged to offer a mobility and high bit rates.

FiWi technology

Fiber Wireless (FiWi) is a technology replacing fibre or radio technologies on short distances. The ONT is an API (from HW to SW). Some LiFi providers propose proprietary solutions, like OLEDCOMM with a 5 meters communication with 5Gbit/s throughput. A FSO solution is reaching 50 Gbit/s at 3 m with a beam powered at 10 dBm [GSQ+16].

OCC technology

Nowadays, literature offers several experimental applications of OCC technology. The technology is relatively recent, and few products are available, although the usage in hospital or public domain are more and more obvious [MHC+19].

5.3.2 Fixed access network

5.3.2.1 Product status

Passive Optical Networks

The Passive Optical Networks (PON) are today widely deployed mainly in the fixed access network segment but have found also some new application cases in enterprise through the Passive Optical LAN, and for the fronthauling at the RAN level. It is today a widely deployed technology with perspectives at 100 Gbit/s and beyond. Based on a tree topology this technology is purely passive, with the active elements are only located at the periphery of the network. It is an eco-designed technology since the optical fibre and the optical coupler have long lifecycles. ITU-T G.984 defines the Gigabit Passive Optical Network (G-PON). Its main characteristics are:

- A 2.488 Gbit/s downstream at 1490 nm / 1.244 Gbit/s upstream at 1310 nm
- Up to 1:64 split
- 20 km reach
- 28 dB link loss budget.

The main elements of a G-PON are:

- Optical Line Termination (OLT) located in the central office
 - o P-OLT: Packet (=data) OLT

o V-OLT: Video OLT

- Optical Network Termination (ONT) at the use side.

The specificity of this network is the adoption of a burst mode operation for the upstream data traffic. The burst mode receiver challenges at the OLT side are the followings:

- High dynamic range: DP = 21 dB
- Short recovery time between bursts: 32 bits = 26 ns
- Long sequences are based on P-Frame interval of 125 μ s identical bits: CID $\geq$ 72 bits.

The downstream adopts P-Frame Intervals of 125 μ s including a Physical Control Block downstream associated to a payload. Each payload can accept “Pure” Asynchronous Transfer Mode cells, or Time Division Multiplex & Ethernet over a G-PON Encapsulation Method section. The upstream is based on bursts emitted by each end user, separated by a guard band. The transmission of burst requires a burst mode receiver to be able to extract the frequency per burst in a very short time.

The XGS-PON is a 10x Gigabit and Symmetrical PON. We need to note that the different versions of PONs (G-PON, XGPON1, NGPON2, etc.) are sharing the large optical bandwidth offered by the optical fibre, to offer on the top of the same fibre infrastructure different versions of PONs. Figure 5-8 shows a multiplexed PON integrating different versions of PONs.

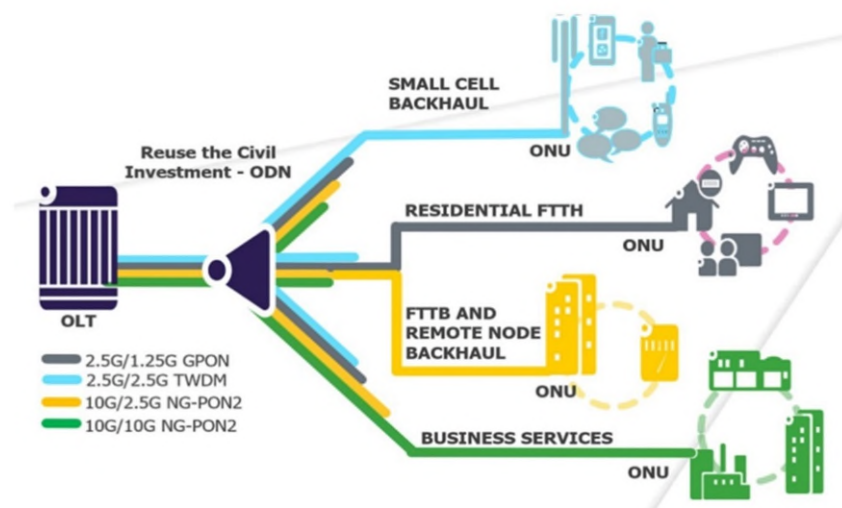


Figure 5-8: Multiple PONs multiplexed on the top of a physical tree topology

The Passive Optical LAN is an approach for Local Area Networks (LANs) based on the PON technology. The UC is the enterprise. Inside buildings the optical technology brings new advantages with respect to a pure Ethernet LAN. A possibility to reduce by 50% the CAPEX and a possibility to reduce by up to 82% the energy consumption. The Passive Optical LAN satisfies the following requirements:

Security

- Intrinsic built-in security features
- Military-grade security with AES-128 data encryption
- Fine grain management control with role & resource-based access control
- Fiber optic is inherently a more secure medium & difficult to tap-in, not subject to EMI nor does it introduce EMI
- ONTs are thin-client devices: can't be managed and accessed locally (unlike switches)

Specific Compliance

- US Government Security standard: FIPS PUB 140-2
- US Department of Defense Joint Interoperability Test Command

5.3.2.2 Research activity

- From a hierarchical to a horizontal topology: for in-building applications, a hierarchical topology is generally adopted to offer massive connectivity. But a hierarchical topology introduces also intermediate processing that impacts the end-to-end latency and increase the Total Cost of Ownership (TCO) of the global solution. One potential direction to explore is the adoption of a horizontal topology offering massive connectivity. This horizontality raises the problem of the cascade of nodes that requires then innovative solutions. The horizontality of the network minimises the number of opto-electronic interfaces.
- Shared versus dedicated resources: this research activity includes technologies such as Wavelength Division Multiplexing (WDM), Frequency Division Multiplexing, or Optical-Electronic-Optical (OEO) conversion, and is mainly motivated by a “pay as you need” approach. The increase of the bit rate up to 100Gbit/s opens then new directions of optimisation at the end user side to reallocate a physical bit rate as close as possible to the guaranteed bit rate.
- Fiber-to-the-Curb (FTTC) opens new optimisation schemes to reduce the energy consumption through a better sharing of the electronic processing.
- Fiber-to-the-Room (FTTR) is the technology that opens new optimisations and has the potential to reduce energy consumption. A research activity is still going on.
- Bit interleaving: This technique studied in early 2010 was abandoned since it can work only on synchronous links. But if a disaggregated bit rate is offered to the end-users, symmetrical synchronous data transmission can be applied, repositioning this technology as a performant approach to reduce energy consumption.
- ONT API: Envisaging an Application Programming Interface (API) for the ONT suppresses the need for physical implementation of an ONT. This approach has to be considered as a highly potential direction to reduce the TCO.
- Microgrids at OLT: Microgrids must be considered at each network element level. A micro grid designed for the central office can contribute to reduce energy demand.

5.3.3 Radio access network

5.3.3.1 Product status

Provide State-of-the-Art of 5G technology and Requirements for 6G including RAN, core and cloud

State-of-the-Art (SotA) for virtualised RAN paradigm used in the industry nowadays, based on an unsustainable overprovisioned approach with many high-consuming and expensive computing processors to process virtual network functions: The current SotA approach in the industry to support virtual RANs while guaranteeing stringent latency constraints to process wireless signals in general-purpose platforms at high reliability (99.999% probability) is based on unsustainable overprovisioning. Indeed, individual virtual Base Stations (and the related virtual functions) are assigned with dedicated general-purpose platforms equipped with dedicated Hardware Accelerators (HAs), which are powerful yet expensive and energy-hungry computing resources, especially in compute-intensive network functions like Forward Error Correction decoding. These HAs can serve at the desired reliability the processing of virtual functions of the Base Station by providing latency gains at the cost of high energy and economic expenditure with respect to general-purpose computing processors like standard CPUs. For example, typical HAs like Intel ACC100 ASIC and NVIDIA V100 GPU may consume up to 52W and 250W respectively [Sil22] [Nvi17] which is around 20-82% of the overall consumption of a commodity server [JBY+20]. This approach casts doubts about its applicability in industry-grade virtualised RAN deployments due to the economic and energy costs.

RAN Energy-saving Enablers from Standardisation Perspective

Energy consumption is a crucial factor in the operational costs of communication service providers. Base stations account for more than 73% of the energy consumption of service providers. Previously, there was a lack of accurate power consumption models for different components and radio resource

procedures within base stations. Therefore, in Release 18 of 3GPP, a decision was made to study power consumption models for various hardware configurations and develop accurate models that could estimate power consumption for different deployments and configurations. Additionally, radio resource management was examined, identifying key players and proposing viable solutions aimed at reducing power consumption in the RAN. Network energy-saving techniques were categorised based on resource allocation across time, frequency, spatial, and power domains as follows:

Power saving techniques in time domain

The lean approach for common signals and channels appears to be power-intensive at the base station, preventing it from switching to sleep mode to conserve energy. To address this, one solution is to increase the periodicity of Synchronisation Signal Block (SSB) and System Information (SI) or other common signals like paging or random access channel. However, altering the periodicity of common cell signals may impact user equipment (UE) in terms of SI acquisition, measurement reporting, or initial access delay, potentially causing service performance degradation.

Similar to the user equipment (UE) wake-up signal, the base station can shift from active to inactive status using a wake-up signal transmitted by the UE. This method requires the base station to detect the wake-up signal even when it is in deep sleep mode. Additionally, the base station must be capable of quickly transitioning from deep sleep mode back to active mode.

Another option is discontinuous transmission and reception at cell through which the base station can reduce its activity time by informing UE about activity time and enhancing current discontinuous reception at UE side.

As previously mentioned, common signals like SSB and System Information Block 1 (SIB1) can affect the power consumption of the base station. Activating these signals on demand, for example, by the User Equipment (UE), may help reduce the base station's power usage. This suggestion is based on the assumption that the UE can access SSB or SIB1 information from other associated carriers or cells.

Power saving techniques in frequency domain

The power consumption of the base station varies with bandwidth size. Enhancing current signalling to support group-common signalling, to adapt the bandwidth part and mute some resources within the active bandwidth part, can help reduce the base station's power consumption. Another technique is to support inter-band carrier aggregation in the cell without SSB signal. As explained, the SSB signal can be retrieved from another cell with SSB support. However, this mechanism requires the base station to support on-demand triggering signals received at the base station across inter-band SSB-less or from another cell or carrier.

Power saving techniques in spatial domain

Spatial element adaptation can assist user equipment (UE) in adjusting the already configured Channel State Information Reference Signal (CSI-RS) settings. This adaptation may involve dynamically or semi-persistently switching the CSI-RS ON and OFF or reconfiguring the CSI-RS settings based on the changed number of spatial elements or ports. By doing so, the base station can enable dynamic adaptation of spatial elements, such as the number of active transceiver chains or the number of active antenna panels at the next-generation Node B (gNB), for transmitting and/or receiving channels and signals.

Power saving techniques in power domain

One effective way to conserve energy on the network side is by adjusting the transmission power or Power Spectral Density of downlink signals. For instance, this adjustment can be made for the power allocated to the Physical Downlink Shared Channel, the SSB, or the CSI-RS, as well as for other broadcast signals such as SIB1 or paging. By doing so, we can reduce energy consumption at the base station. To implement this successfully, the User Equipment (UE) feedback procedures and user behaviour will need to be enhanced.

Pre-distortion is a technique employed at the base station to tackle the non-linearity issues of radio transmitter amplifiers. In this process, the base station applies "inverse distortion" to the input signal of the amplifier, which helps to reduce any non-linearities. Additionally, the performance can be further

enhanced by utilising UE assistance information. This information allows the base station to effectively manage and improve the linearity of the power amplifier.

Reducing the PAPR can help decrease power consumption at the base station. One effective method for achieving this is tone reservation, where specific Orthogonal Frequency Division Multiplexing (OFDM) subcarriers are set aside and do not transmit any data. Instead, these reserved subcarriers are utilised to alleviate the high peaks in the transmitted signal, thereby reducing PAPR.

Other solutions, such as controlled cell selection, can be implemented for UE in idle mode. This allows a UE to select a non-network energy-saving cell, which helps ensure that a base station can enter energy-saving mode without being obstructed. In contrast, mechanisms like Channel Condition Handover are designed to manage UEs that are actively engaged in a conversation. These mechanisms prevent UEs from being handed over to cells that are in energy-saving mode.

RAN deployment of Energy Saving solutions applying AI as enabler

The study of 3GPP in TR37.817 aimed to establish an AIML framework for assessing the applicability of artificial intelligence in Radio Access Networks (RAN). The findings resulted in the proposal of a framework consisting of four key components: data collection, model inference, model training, and an actor. This framework is illustrated in Figure 5-9.

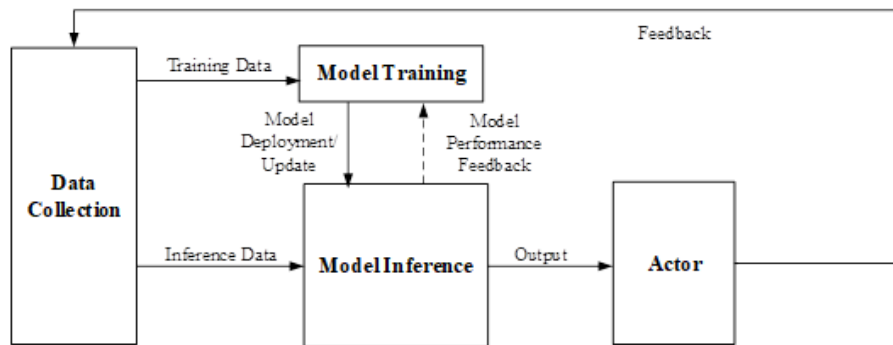


Figure 5-9: AIML model Framework in RAN (3GPP TR 37.817)

Data collection involves gathering data from the Radio Access Network (RAN) to support the training module, which is designed for a specific UC. The collected training data is then processed and validated to ensure its quality. Once validated, it is delivered to the inference module. The inference module functions to make predictions based on radio parameters or network traffic. The output from this module is then applied to the environment, which could be a cell site, radio parameter, or a specific procedure. Lastly, the impact of these predictions is observed within the affected environment. This information is collected by the data collection process to facilitate further fine-tuning of the training module.

It is worth mentioning that the location of different components of AIML frameworks can be in RAN itself or a different part of RAN in the case of split RAN architecture, i.e., Data Unit (DU), Central Unit (CU) setup. This arrangement depends on the UC and the signalling and measurement burden due to data collection and training data in the RAN element.

Finally, the potential for energy savings using AIML in RAN was examined. The adoption of cell activation and deactivation based on traffic load offers a viable solution for optimising energy savings in RAN networks through various AIML algorithms.

AI/ML-based Energy Saving solutions in 5G RAN – academy/research view

AI/ML Energy Saving solutions in 5G RAN networks have garnered significant attention from academy in recent years. Those solutions could be systematically categorised into the following groups based on energy saving actions they execute [ZWX+22], [RTY+21].

- **Cell Switch Off (CSO)** – selectively tuning off certain cells during low traffic demand periods.
- **Channel shutdown** – Massive MIMO is one of the main concepts introduced in 5G for boosting capacity. Similarly to CSO, when specific low traffic conditions are met, selected transmit RF channels could be shut down.

- **Symbol shutdown** - selectively turning off certain symbols within a transmission frame when they are not needed for data transmission.
- **Base Station Sleep Mode (SM) strategy** – it encapsulates deactivation and activation of different base station hardware modules. Different Sleep Modes are defined based on the set of modules that should be shut down (e.g., power amplifier, digital baseband etc.) [MPFV23]

AI/ML-based CSO / Channel shutdown / Symbol shutdown solutions have the focus on energy saving windows optimisation. That could be achieved using load prediction and energy saving thresholds tuning.

Load prediction can be addressed using either classical statistical methods or AI/ML-based approaches. Classical statistical methods e.g., ARIMA [TSF+22], [GCLZK20] second-order exponential smoothing [TSF+22], Holt Winters Additive Method [PDL+21], [PDB+21] and similar could have challenges to deal with complex data patterns and long-term forecasting. Conversely, AI/ML methods may exhibit better performance in those scenarios. An overview of commonly utilised AI/ML methods in the context of load prediction is provided below:

- Multi-Layer Perceptron Neural Networks [SGM22]
- LSTM [TSF+22], [GCL+20], [DS22], [LSZ+24]
- FB Prophet [GCL+20]
- Random Forest [GCL+20]
- Ensemble Learning – combination of multiple learning algorithms [GCL+20]
- Graph Convolutional Networks [PDL+21], [PDB+21]

The predicted load values, along with the intended goals and constraints, can be utilised to optimise energy-saving load thresholds, for instance, by employing classical optimisation algorithms. In addition, there are even more advanced concepts specifically accustomed for energy saving load thresholds optimisation e.g., *Bayesian learning* approach [MMC+23]. The primary criteria for selecting appropriate AI/ML methods could be listed as follows:

- expected prediction horizon (short term or long term)
- required accuracy metrics' levels
- input data granularity and input data distributions
- computational complexity, available computational resources and similar
- training/test/inference time

In addition, it is important to mention that in realistic scenarios certain levels of QoS should be preserved.

Another significant class of AI/ML-based Energy Saving solutions would include algorithms that are oriented towards Base Station Sleep Mode strategy. The primary objective is to orchestrate multiple Sleeping Modes. In the simplest case, Base Station has 1 Sleep Mode with only two states: ON and OFF. This scenario could be handled using various heuristic algorithms like *Genetic Algorithm (GA)* [GB23], [FMF+23], *Particle Swarm Optimisation (PSO)* [GB23]. Since those heuristic algorithms require wider network overview, they could be suitable for some form of SON (Self Organising Network) solution.

In general, it is better to have more granular energy saving actions as they can lead to higher energy savings considering QoS constraints. As a result, realistic scenarios involve multiple Sleep Modes where each of them could be in ON or OFF state. For example, B. Debaillie et al propose four different Base Station Sleep Modes [DDL15] that are later used by F. Salem et al in the context of Energy Consumption and Reinforcement Learning [SGA+17], [SAG+18]:

- SM1 – the time unit is the OFDM symbol where Power Amplifier and some processing modules affected.
- SM2 – the time unit is TTI with more modules being affected;
- SM3 – the time unit is a radio frame, majority of hardware modules affected;
- SM4 – 1s time unit where Base Station is in stand-by regime.

Reinforcement Learning (RL) is appropriate AI/ML paradigm for problems which include control / decision-making. RL can adapt to environment changes, and it can choose optimal Sleep Mode considering the current state and maximisation of cumulative reward. The reward definition should include potential energy savings and QoS metric degradation penalties (if there are QoS constraints). To deal with complex environments where state and action spaces is huge, Deep Reinforcement Learning (DRL) could be used instead of conventional RL. An overview of used RL/DRL methods used for Base Station Sleep Mode strategy is presented below:

- Q-learning / Distributed Q-learning [SAG+18], [EIH+19a], [EIH+19b], [ADN20], [ACH+22]
- SARSA [MPF23]
- Deep Q-Network (DQN) [JKK+20]
- Double DQN [MS24]

A comprehensive survey of DRL and Sleep Control in 5G and Beyond Networks could be found in the paper written by N. Trabelsi et al [TMF+24].

In addition, there are attempts to use other non-conventional RL/DRL methods in similar context, but it is important to note that the combination of two different models may make training, testing, and troubleshooting this type of solution more challenging: Gradient Boosting Decision Tree + Factor Decomposer [LSZ+24].

5.3.3.2 *Research activity*

Towards zero-watt at zero load target: RAN energy consumption models

Power Consumption modelling is the first step towards developing energy efficient Radio Access Network infrastructure. Consumption modelling has been first used to assess different 4G/5G Base Station (BS) configurations (Rx/Tx chains, number of frequency bands, ...) regarding KPI (throughput, coverage...) and instantaneous cell load. Moreover, consumption modelling can also be used to anticipate deployment of new technologies by mixing existing data and considering some hypothesis of future implementations.

Literature on this subject started in the early 2010s and have been enriched since. In 2012, mathematic models of power consumption of Long-Term Evolution (LTE) BS are established in [Des12] separating uplink and downlink transmission and quantifying the most impacting components (Power Amplifier, Base Band Unit...) regarding the size of the cell (macro or small cells). In 2014, [DDL14] establishes a power consumption model for Large-Scale Antenna System BS considering Time Division Duplexing with four main parameters: bandwidth, spectral efficiency, number of antennas and system load. In 2019, [SCA+19] gives complementary information on the BS power consumption according to different sleep modes strategies in 5G. Recently, [GAR+24] presents a parametric power model partially based on on-site consumption measurements. Twelve equations are presented to calculate the total BS consumption along with the power consumption of each component – i.e. power amplifier, analogue front-end, digital base band and power supply and cooling system. The models consider transmission (TX) and reception (RX) of the signal as well as idle and sleep modes.

As 6G envisages the FR3 frequency band (from 7 to 12 GHz), it is relevant to update and complete such models. For example, compared to sub-6GHz architecture, the Active Antenna Unit architecture may be revisited to contain the impact of larger number of TX/RX chains but also the low load behaviour of PA consumption. The challenge with RAN power consumption modelling is to balance its using complexity and its robustness to support large diversity of energy saving solutions for the different Network loads conditions.

Radio Frequency Technology for a sustainable massive connectivity

The radio frequency technology provides a shared resource in a n efficient way to offer a massive connectivity. It is then a required technology for a massive deployment of antennas in the public domain and offer a full coerture to be connected anywhere and at any time. But when increasing the physical bit rate, the key question must be: how can we continue to provide a massive connectivity at a minimum energy consumption? And this question is fundamental to design the 6G. another approach is to limit the physical bit rate, and to massively use a fixed wireless access technology at deterministic points to

offer a high-capacity channel. So, in the optimisation it is important to find a trade-off between a massive connectivity and high bit rate connections through an heterogeneous approach.

Eco-management of BS

The eco-management of BS can be efficient outside the peak hours, and in the rural area. So the objective here is to quantify the benefits that this technique will provide in terms of percentage of gain at the energy consumption level per antenna, but also at the level of a mobile network to have an average value. Eco-management must be provided without impacting the MTBF. So, the sleeping mode must be accurately studied to quantify the possible impact on the reliability of the global system with putting in sleeping mode or several boards of a system.

Micro-grids

Micro-Grids for reducing the energy demand and to build an efficient energy management system
Micro-grids for reducing the electricity demand to the national production of electricity are mandatory. These micro-grids can be deployed in the short term for already deployed network elements. The distributed approach for the electricity production is not only a proposal for telecom network elements but it is today envisaged everywhere when it is possible to deploy solar panels or eoliennes. Knowing that the base stations represent 72-73 % of the electricity bill of an operator, it becomes, this technology can reduce efficiently the electricity demand while reducing the electricity bill of operators. This topic represents on pillar of the strategy when addressing a reduction of the electricity demand to the world-wide production of electricity.

5.3.4 Metro & core networks

5.3.4.1 Product status

Multi-Protocol Label Switching (MPLS) segment routing, Optical Add-Drop Multiplexers (OADM)

For the metro/core network, Reconfigurable OADMs (R-OADMs) are massively used to reduce the switching size of the IP/MPLS switches/routers and to minimise the end-to-end latency. A network based on R-OADM offers point to point connections crossing OADM, for an ultimate performance. This technology is fundamental in particular with the introduction of AI.

For the backhauling: FSO, mmWave RF

For the backhauling, different technologies are deployed from point-to-point connections using optical wireless technologies (FSO) or using pure RF technologies. But the backhauling can offer also different topologies to provide a concrete solution to the interconnection of base stations. For the interconnection of base stations, optical networks based on R-OADMs are today deployed for a high-capacity network exploiting efficiently the optical transparency to minimise the end-to-end latency.

5.3.4.2 Research activity

Metro and backhaul

For the metro and for the backhaul, a research activity is still required to integrate efficiently the needs of the Artificial Intelligence. In particular optical technologies can provide advantages, and open opportunities for a low power consuming network.

Core networks

For the core networks, the perspectives of capacity increase pushing for multicore fibres needs to rethink the structure of the R-OADMs to support a new generation of fibres.

5.3.5 Data Centres and service core

5.3.5.1 Product status

Data servers

The data servers have a large impact on the energy consumption of a data centres. Different types of servers of data are deployed but optimisations are required in a sustainable approach.

Cooling systems

The cooling is generally based on air flows. The liquid cooling is today seriously considered and deployed to increase the energy density of racks or to reduce the energy consumption of the cooling system.

Communication systems

The communication system has to be analysed for offering flexible functions to manage efficiently the data. One example in the adoption of optical cross-connects to provide a reconfigurable physical connection of data servers and have the possibility to better manage the data location. Even if the data communication system impacts in a minor part the energy consumption of a data centre, it can contribute to active sleeping modes to have an indirect impact on the energy consumption of data centres but at the servers of data level.

Edge routers and load balancers

Edge routers can be optimised using integrated optical functions. The load balancers are deployed to optimise the load of the line cards of the switch/router.

5.3.5.2 Research activity

Liquid Cooling

The liquid cooling is a key research topic. Single phase liquid cooling or dual phase liquid cooling are currently investigated to provide an efficient solution facilitating also the sleeping mode.

Sleeping modes in servers of data

The sleeping mode in the servers of data is fundamental to put a part of the servers in a sleeping mode. There is a need for ML, to collect the characteristics of data (some of them are sleeping data), and to exploit them to relocate sleeping data in some servers themselves put in sleeping mode. This topic is still relevant for a sustainable approach.

New communication networks

Research is still ongoing in new communication networks. In particular native-Ethernet could be adapted to data centres through the exploitation of the Time Division Multiple Access protocol that opens solutions for deterministic services.

Energy Harvesting

In the data centres we have a lot of wasted energies. Some of them are currently exploited but some of them are not at all exploited. Research activities are going on through different energy harvesting techniques. One energy that is not currently exploited is the light used for illumination of spaces. It could be efficient to re-exploit this light system for the transmission of data, or through a conversion in electricity by adopting advanced solar panels.

5.4 State-of-the art per technology

5.4.1 Artificial Intelligence

5.4.1.1 Overview of AI/ML used in 6G SNS projects

The Smart Networks and Services (SNS) Joint Undertaking (JU) aims at developing 5G and 6G technologies within Europe. Within the context of Horizon Europe, it has funded numerous projects in order to drive the development of 6G technologies. Within these projects AI/ML has become a key technology in advancing 6G objectives, including enhanced network performance, energy efficiency, and security [6gs25].

A survey across 33 projects within SNS JU [6gs25] reveals that 199 AI/ML-based methods are being developed. These AI/ML methods focus on Radio Access Networks (RAN), resource management, energy efficiency and others. More specifically, the use of AI/ML can be divided into eight high-level categories as can be seen in Figure 5-10. From this it is clear that AI/ML is being developed for a wide variety of applications. When looking at the usage of AI/ML for different network segments it can be noted that the majority of the work done in SNS projects targets the RAN (43%). However, other

network segments are also targeted such as the fronthaul, backhaul, transport, edge, core and far edge. Across these applications and network segments, the goal of using AI/ML varies widely depending of the focus of the project at hand. However, the four major trends can be identified as optimisation of resource allocation/QoS (31%), security/privacy/trust (19%), improving energy efficiency (17%) and improving throughput (12%).

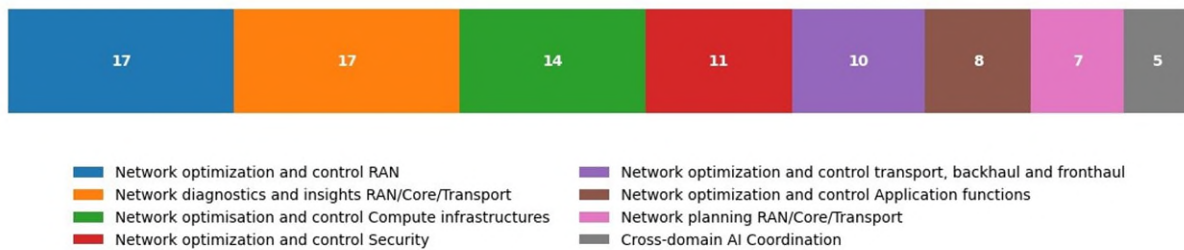


Figure 5-10: Number of Projects using AI/ML in Each Category [6gs25]

AI/ML covers a broad range of methods. In order to gain insight into which techniques are frequently used in SNS projects we focus on the breakdown of the AI/ML methodology used in SNS projects. From a high-level perspective AI/ML methods can be divided into three major categories: supervised learning, unsupervised learning and reinforcement learning. Supervised learning requires a labelled dataset to train the model, while unsupervised learning does not require labels. Next to this reinforcement learning aims at training an agent that maximises future reward by taking the correct action given the current state. Note that reinforcement learning also does not require a (labelled or unlabelled) dataset, as its reward signal is generated from the environment based on the action it takes. Within SNS projects supervised learning is most prominent with 48% of AI/ML UCs, followed by reinforcement learning (24%) and unsupervised learning (12%) (Note that the remaining 16% of methods was not specified) [6gs25]. A more detailed analysis reveals that 51% of AI/ML methods utilise neural networks/deep learning. Next to this, it is worth noting that most methods focus on low(er) complexity models in order to provide (near) real-time inference speeds.

Finally, [6gs25] reports that the majority (83%) of the AI/ML methods investigated in SNS projects are still conceptual designs/preliminary results. Consequently, for a widespread adoption of AI/ML within 6G networks further consolidation is required. This necessitates the development of standardisation concerning data collection for model training and the adoption of AI/ML within 6G networks in order to provide reliable and performant AI/ML solutions [3gp25].

5.4.1.2 Research activity

Current trends related to in-network edge artificial intelligence, solutions to balance energy consumption, performance and value of edge intelligence tasks.

Wireless communication networks are evolving towards giving access to more and more services and application that require computing resources to be reached within low latency and usually kept locally for privacy and security reasons [LSL+22]. These resources are needed to process the myriads of data that are generated by heterogeneous entities such as sensors, users and machines. Among others, the processing related to Artificial Intelligence, both as enabler and enabled technology is becoming more and more prominent and requires special attention from an environmental, economic and societal perspective. Environmental and economic aspects are mainly driven by the energy consumption and its associated cost, as well as the deployed hardware resources (CPUs, GPUs, etc.). The societal perspective mainly pertains to data exposure and management (i.e., privacy, etc.), but also safety in industrial environments among others. The power and potential (and already demonstrated) values of AI cannot be ignored, but their sustainable life cycle must be at the centre of their development. The entire lifecycle of AI goes from raw material acquisition to production, use, and end of life. The production and use include training, while inference is only related to the usage phase [Kal24], which can take constantly depending on the application, thus potentially representing the biggest impacting phase in the lifecycle, from the perspective of energy consumption [NGA25].

This becomes even more challenging with the current advancements, deployment and daily use of generative AI as an extremely powerful tool to optimise processes in almost all domains, including that of telecommunication networks [ZZT+24]. As a reference figure, [NGA25] reports that the computational power needed to keep up with AI processing is doubling every 100 days. As already mentioned, this not only concerns training, but also to the inference phase in the cases it is deployed as a continuous service. Even without considering training (which can consume energy but only once or, at least, not frequently), inference is also estimated to consume a considerable amount of resources (e.g., energy and water). According to [NGA25], the inference phase accounts for 80% of the total AI footprint overall. According to other sources, it was estimated that 60% of Google Machine learning energy use in 2022 went to inference, while single query on ChatGPT requires 2.9 Wh of electricity, i.e., 10 times a Google search [Cap25]. Considering other resources, it is estimated that running 20-50 queries on a Large Language Model (LLM) uses about 500 ml of water for cooling [Cap25]. With the increasing use of LLM for several purposes, these figures evolve constantly at short time scale.

Thus, also AI, as 6G, comes with the double facet of “AI for sustainability” and “sustainability for AI” [Nex25]. When introducing AI in communication networks in all segments (both as enabler and enabling technology) we must evaluate its positive impacts and values against its negative impacts (e.g., footprint) across the whole life cycle. The latter includes hardware resources (e.g., GPUs etc.), training and inference phases (with the latter running constantly), and end of life. One of the key enabling technologies to embed in-network AI is *Edge Artificial Intelligence (edge AI)*, which has extensively been proposed as an enabler of 6G [LSL+22], and aims at running AI-related workloads at the edge of communication networks, close to the source of the data and the end service consumers. The challenge is to embark AI in resource poor or edge nodes, rather than in central clouds. This comes with benefits in terms of latency (including communication and computing), privacy and secrecy, and energy consumption [Edg24]. On the other hand, several challenges arise, from the deployment (to minimise hardware resource waste while guaranteeing effectiveness) to resource management (to accommodate the different requests on limited resource and distributed infrastructure), also including energy and carbon-aware scheduling techniques.

Starting from the deployment problem, too complex (though highly performing) models cannot run at the edge (especially in case of strict latency constraints – the same for which they cannot run in central clouds), due to the limited computing resources and energy availability/awareness. This highly depends on UC specific requirements. In this direction, from an energy consumption perspective, there exist several methods to reduce AI inference footprint during the inference phase. Among others, model compression techniques help reducing possibly redundant information, thus reducing the number of FLOPs or memory footprint. This is obviously to be traded off with performance, e.g., in terms of accuracy, with potential losses that could degrade system level performance as a consequence. Model compression techniques include model quantisation, pruning, and sparse representation [MYH+24].

Going beyond model optimisation techniques, which are usually *static*, ***adaptive computation*** can also help in several directions, including early exiting techniques [MLR22], to balance “patience” and performance [PMD+24], DNN splitting [ZAD+24], [BMB+24], adaptive model selection, and energy-aware scheduling (e.g., to schedule costly operations during off-peak hours or when renewable energy availability is maximised) [PBE+22], [MZZ+23], [KPR23], [KPR24]. All the previous techniques are fundamental to embed AI in resource poor devices i.e., in a frugal way) and in small computing nodes with respect to central clouds, with the goal of reducing workload as much as possible to deploy the just enough hardware that best balances resource consumption and values.

Embedding edge devices (including end devices and edge servers) with AI capabilities potentially enables networks to share only relevant information (or, *semantic communication*) for a specific objective (or, *goal/task-oriented communication*) [CDS+24], [ZAD+24]. As an example, DNN splitting is a way of extracting and transmitting only the semantics or the information needed to achieve a goal, rather than sharing raw data. This has been shown in different works to reduce the size of the transmitted information but also increase the robustness to channel errors. Therefore, the vision of edge AI cannot be separated from the conception, design and optimisation of communication networks (e.g., 6G). The whole system, including communication, computing and learning must be considered as a single system, and consequently optimised in a holistic fashion, in which the trade-off between computation and communication costs is constantly monitored and improved, along with the values they create.

To summarise, a joint perspective of communication (i.e., the way information is transmitted) and computing (i.e., the way information is processed by the different network nodes) is a promising to strike the best balance between costs in the holistic fashion SUSTAIN-6G promotes. The reported techniques can in part be exploited to design algorithms for resource allocation and scheduling to improve the trade-off between energy and performance, with the latter including different aspects related to AI inference.

5.4.1.3 Sustainable Pillars of AI

Sustainable AI and AI for Sustainability represent two interrelated approaches. While AI for sustainability focuses on deploying AI to improve sustainability, Sustainable AI, or the sustainability of AI, focuses on enhancing the sustainability of AI itself.

According to [Wyn21], '**Sustainable AI**' is a field of research that applies to the technology of AI (the hardware powering AI, the methods to train AI, and the actual processing of data by AI) and the application of AI while addressing issues of AI sustainability and/or sustainable development. Sustainable AI deals not exclusively with the implementation or use of AI but ought to address the entire life cycle of AI, the sustainability of the: design, training, development, validation, re-tuning, implementation, and use of AI.

It was defined as a movement to foster change in the entire lifecycle of AI products (i.e. idea generation, training, re-tuning, implementation, governance) towards greater ecological integrity and social justice. As such, Sustainable AI is focused on more than AI applications; rather, it addresses the whole sociotechnical system of AI.

In [RWM+24] **Sustainable AI** refers to the development and deployment of AI systems while balancing technological advancement with ethical considerations, societal impact, and environmental responsibility.

Initial research activities on sustainable AI have focused on singular dimensions of sustainability, with rare exceptions considering two dimensions. Authors in [RWM+24] has proposed a more comprehensive perspective by covering multiple dimensions: ecological, societal, and economic. This study introduced the SCAIS Framework (Sustainability Criteria and Indicators for Artificial Intelligence Systems), an assessment framework that includes a set of sustainability criteria and indicators based on the results of the literature review, providing a more complete picture of sustainable AI.

However, sustainable AI still lacks maturity in terms of regulation and standardisation, and the interdependencies between sustainability-related impacts still need to be investigated.

The following section focuses on **AI's sustainability Pillars**, environmental, societal and economic sustainability.

AI's environmental Sustainability

Environmentally sustainable AI refers to the consideration of the environmental impacts of AI systems when designing and using AI with sustainability in mind.

Several Standards Development Organisations (SDOs) are actively addressing the environmental sustainability of AI and ML technologies, reflecting a growing commitment to minimising the ecological impact of these transformative technologies.

The ISO/IEC JTC 1/SC international standards committee, is at the forefront of AI standardisation, including its environmental sustainability aspects. This group is developing frameworks such as ISO/IEC TR 20226, which focus on measuring and improving energy use, water consumption, and the carbon footprint of AI systems. The goal is to ensure that AI technologies are not only innovative but also environmentally responsible in their design and implementation.

The International Telecommunication Union - Telecommunication Standardisation Sector (ITU-T) has also prioritised the creation of standards for "green AI" to minimise its environmental impact. ITU-T's work includes methodologies for assessing and improving energy efficiency and greenhouse gas emissions of AI systems.

Standardised environmental KPIs for AI are still developing within ISO and ITU-T. While efforts are underway, universally adopted KPIs for AI's environmental impact, like energy use per task or carbon emissions per AI model, are not yet fully mature. Recent initiatives have introduced Key KPIs to assess the environmental impact of AI models. Hugging Face's **AI Energy Score** [Hug25] rates AI models on

their energy efficiency, with a 1 to 5-star scale, enabling developers choose more sustainable options. Meanwhile, **Google's Carbon Indicator** [PR25] tracks the carbon emissions of AI workloads on its infrastructure, offering transparency and promoting eco-friendly decisions.

3GPP has several working groups addressing the use of AI and ML within the context of 5G and beyond. R20 is advancing AI-native architectures and sustainable communication as a part early 6G preparations. SA1 will finalise study item descriptions for AI-driven and sustainability-focused services by mid-2025. Meanwhile, SA2 is advancing AI-native 6G architecture, ensuring sustainability is embedded as a core design principle.

Nokia has published a White paper titled “A transparent and standards-based way to assess the environmental impact of AI systems” [Kal24]. It proposes an ENVironmental Impact Assessment of AI systems framework that provides a comprehensive approach to evaluating the environmental impact of AI systems by integrating the AI system life cycle with the environmental Life Cycle Assessment (LCA) methodology. The framework separates the environmental impacts of AI system development and initial training from those of hardware manufacturing, categorising the latter as embodied emissions.

The Next G Alliance published a report on sustainable AI in the telecommunications sector [Nex25]. It emphasises the importance of evaluating the entire lifecycle of AI systems to mitigate environmental impacts, focusing on reducing embodied emissions, transitioning to renewable energy, and minimising energy consumption during ML processes.

The document also addresses challenges such as emissions, water usage, and waste management, and highlights the importance of Key Performance Indicators (KPIs) and Key Value Indicators (KVIIs) in assessing the sustainability impact of AI technologies in telecommunications. Examples of KPIs include energy consumption efficiency and carbon footprint, which are quantifiable measures used to evaluate the efficiency and performance of specific activities. KVIIs, on the other hand, focus on broader, qualitative outcomes such as the reduction in resource depletion and improvements in biodiversity conservation. Another important aspect that has been also addressed in [Nex25] is the trade-off between energy consumed and energy saved in AI for the network.

Samsung has published a 6G white paper titled “AI-Native & Sustainable Communication” that discusses trends in AI-native and sustainable communication technologies [Sam25]. It highlights the importance of energy-efficient AI in the context of 6G networks and discusses the development of lightweight AI models and optimised AI algorithms that minimise energy consumption for nonlinearity compensation and modulation constellation optimisation. Authors in [Das25] have proposed a framework employing multi-objective optimisation techniques to minimise energy usage during AI model training and inference while maintaining high performance. This framework achieves a 30.6% reduction in energy consumption with only a 0.7% decrease in model accuracy.

AI has demonstrated significant potential in enhancing energy efficiency mainly within RAN. For instance, KDDI operator, implemented Nokia's AVA for Energy Efficiency, an AI-based solution that analyses and predicts traffic patterns. This deployment led to a reduction in power consumption by up to 50% during low-traffic periods and up to 20% per cell on average [Nok25]. Similarly, Ericsson's AI-powered RAN energy-saving solutions have achieved energy reductions for certain operators.

However, while these examples highlight the energy-saving benefits of AI, there is a notable lack of precise data regarding the environmental impact of AI itself within the telecom sector, particularly concerning energy consumption and CO₂ emissions. This gap in data is partly because AI/ML models currently employed in 5G and earlier generations are not as computationally intensive as the latest LLMs. As the industry progresses towards 6G, integrating more advanced AI models will likely introduce new challenges related to energy consumption and environmental sustainability. To address these challenges, comprehensive strategies are needed to balance the benefits of AI with its environmental costs, particularly those associated with deploying more complex models.

AI's societal Sustainability

Societal sustainability of AI refers to the development and deployment of artificial intelligence technologies in ways that promote fairness, inclusivity, human rights, and positive societal impacts [Mal24].

Standard bodies such as ISO/IEC 42001 and UNESCO's Recommendation on the Ethics of AI [Une21] provide frameworks to guide the development and deployment of AI systems, emphasising societal

sustainability. Quantitative/key indicators or metrics were not defined but key principles that should be considered were outlined.

ISO/IEC 42001 defines the following societal sustainability principles:

- **Security:** Safeguarding AI systems against unauthorised access and potential threats.
- **Safety:** Ensuring AI functions without endangering humans or property.
- **Fairness:** Encouraging impartial decision-making and mitigating discrimination.
- **Transparency:** Offering clear visibility into AI operations and decision-making processes.
- **Data Quality:** Preserving the accuracy and reliability of data utilised by AI systems.

UNESCO's AI Ethics Recommendation takes a broad approach, focusing on ethical AI development and use. It stresses the need for AI to support human rights, sustainability, fairness, inclusion, and gender equality.

SDOs play a crucial role in shaping ethical AI, but when it comes to societal sustainability, there are still significant gaps. One major issue is the lack of clear, measurable indicators and mature regulations. While these organisations promote fairness, transparency, and human rights, they don't always provide concrete ways to assess AI's real-world societal impact. Another challenge is that these frameworks often take a one-size-fits-all approach, overlooking the unique ways AI affects different industries and regions. Also, a major gap in AI's societal sustainability is the lack of focus on long-term impacts and future networks. While current guidelines address issues like bias and privacy, they often overlook how AI might affect power dynamics, inequalities, and human connections. As AI becomes more embedded in society, we need a deeper approach that considers these broader concerns and ensures technology benefits all.

On top of that, societal and environmental concerns are often treated separately, even though they are deeply connected.

The societal sustainability of AI is still in its early stages in research, though it is gaining significant attention.

Authors in [PSA23] present a systematic literature review analysing the societal impacts of AI. This study aimed to systematically review the main societal impacts of AI, as well as the most common strategies to mitigate impacts. Nine societal impacts and twelve mitigation actions were mapped. Among the impacts, bias and discrimination growth due to the use of AI (26%) stand out, followed by the possibility of autonomous systems hurting humans (16%), and then the impact related to the violation of data, privacy, and freedom (15%).

Authors in [CJL+24] addressed the negative societal impacts of AI including job displacement, bias, privacy violations, lack of accountability, and social isolation. It also discusses key mitigation strategies, such as ethical AI design, reskilling workers, implementing regulations, and fostering public awareness to reduce harm and ensure responsible AI use. Metrics to assess the societal impacts of AI include tracking job displacement rates and changes in workforce composition, measuring bias and discrimination in AI decisions across demographic groups, monitoring privacy violations through data breaches and unauthorised use, evaluating transparency and accountability in AI decision-making, and surveying social well-being related to AI's effects on isolation and mental health. To assess mitigation, indicators include the success of reskilling programs, the adoption of ethical AI standards, and the effectiveness of regulations addressing AI risks.

Authors in [EHA24] investigate the impact of generative AI on societal sustainability by integrating AI attributes, the Theory of Planned Behaviour (TPB), and the Technology-Environment-Economy-Society-Sustainability Theory (T-EESST). Using a hybrid approach that combines Structural Equation Modeling (SEM) with Artificial Neural Networks (ANN), the paper explores how AI adoption influences societal outcomes, considering factors like ethics, societal impact, and sustainability. The findings offer a comprehensive framework for understanding the role of AI in fostering or hindering societal sustainability.

Trustworthy AI plays a crucial role in advancing the societal sustainability of AI. While societal sustainability is broader and considers the long-term societal impact including equity, inclusion, and human well-being, trustworthy AI provides the technical enablers to achieve these goals by reducing bias, enhancing transparency, and ensuring AI aligns with human values.

The research community, standardisation and regulatory bodies have identified seven key requirements for trustworthy ML which depends on the risk-level of an ML UC, i.e., unacceptable, high, limited, or minimal (with [R2024/1689] being the prominent one) and can be summarised as follows:

- *REQ1: Human agency & oversight achieved via human-in-the-loop, human-on-the-loop, and human-in-command approaches.*
- *REQ2: Transparency achieved through traceability mechanisms with ML systems and decisions being explainable in a way adapted to the concerned stakeholder.*
- *REQ3: Technical robustness & safety to minimise both unintentional and intentional harm that can be achieved through fallback plans in case of undesired events and via defence mechanisms against ML pipeline poisoning, but also providing accurate, reliable, and reproducible outcomes.*
- *REQ4: Diversity, non-discrimination & fairness should enforce unfair bias to limit its impacts, from marginalisation of vulnerable groups to prejudice and discrimination.*
- *REQ5: Accountability should be put in place to ensure responsibility and accountability for ML systems and their outcomes, e.g., through auditability of design processes.*
- *REQ6: Privacy & data governance to ensure data protection, with adequate governance mechanisms to ensure quality and integrity of the data and legitimised access to data.*
- *REQ7: Societal & environmental well-being to ensure ML systems are sustainable and environmentally friendly, with their social and societal impact also being carefully considered.*

The ETSI Conference "How Standardisation is Shaping the Future of AI" [Ets25], in February 2025, focused on how standards can ensure trustworthy AI, highlighting the importance of making AI reliable, secure, and ethical. It emphasised collaboration across industries to promote accountability and privacy, while also pushing for fast innovation without compromising trust.

In the telecommunication domain or industry, there is the typical constellation with three parties where a *telecommunication service provider* provides services to *end users* (subscribers) using or deploying equipment, implementations and services provided by a *telecommunication vendor*. In this constellation, AI technology is used at the network side for increasing number of functions and entities designed and provided by the vendor but deployed by the service provider for their services brought to the subscribers. The *Human agency and oversight, transparency and accountability* requirements are more important and applicable for the service provider and vendor relation, while *non-discrimination and fairness* are more important for the service provision from the service provider to the subscriber. *Robustness & safety* depend strongly on the harm potential of the service, this potential is clearly visible for emergency call services and related services (like positioning), but for the higher number of AI deployments driving service optimisations a harm potential cannot be identified.

Trustworthy AI aspects for 5G-advanced were studied by 3GPP SA5 in Release 18 document [28.908], and requirements for related indicators and reporting capabilities were proposed, but so far, no Trustworthy AI related feature is part of a Release 19 normative standard. They are still candidates for coming release 20 and further versions of Release 19.

AI's economic Sustainability

AI will significantly enhance productivity, accelerate innovation and drive sustainability by optimising resource use and reducing environmental impact. However, challenges such as job displacement, widening economic inequality and the high infrastructure costs pose critical challenges.

While there isn't a standardised definition of AI's economic sustainability, various global frameworks and standards emphasise the importance of AI contributing positively to both economic growth and societal well-being. The IEEE's ethical guidelines and the OECD's principles highlight AI's role in fostering inclusive growth, creating new job opportunities, and ensuring that the benefits of AI are widely distributed. While the exact term "economic sustainability" isn't defined, these frameworks stress the need for AI to be developed in a way that maximises long-term economic benefits, supports job creation, and contributes to equitable and sustainable economies.

Reports from organisations like the Organisation for Economic Co-operation and Development (OECD) [Org23] and the European Commission [Eur23] emphasise the need for policies that maximise AI's

positive economic impact while mitigating risks. Research from McKinsey [Mck25] and the World Economic Forum [Wor25] further explores AI's role in reshaping global economies and labour markets. The report "Gen-AI: Artificial Intelligence and the Future of Work" [Imf24] by the International Monetary Fund explores the impact of AI on the global economy, particularly focusing on labour markets. It highlights that about **40%** of global jobs are exposed to AI, with advanced economies more at risk but also better positioned to benefit. AI could increase labour income inequality, especially if it complements high-income workers more, and exacerbate wealth inequality through capital income gains. College-educated and younger workers are more adaptable to AI changes, while older workers may struggle more. Advanced and some emerging market economies are better prepared for AI adoption due to strong digital infrastructure and skilled labour forces, whereas low-income countries need to focus on building foundational infrastructure and digital skills.

Some metrics assessing the economic sustainability of AI have been proposed:

- **AI profitability and ROI**, essential for evaluating financial viability, are referenced in *OECD AI Policy Observatory* and *McKinsey AI Economic Models*.
- **Adoption rates across industries** are tracked by the *WEF AI Readiness Index* and *OECD AI Policy Observatory*.
- The **cost-to-revenue ratio** is used in *McKinsey AI Reports* and aligns with *ISO/IEC 42001* on AI management.
- **Job market impact**, measured by net employment change, is examined in *OECD AI Employment Studies* and *IEEE P7010* (well-being metrics).
- **Energy efficiency and carbon footprint** are critical for sustainability, with *ISO 14067* providing carbon impact guidelines.
- **Investment growth in AI**, monitored by *OECD* and *WEF AI Investment Reports*, helps assess AI's economic trajectory.
- **Job displacement due to AI automation** is analysed by the *OECD AI Employment Impact Studies* and *IEEE P7010*, which tracks AI's effects on workforce well-being.
- **Net job impact** metric, calculated as the difference between AI-driven job creation and displacement.

While these indicators have been defined, their standardisation across industries remains a work in progress.

When evaluating the sustainability of AI, it is essential to integrate economic, environmental, and societal dimensions, recognising their interconnectedness. The economic potential of AI must be considered alongside its broader impact on society and the environment.

By integrating AI into 6G with a focus on these interconnected goals, we can create an intelligent ecosystem that enhances human well-being, reduces environmental impact and promotes global equity.

5.4.2 Cloud native technologies, cloud/edge continuum, SBA

5.4.2.1 Cloud Native technologies

Cloud computing has significantly contributed to the transformation of information processing services, and the mobile communication technologies from 5G and then. Sustainability aspects have taken attention mainly due to the carbon footprint and the energy consumption needs of cloud computing. The sustainable cloud computing landscape is evolving to several dimensions, including measurement, observability, intelligent scheduling at a cluster level, cooling, scaling and on-node power tuning [CNCf24].

Furthermore, the **cloud native** architecture is the approach for developing and operating applications that fully leverage the advantages of cloud computing, involving the following core **technologies**:

- **Microservices**, which are small, independent software components that facilitate modular development, application update and scaling
- **Containers** that package microservices with all their dependencies, enabling their consistent operation across different environments, while supporting the efficient resource utilisation

- Continuous Integration and Continuous Delivery (CI/CD) practices that automate the integration and deployment of code changes, enabling faster and more reliable application deployment
- DevOps practices that enhance collaboration between development and operations teams, by promoting a culture of continuous improvement and automation, aligned to the speed and reliability objectives of the cloud native model

While cloud native applications are bringing important benefits, power management capabilities are missing due to the lack of knowledge about the execution characteristics and the requirements of individual applications deployed in a cloud-native environment [JHS24]. For an improvement in this direction, the energy-saving mechanisms in the infrastructure (from the host operating system, the CPU cores and fabric) must be utilised. *To save energy without compromising application KPIs, any available energy-saving mechanism must be applied differently depending on the needs of each application.*

The method assumed in the **representative proof-of-concept by Ericsson** [JHS24], is based on the Kubernetes QoS classes, being used to manage and prioritise resources within a cluster. More precisely:

- Guaranteed QoS class is used for services in traffic execution that need deterministic performance to fulfil application KPIs. This is ideal for critical applications that require consistent performance and cannot tolerate resource contention
- Burstable/BestEffort QoS is used when the performance requirements and fast response times are more relaxed. This is appropriate for non-critical applications or batch jobs that can tolerate resource variability and do not require guaranteed performance

An interception mechanism is introduced and activated upon Kubernetes starting a new container. For a guaranteed container, the infrastructure is being configured to set the CPUs and fabric frequency as high as possible. On the other hand, the CPUs to be used by burstable services are configured to be managed by the host OS, to execute at the lowest possible core frequency, to enter the lowest possible CPU halt state when the cores are idle and prohibited from entering opportunistic states (frequencies). This enables the system to save energy for services that are not guaranteed and avoid unnecessary scale-up of the frequency for non-critical services.

The subject approach indicated that it is possible to achieve energy consumption reduction and improve performance for the applications with increased requirements, by making available application knowledge, taking advantage of the energy savings mechanisms in the cloud environment, and the introduction of energy saving functions that do not put the application KPIs at risk [JHS24].

On another approach, **Kepler (Kubernetes-based Efficient Power Level Exporter)** is utilising eBPF (extended Berkeley Packet Filter) to probe per-container energy consumption related to system counters and other system statistics and exports them as Prometheus metrics. These metrics help end users to monitor their containers' energy consumption and cluster administrators to make intelligent decisions towards achieving their energy conservation goals.

An internal model server is providing Kepler with ML (Machine Learning) models for estimating power consumption on Kubernetes workloads. The models are pre-trained with node energy statistics (labels) and node performance counters (features), from Prometheus metrics, on a variety of Kubernetes clusters and workloads. Once the *models* achieve an acceptable performance level, they are exported and being utilised by Kepler to *calculate energy consumption metrics given performance counters*. Model training and tuning is ongoing, by continuously using node data from the cloud clusters [CNC24] and available at [SIX+24].

Another approach is based on Kubernetes Vertical Pod Autoscalers (VPA), which allow for automatic CPU and memory request and limit adjustment based on historical resource usage measurements. A VPA deployment involves a Recommender, an Updater, and an Admission Controller. In that respect, **CLEVER (Container Level Energy-efficient VPA Recommender for Kubernetes)**, is an intelligent recommender that ensures the workloads performance are not compromised when adjusting the cluster CPU frequencies.

Given a CPU frequency tuner deployed in the cluster. When lowering down the frequencies, energy saving is achieved but the workloads performance is also decreasing. By taking cluster state information, CLEVER is computing a new recommendation for increasing CPU allocation, and this is the measure to guarantee the QoS [CNC24] and available at [Git25].

k8s cloud-native sustainable mechanisms

As cloud computing continues to evolve, sustainability has become a critical consideration in modern infrastructure design. Kubernetes [Kub24], the de facto orchestration platform for cloud-native applications, plays a crucial role in enabling energy efficiency and carbon footprint reduction through intelligent resource management. With the increasing adoption of cloud and edge computing, the challenge is not only to ensure high performance and scalability but also to optimise power consumption, reduce waste, and enable eco-friendly computing environments.

Several sustainability mechanisms have emerged within the Kubernetes ecosystem, providing advanced capabilities for energy-aware orchestration, intelligent scaling, and workload optimisation.

Kubernetes' Horizontal Pod Autoscaler (HPA) [Kub24] is a pivotal feature that enhances both the performance and sustainability of cloud-native applications. By automatically adjusting the number of pod replicas in response to real-time metrics like CPU or memory usage, HPA ensures that applications scale dynamically to meet demand without over-provisioning resources. This elasticity not only maintains optimal performance during varying workloads but also contributes to energy efficiency by reducing unnecessary resource consumption.

Besides, The Kubernetes Power Manager [Int22] is an operator developed to bridge the gap between Kubernetes' container orchestration and hardware-level power management features, specifically Intel's Speed Select Technology (SST). It provides fine-grained control over CPU performance states on a per-core basis, allowing for dynamic adjustments that balance performance requirements with energy efficiency. By exposing power management capabilities within Kubernetes, it enables intelligent scheduling decisions that consider both workload demands and sustainability goals. And, finally, the Cluster Autoscaler [Kub25] is a Kubernetes component that dynamically adjusts the number of nodes in a cluster based on the resource requirements of running workloads. It adds nodes when there are pending pods that cannot be scheduled due to insufficient resources and removes nodes when they are underutilised, thereby optimising resource utilisation and energy consumption. This elasticity ensures that the infrastructure scales in response to workload demands, promoting both performance efficiency and sustainability.

Serverless computing

Serverless computing [LLW+23] allows developers to deploy code without managing the underlying infrastructure, with resources being allocated only when specific functions are executed. This on-demand resource provisioning minimises idle capacity, leading to potential energy savings. Platforms like AWS Lambda, Google Cloud Functions, and Azure Functions exemplify this approach, handling provisioning, scaling, and resource management, thereby enabling developers to focus on core application logic. However, while serverless architectures aim to enhance resource utilisation, their impact on overall energy consumption depends on various factors, including workload characteristics and system design. Research indicates that optimising serverless environments for energy efficiency can lead to substantial reductions in energy usage. For instance, the EcoFaaS [SIX+24] framework has demonstrated a 42% decrease in total energy consumption within serverless clusters by implementing energy-aware scheduling and resource management strategies.

Embracing cloud-native architectures contributes to sustainability by optimising resource utilisation and reducing carbon footprints. Key strategies include:

- **Resource Efficiency:** Designing applications to scale dynamically ensures that resources are allocated based on demand, minimising waste. This approach not only enhances performance but also reduces energy consumption.
- **Energy-Aware Scheduling:** Implementing intelligent schedulers that orchestrate the execution of serverless functions can minimise energy consumption. By aligning function execution with periods of lower energy costs or higher renewable energy availability, overall sustainability is improved [TPK23].
- **Observability and Monitoring:** Utilising tools like Kepler (Kubernetes-based Efficient Power Level Exporter) enables real-time monitoring of per-container energy consumption. This data empowers administrators (e.g. operators) to make informed decisions to achieve energy conservation goals.

Green Data centres

Green Data Centres [Car09] are facilities designed with a strong emphasis on minimising environmental impact through energy-efficient technologies and sustainable practices. These data centres implement various strategies to reduce energy consumption and carbon emissions, including:

- **Energy-Efficient Infrastructure:** Utilising energy-efficient hardware and optimising cooling systems to reduce power usage.
- **Renewable Energy Integration:** Powering operations with renewable energy sources such as solar or wind to minimise carbon footprint.
- **Waste Heat Reuse:** Capturing and repurposing waste heat generated by servers for heating buildings or other facilities [WPR+18]
- **Sustainable Building Practices:** Constructing facilities with eco-friendly materials and designs that enhance natural cooling and reduce energy needs.

By adopting these measures, Green Data Centres aim to support the growing demand for digital services while promoting environmental sustainability.

Green Mobile networks

In mobile networks, there is an accelerating trend to transition network functions, including parts of RAN and Core, to a cloud-native architecture in the current generation and the future 6G network as well. Since the introduction of the Service Based Architecture in 5G core network, all core network functions are migrating to cloud-native based and deployed into the virtualisation technology-based cloud infrastructure. In addition, with the more disaggregated and split architecture introduced into the radio access network (e.g., O-RAN), it's also expected that more and more centralised computation components in the radio access network will be deployed into the cloud infrastructure as cloud-native network functions. Cloud native network functions usually adopt a microservice based modular and elastic architecture which can adapt quickly to the running environment.

Microservice-based architecture provides opportunities to optimise resource usage which can lead to energy savings. This is achieved, for example, by allowing more fine-grained control over resource usage and scaling of individual services based on demand. Cloud platforms, such as Kubernetes, offer services to upper-layer applications like micro-service-based application through virtualisation technologies, such as containers. They create an abstraction layer that allows applications to access underlying hardware resources, such as CPU and memory, enabling resource pooling, elasticity, and other features.

Realising energy savings requires careful design, monitoring, and management of both the application architecture and the underlying infrastructure. In this context, research and development are ongoing to make cloud platforms more energy aware. Specifically with Kubernetes, a de-facto cloud-native orchestration platform, efforts are underway to incorporate energy-awareness into its operations throughout the entire lifecycle management of services, including deployment, execution, and scaling.

Energy-aware Kubernetes operations

Regarding energy-aware scheduling, efforts involve incorporating resource or energy metrics into scheduling decisions to reduce the energy consumption of the cluster. For instances, Trimaran is a multi-dimensional resource-aware scheduling framework for Kubernetes designed to enhance the default Kubernetes scheduler by considering additional resource metrics. It achieves this through a set of plugins that modify the scheduling process. One of these plugins is focused on load packing, which is a technique used to consolidate workloads onto a subset of nodes to optimise resource usage and potentially improve energy efficiency. PEAKS (Power Efficient and Adaptive Kubernetes Scheduler) is another scheduler designed to optimise aggregate power consumption of the entire cluster at the scheduling time.

PEAKS uses pre-trained Node Utilisation vs Power Consumption ML models to predict the energy consumption of workloads and schedules them on nodes that can handle the tasks most efficiently. It relies on Kepler (Kubernetes-based Efficient Power Level Exporter) to gather detailed power consumption data from nodes, providing insights into how much energy each node and workload consumes.

Apple's power-aware scheduling focuses on optimising energy efficiency by implementing power capping and load balancing. The scheduler uses power capping to limit the energy consumption of nodes or workloads, ensuring that they do not exceed predefined power limits. Load balancing is used to distribute workloads evenly across nodes, reducing the likelihood of overloading any single node and thus improving overall energy efficiency.

A Low Carbon Kubernetes Scheduler aims to reduce the carbon footprint of Kubernetes clusters by scheduling workloads in regions and data centres that use renewable energy sources or have lower carbon emissions. It may also consider energy prices and carbon intensity signals to make scheduling decisions that align with sustainability goals.

Regarding scaling, by design, cloud platforms often support auto-scaling, which can contribute to energy efficiency by automatically scaling in and out the number of active resources (such as containers/pods) based on current demand. During periods of low demand, resources can be scaled down, reducing energy consumption. Conversely, resources can be scaled up during peak demand to ensure performance, but without permanent over-provisioning. Vertical Pod Autoscalers in Kubernetes allow for automatic CPU and memory request and limit adjustment based on historical resource usage measurements. VPA Recommender, one of the main components of the VPA, can be replaced with a custom Recommender. CLEVER, a container-level energy-efficient VPA recommender for Kubernetes, utilises a custom Recommender to maintain the QoS and performance of workloads while adjusting cluster CPU frequencies. It dynamically recalculates CPU request recommendations for pods managed by the VPA based on the latest CPU frequency data. This approach ensures that workloads can achieve similar QoS by, for example, reducing frequencies to save energy while simultaneously increasing CPU allocations.

Another useful mechanism is to utilise the power capping/management together with performance consideration. For example, PRESTO [BS20] defines an Observe Decide Act (ODA) loop to manage power consumption and average latency of microservice-based workloads by considering all the network interactions between microservices in the cluster. Similarly, PEGASUS [LCG+14] uses request latency statistics to dynamically adjust server power management limits in a fine-grain manner, running each server just fast enough to meet global service-level latency objectives.

Power management in Kubernetes

In cloud infrastructure, the low-level hardware vendors like Intel and AMD have provided many power saving mechanisms such as frequency scaling, different P-state and C-state of CPU core, power capping, and some more advanced like Intel Speed Selection Technology. However, these mechanisms are controlled either at the hardware level or operating system level. The extra layer introduced by cloud platforms prevents applications from directly interacting with lower layers, which limits their ability to fully leverage power-saving mechanisms like deep-sleep and dynamic voltage and frequency scaling. To address these challenges, some techniques have been proposed to bridge this gap. Examples include the Intel Kubernetes manager and OpenShift pod-level power management. Kubernetes Power Manager is a Kubernetes Operator designed to expose and utilise Intel-specific power management technologies in a Kubernetes environment. It provides cluster users with a mechanism to request adjustment of worker node power management settings applied to cores allocated to pods. By doing so, the Kubernetes Power Manager bridges the gap between the container orchestration layer and hardware feature enablement, such as Intel Speed Selection Technology. This allows users to fine-tune core frequencies and set priority levels for individual cores or groups of cores.

There are also some previous works which utilise the microservice level fine-granular and dynamic power management to achieve optimised performance and power consumption balance. ANT-Man [HLL+20] proposes an auto power budgeting scheme for reducing the power coordination latency at the datacentre level. It can proactively determine the power budget tailored to each individual microservice. In addition, ANT-Man proposes a native and transparent power control scheme to overcome the power configuration latency for each microservice. It enables super-fast power budget enforcement with nanosecond-scale performance scaling [XHY+22].

5.4.2.2 Cloud/Edge continuum

The evolution of 6G networks introduces the need for a more dynamic and integrated approach to managing resources across the Cloud/Edge continuum. The Operator Platform serves as the foundation

for enabling this distributed computing paradigm by leveraging cloud-native principles, AI-driven orchestration, and sustainability-focused infrastructure management. The introduction of the far-edge domain—comprising end-user devices such as IoT gateways, eXtended Reality (XR) systems, and industrial sensors—adds new challenges and opportunities for efficient resource utilisation and network service continuity.

Edge computing brings computation, storage and networking capabilities, at the edge of the network, and in proximity to the data sources, thus contributing to lower latency experienced by the applications users. Furthermore, the **cloud-edge continuum** refers to the seamless interconnection and abstraction of computing power and storage capacity between the cloud and edge environments, aiming to an efficient operation of the deployed applications and the coordinated resource management, including energy consumption.

Preliminary studies on federated cloud–edge systems exist, and their evolution provides research opportunities for energy-aware cloud-edge computing continuum models. A comprehensive model is presented in [PTS+24], involving an application manager, the computing infrastructure, a network offloading manager, the energy provider policies & metrics, controller components, and the interconnection between them.

In particular, the application manager is processing different types of incoming workloads, based on their resource consumption, duration, network and energy characteristics, while utilising various hosting engines for the workload execution (such as containerisation platforms). Future work in this area involves the model development and formal reasoning over energy-aware continuum systems, followed by simulations that could enable the testing of autonomous management approaches.

The above model can be combined with other techniques, such as cloud bursting and edge caching. Cloud bursting is utilised when local resources are exhausted, and computation can be scheduled to other (more sustainable) locations, while edge caching is storing data in nearby edge resources (caches) to improve latency and speed-up execution. Intelligent placement decisions within the cloud–edge continuum can be made, balancing latency and task execution gains with overall energy efficiency and sustainability.

Cloud-Native Sustainability in the Operator Platform

A key driver for sustainability in 6G is the adoption of cloud-native environments, where lightweight microservices and Function-as-a-Service paradigms optimise resource usage. The NextG Alliance emphasises that 6G systems will feature cloud-native capabilities relying on cloud technologies, enabling seamless integration of compute and data resources across devices, edge, and cloud. This integration optimises performance and energy efficiency across 6G applications [6gw24].

Furthermore, the Hexa-X project [HEXAX21] jointly with [SGH+25] highlight the importance of designing 6G with sustainability at its core. It aims to reduce direct negative life cycle impacts of 6G systems and maximise positive environmental, societal, and economic effects in other sectors. This includes enabling emission reductions in 6G-powered sectors and improving energy efficiency.

The Operator Platform serves as a unified framework that manages resources spanning from centralised cloud infrastructures to edge and far-edge devices. This continuum enables seamless deployment and management of network functions and services across diverse environments. The 6G-Cloud project [6G-CLOUD25] exemplifies this by investigating and testing key technologies to achieve an AI-native and cloud-friendly system architecture atop the cloud continuum. This initiative focuses on integrating cloud resources from multiple stakeholders, allowing flexible and dynamic composition of network functions across various 6G segments in hybrid cloud settings.

The Operator Platform plays a crucial role in sustainability by:

- **Energy-efficient orchestration:** AI-driven automation predicts resource demands, enabling intelligent scaling of network functions across edge and cloud environments.
- **Carbon footprint reduction:** Optimised workload distribution minimises energy consumption by dynamically placing workloads in the most efficient locations.
- **Circular economy integration:** The reuse of underutilised computing resources in far-edge devices ensures longevity and reduces e-waste.

- **Scale-in and scale-out of the cloud application:** Optimising the number of cloud application instances in time of high load and in times of lower load contributes to the energy efficiency of the cloud-native system.
- **Renewable and clean energy integration:** Operators can further leverage renewable and clean energy sources (e.g solar, wind, hydrogen) to power the cloud, edge and far edge platforms.
- **Energy efficient hardware and computing** [EF23]

Challenges and Solutions at the Far Edge

The far-edge domain, encompassing end-user devices like IoT sensors and XR systems, presents unique challenges due to its heterogeneity and dynamic nature. Devices in this domain often have limited computational resources, intermittent connectivity, and varied security postures. Efficient orchestration of these resource-constrained devices can synthesise a "meta edge server," providing services at the very edge of the network. However, this requires addressing the inherent heterogeneity and uncertainty of far-edge computing [ASB24]. To manage these challenges, the Hexa-X project [HEXAX21] proposed extending End-to-End (E2E) orchestration functionalities to end devices at the far edge. This involves developing infrastructure management capable of handling the high volatility and random behaviour of these devices. The project also highlights the necessity of AI/ML methods to facilitate predictive orchestration, enabling the network to anticipate and adapt to changing conditions dynamically.

In summary, the Operator Platform in 6G networks aims to create a cohesive and sustainable ecosystem by integrating cloud-native architectures, addressing far-edge challenges, and implementing AI-driven orchestration across the Cloud/Edge continuum.

Service-based Architecture

With 5G some network functions became a cloud application in a cloud-native infrastructure following the Service-based Architecture (SBA) principles. This will continue in 6G.

Cloud native applications act in a client-server way. The service is onboarded but inactive. It consumes memory of the cloud resources. The service becomes active through a request via the Service-based Interface. Through this request certain parameter are given to the service process. The service will request the rest of the parameters and state information for the execution from a database (NDL reference). After execution the request, the service returns the results, and the changes of parameters or state information are written back to the database. The service becomes inactive. And once again, it consumes only memory of the cloud resources.

Services are represented via several service instances through scale-out and scale-in according to the load of requests. SBA and cloud-nativeness means the service and interface are stateless and not sticky this means – as described – parameters and state information are externalised in a database and the service is only active and consumes energy during execution. SBA offers also the possibility to move temporarily the services and service instances to more energy efficient cloud locations or to location with a lower carbon footprint, depending on the UCs. For example, the network services and their service instances can be moved to the edge in times of overload and can be concentrated with a reduced number of service instances in a central cloud in the rest of the time.

5.4.3 Security and Privacy in the Network

Modern digital security hinges on two critical functions: authentication (verifying identity and trust) and data protection (ensuring confidentiality and integrity). Symmetric cryptographic algorithms like Advanced Encryption Standard (AES) [DR02] are widely used for data encryption due to their low latency and computational efficiency, making them suitable for resource-constrained devices such as IoT sensors or embedded medical implants. While symmetric cryptography is generally favourable from a sustainability viewpoint, key management complexity, frequent session key generation, and scaling overheads in secure communication-intensive applications can challenge its sustainability. For establishing trust over untrusted networks, asymmetric cryptography (e.g., Rivest–Shamir–Adleman (RSA) [RSA78], Elliptic Curve Cryptography (ECC)) enables secure key exchanges and digital signatures, foundational to protocols such as Transport Layer Security (TLS) 1.3, Internet Protocol Security (IPsec), and 5G Authentication and Key Agreement (5G-AKA) [33.501]. Algorithms like RSA

(2048–4096-bit) and even ECC (256–521-bit) are computationally intensive. They require modular exponentiations or elliptic curve point multiplications, which consume significantly more energy than symmetric counterparts. In healthcare, for instance, secure transmission of real-time telemetry from wearable devices to hospital servers relies on robust asymmetric key infrastructures and mutual authentication. Similarly, in 5G networks, the 5G-AKA protocol integrates asymmetric cryptographic primitives to securely bind subscriber identities and derive session keys across diverse access technologies.

However, quantum computing poses a fundamental threat to asymmetric cryptographic schemes, particularly those based on number-theoretic assumptions like RSA and ECC. This has prompted the integration of Post-Quantum Cryptography (PQC) [Nat25], with lattice-based schemes (e.g., CRYSTALS-Kyber for key exchange and CRYSTALS-Dilithium for signatures emerging as National Institute of Standards and Technology (NIST)-recommended standards. While PQC ensures long-term cryptographic resilience, many proposed algorithms exhibit higher computational complexity, larger key sizes, and increased memory and bandwidth requirements. This leads to elevated energy consumption, a critical concern for sustainability in edge environments such as battery-operated medical devices, smart meters, or satellite-based systems with limited power budgets. Hence, sustainability-aware security mandates energy-efficient cryptographic design, context-aware protocol selection, and minimal re-authentication overhead. In mission-critical UCs like remote surgery or autonomous drone coordination, where secure, continuous, and low-latency communication is vital, balancing cryptographic strength with computational and environmental efficiency becomes imperative.

To distinguish between different concepts in the security realm, privacy problem is defined as in the followings: leakage of individual identifiable information by certain information exposure functions. This includes training an AI model on private data, and sharing the inference results to the public, e.g., an AI model in e-health applications trained on patients' information or training location-based services on real world traces of individuals. A few Privacy Enhancing Technologies (PET) have been developed to provide information-theoretic post-quantum proof against private data leakage. Among them, Differential Privacy (DP) [Dwo08] has been adopted widely due to its low computation cost and versatility. DP limits the disclosure of membership information about individuals in statistical data analyses. The societal impact of PETs could be further enhanced by introducing mechanisms that allows auditing its functionality. While applying PETs is essential in ensuring societal sustainability and complying to the regulations, in many cases it can increase the total energy consumption of the network and the particular service that requires private data. Considering energy consumption as a design criterion for developing a PET is a crucial step towards its energy sustainability.

5.5 *Eco-design rules and key technology enablers*

5.5.1 Eco-design rules for a sustainable 6G

The eco-design rules have been comprehensively listed in Section 3.1.1.2. However, it is important to note that societal and economic values must be considered alongside environmental values to ensure sustainable 6G design.

To deliver **societal value**, wide ranging user requirements must be central to development. This will ensure judicious use of energy and resources in design and development as well as higher user acceptance levels. Examples for such user requirements are, for example, cost reduction, technology acceptance through less impact (EMF, disruption through installation), quality improvements, and improvements to resilience and reliability.

To deliver **economic value**, we must be cognisant of the cost of introducing new technology. We must build on existing technology and standards to leverage investments. New design must intentionally minimise the need for new (i.e., virgin) materials and resources and enable a smooth transition to low carbon, high performing 6G systems that support new UCs. Furthermore, resilience and reliability can play an important role for certain businesses. Finally, the opportunity for new businesses, or even new business models plays a role in the context of economic values.

5.5.2 Key technology enablers for 6G

The identification of key technology enablers is required for the sustain design of any 6G solution. We define a key technology enabler as a technology able to contribute to the cost and energy consumption reduction of a solution.

In this paragraph we are listing a preliminary list of key technology enablers, from the state of the art.

Table 5-2: Key enabling technologies for access points

Key technology enabler or/and Key eco-design Rule	Environmental impact	Societal impact	Economic impact
LiFi	Reuse of the visible light of LEDs for a minimum energy consumption. Use of high energy efficient VCSELs in IR.	No EMF emission	Can be low cost with a massive deployment. Compatible with a FTTR technology.
OCC	Quasi zero energy system. Reuse of existing LEDs to minimise the carbon footprint.	New service offered to end-users: GPS for in-buildings.	New added value service offered at quasi zero energy.
FiWi	Extension of a fixed line. Energy savings through replacement of radio link.	No EMF emission	Compatible with a FTTR technology. Lower cost compared to fixed line / fibre.
FSO	Higher energy efficiency than radio-based backhauling solutions.	No EMF emission. Can be better secured than radio link.	Can be a solution for the defence or for rapid deployment at low cost (no civil works).

Table 5-3: Key enabling technologies for fixed access

Key technology enabler or/and Key eco-design Rule	Environmental impact	Societal impact	Economic impact
Bit interleaving.	Effective energy consumption reduction at the receiver side.	Lower equipment cost for end users	Can boost the market. Lower CAPEX and OPEX.
Towards dedicated resources (by adopting OE interfaces or all optical conversions).	Effective energy consumption reduction.	Lower equipment cost for end users	Can boost the market. Lower CAPEX and OPEX.
Relocate the ONT in the building to share the processing.	Effective reduction of the energy consumption per user. Reduced new material needs due to upgrade possibilities.	Lower equipment cost for end users	Accelerate the adhesion of new system versions, upgrade facilitation
Sleep mode on ONTs.	Effective energy consumption reduction.	Risk for acceptability if the “on” state takes too much time. Can be attractive in case of high energy cost.	Opportunity for new products.
Active power supply.	Can reduce the energy consumption when the ONT is off.	Transparent to the end user.	Opportunity for new products.

Optical cross-connect at the OLT rack level.	Can reduce the energy consumption when there is a low traffic.	Transparent to the end user.	Can be of interest for the operators.
---	--	------------------------------	---------------------------------------

Table 5-4: Key enabling technologies for Radio Access Network

Key technology enabler or/and Key eco-design Rule	Environmental impact	Societal impact	Economic impact
Cell sites			
Sleeping mode	Reduction of the energy consumption. Efficient in the rural part.	Risk for acceptability if the “on” state takes too much time. Can be attractive in case of high energy cost.	Energy cost reductions
Power shedding (dynamic adaption to the power of the antenna)	Reduce the energy consumption of the antennas. Efficient for fixed objects.	Risk for acceptability if the “on” state takes too much time. Can be attractive in case of high energy cost.	Energy cost reductions
Tracking optimised	Contribute to reduce the energy consumption. Tracking sopped for fixed IoT.	Not visible. Contribute to the CO ₂ emission reduction.	Energy cost reductions
Option optimisation (6, 7&, 7b, 7c)	Trade-off between the physical bit rate and the energy spent for a pre-processing. It can contribute to have a very low power consumption cross-haul.	Not visible. Contribute to the CO ₂ emission reduction.	Energy cost reductions
Micro Grid	Contributes to reduce significantly the electricity demand to the grid. Reduce the global national figure (x CO ₂ /kWh).	Potential energy cost reduction leading to lower connectivity prices. Improvements in resilience / reliability.	Energy cost reductions. Relax constraints in other sectors (transport, industry, ...) Improvements in resilience / reliability Boost the renewable energy market.
Liquid cooling	Reduces dramatically the energy consumption of the cooling.	Potential energy cost reduction leading to lower connectivity prices. Potential improvements in resilience / reliability.	Mandatory technology for e.g. sleeping regimes without impacting the reliability. Reduction of outages, improvements in resilience / reliability
AI for the EMS	Contributes to optimise the energy delivery and reduces the energy demand.	Potential energy cost reduction leading to lower connectivity prices. Improvements in resilience / reliability.	Booster for the market. Improvements in resilience / reliability
Storage	Provides a stabilisation of the electricity delivery and contributes to better exploit the local production.	Potential energy cost reduction leading to lower connectivity prices. Improvements	Improvements in resilience / reliability. Cost trade-offs to be investigated.

		in resilience / reliability.	
Front-haul / Cross-haul / Mid-haul			
Point to point	Point to point communication between the cell site and the vDU.	Not visible.	Exploitation of existing fibres.
WDM	Reduced use of material due to less fibre installations.	Reduced impact by construction / installation.	Less expensive solution with respect to the point-to-point solution. Protection can be proposed.
PON	Reduced use of material due to less fibre installations.	Reduced impact by construction / installation.	Extend the market of PONs.
Optical Ring	Low power consumption solution offering new functionalities with respect to PONs like a self-protection in bi-directional rings.	Reduced impact by construction / installation. Potential energy cost reduction leading to lower connectivity prices.	Provides new features like direct connections between antennas. Can contribute to minimise the traffic in central.
WDM TRX	Exploitation of the optical parallelism to reduce the energy consumption of TRX.	Can contribute to have a latency independent to the traffic load.	Can open new market perspectives.
Bit interleaving	Reduced processing needs towards reducing the energy consumption.	Potential energy cost reduction leading to lower connectivity prices.	Can be efficient in PON for the DS.
Towards dedicated resources	Can contribute to adopt the physical bit to the exact demand at the antenna side.	Not visible	Can reinforce the market.
vDU & vCU			
Sleeping mode	Effective reduction of the energy consumption. Efficient for sleeping data.	Potential energy cost reduction leading to lower connectivity prices.	Can be important for increasing the market.
Liquid cooling	See above	See above	See above
Data management helped by AI	Reduction of energy consumption for (operational) data transfer.	Potential energy cost reduction leading to lower connectivity prices. Improvements in resilience / reliability.	New features / business opportunities, booster for the market.
AI for Energy Management System (EMS)	Contributes to optimise the electricity delivery and reduces then the electricity demand to the grid.	Potential energy cost reduction leading to lower connectivity prices. Improvements in resilience / reliability.	Booster for the market. Improvements in resilience / reliability

Table 5-5: Key enabling technologies for converged fixed-mobile networks

Key technology enabler or/and Key eco-design Rule	Environmental impact	Societal impact	Economic impact
---	----------------------	-----------------	-----------------

Horizontal network	Leads to a minimum energy consumption through a massive suppression of all not required OEO conversions.	Ultra-low latency offered for real time services.	Opens new markets for in-building UCs.
OADM	Reduces the energy consumption of the node. Offers a transparent bypass. 10x more efficient compared to Ethernet switches. Long lifetime for the bypass part.	Contributes to offer ultra-low latencies.	Can open new features for end-users.
PON compliant	Propose a modular access node to pay as you need and at a minimum energy consumption.	Potential to contribute to end-user cost reductions through pay-as-you-need.	Can open new market opportunities. Retro-compatibility with Passive Optical LAN.
Optical regeneration	Can be more energy efficient than OEO regenerators and can support different bit rates.	Potential energy cost reduction leading to lower connectivity prices.	Can be used in different applications cases, offering new business opportunities.
Optical switches	Can reduce the energy consumption of the aggregation node.	Potential energy cost reduction leading to lower connectivity prices.	Can open the path to hybrid switches, offering new business opportunities or e.g. deterministic applications.

Table 5-6: Key enabling technologies for Metro & Core networks

Key technology enabler or/and Key eco-design Rule	Environmental impact	Societal impact	Economic impact
R-OADM	Contributes to reduce the size of the IP/MPLS segment routing and therefore the energy consumption of the node.	Contributes to reduce the end-to-end latency. Potential energy cost reduction leading to lower connectivity prices.	Widely deployed.
Optical exchange	Contributes to switch fibres at a high granularity. It contributes to reduce the energy consumption of the global node.	Contributes to reduce the end-to-end latency. Potential energy cost reduction leading to lower connectivity prices.	New potential markets with the adoption of multicore fibres.
Coherent technology	Enabler for a sensing technology that can contribute to reduce the energy consumption of the system by extending the lifetime.	Potential energy cost reduction leading to lower connectivity prices. Potential to reduce impact by extended lifetime	High potential market.
Network resources for AI	Required to optimise the resource allocation for the AI. By facilitating the exchanges in the backbone, we reduce its energy consumption impact on the ICT.	Contributes to reduce cost of the AI.	High potential market.

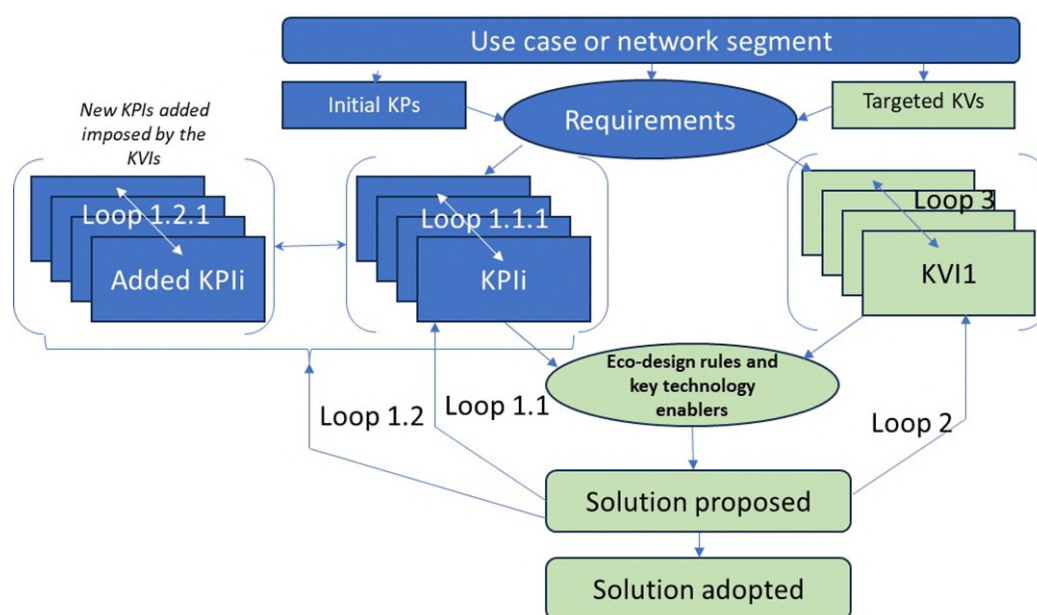
Table 5-7: Key enabling technologies for data centres

Key technology enabler or/and Key eco-design Rule	Environmental impact	Societal impact	Economic impact
Liquid cooling	See above	See above	See above
Management of Data	Contributes significantly to the energy consumption reduction of a data centre.	Important	Facilitated with a liquid cooling of the racks.
Optical switch for disaggregated servers	Can contribute to reduce the energy consumption for simple functions.	Not visible	To be defined.
OXC for easy data management	Contributes to a long-life cycle solution offering an energy consumption reduction.	Not visible	Existing market that can be reinforced.
Optical ring with native-Ethernet for ultra-low latency	Has the potential to reduce the energy consumption compared to an Ethernet based network.	Not visible	Potential new market.
Fast switch for load-balancing	Can contribute to reduce the energy consumption of electronic load balancers.	Not visible	Potential new market.

Per network segment, there is a need to quantify the gain of the different key technology enablers through a comparison to a reference scenario. In a second step, there is a need also to quantify the impact at the ICT level, through the adoption of macroscopic assumptions and a massive deployment of the technologies proposed. These key enablers represent a draft for further discussions and interactions to complete the lists per network segment and to position each technology enabler in a timeline to position them in a short, medium and

5.6 Preliminary methodology for the identification of an optimised solution

Figure 5-11 proposes a preliminary methodology for a sustainable design of a product, without considering the physical limits, or the interdependencies of different sub-part of a product.

**Figure 5-11: Methodology for the sustainable design of one solution**

The methodology starts with the relevant network segment or UC. Compared to existing methodologies for identifying solution requirements that build on KPIs, in the context of a sustainable design, KVIs reflecting environmental, societal and economic criteria need to be reflected as well when building the set of requirements. While KPIs typically are quantifiable, KVIs may be quantitative or qualitative, and they furthermore may have different time scales to be reflected (short- to long-term). KVIs may further impose the definition of additional KPIs.

The solution design, reflecting the KPIs and KVIs, needs to adopt the eco-design rules as outlined in Section 3.1.1.2, and build on the identified technology enablers as described in Chapter 5. The identified solution (set) will then undergo evaluation with respect to the identified KPIs and KVIs. The evaluation outcome may then lead to a reconsideration of the applied technical enablers in case KPI or KVI targets cannot be achieved, or to a revision of the KPIs and KVIs, e.g., regarding the mapping between KVIs and KPIs. Multiple such loops may be required, from the perspective of sustainability improvements at the network (technology enabler) as well as the UC level, towards an E2E optimum.

In summary, it becomes clear that essential components for this methodology are to have:

- An appropriate list of eco-design rules
- Key technology enablers that contribute to the desired performance and sustainability values
- Key Value Indicators that are as concrete as possible.

5.7 Conclusion

This chapter first presents a list of requirements for both 5G and 6G, positioning each proposed technology within the broader scope of 6G. It further outlines essential eco-design principles to ensure that the fundamental rules for optimised solution design are not overlooked. Furthermore, it identifies the key technology enablers highlighted in the current state of the art, which should be further developed and complemented. Finally, the chapter proposes a structured methodology for the sustainable design of new solutions, combining eco-design rules and technology enablers to guide the process towards an optimised outcome.

The provided information is essential to conduct the further work in the SUSTAIN-6G project, in particular for the following Work Packages (WPs):

- WP 3 “Sustainable 6G Technology” on the 6G technology enablers
- WP 4 “6G Solutions for Sustainable Applications” on the vertical UCs implementing 6G technology
- The interworking between WPs 3 and 4 towards implementing a recursive approach (following the methodology outlined in Section 5.6) for optimising the E2E sustainability effects
- WP 5 “Proof-of-Concept and E2E integration testing” on proving the sustainability effects of the developed 6G enablers and their integration to vertical UCs.

6 Use Case-driven sustainability needs and technical requirements

6.1 *Broad applicability of 6G for sustainability in vertical sectors*

This brief introduction of the aforementioned vertical sectors — agriculture, smart grid, and telemedicine — simplifies their needs and requirements to certain capabilities only and will be expanded on in the subsequent sections of this document. However, UCs across a broad array of vertical sectors demand a comprehensive range of communication technology capabilities, as outlined in the IMT-2030 framework (International Telecommunication Union, 2023). These include, among others: coverage, throughput, reliability, security, energy efficiency, and ultra-low latency. These capabilities collectively enable addressing diverse goals and values across the societal, environmental, and economic dimensions of sustainability. Beyond the examples discussed, numerous other verticals, such as smart cities, transportation, automotive, railways, education, manufacturing, media and entertainment, have their own unique demands and contributions to sustainability. Insights gained from detailed analyses of UCs in any vertical sector, focusing on their sustainability-related technical enablers and impacts, can inform the development of solutions applicable to other vertical sectors. This extrapolation underscores the role of 6G as both an enabler and a driver of sustainability, balancing its first-order effects with its second-order effects.

Addressing sustainability at scale thus requires a holistic perspective that not only considers the specific needs of individual vertical sectors but also integrates these needs into a unified approach that leverages the full spectrum of advanced communication technologies. This ensures that 6G networks serve as a transformative force across all domains, concurrently driving innovation and sustainability.

On the opportunity of the 3GPP Stage 1 workshop on IMT2030 UCs, the 6G-IA consolidated and presented a coherent view on 6G UCs based on ongoing work of SNS JU projects. For 6G to meet its full potential, sustainability must be embedded as a core pillar in standardisation efforts. This includes minimising the first order effects of ICT operations (“Sustainable 6G”) and maximising the technology’s positive contributions across other sectors (“6G for Sustainability”). Emerging concepts like Key Value Indicators (KVI) offer a structured way to assess and guide these impacts. The 6G-IA recommended that 3GPP SA1 activities incorporate KVI into their evaluation of UCs and requirements, ensuring that sustainability is measured, prioritised, and translated into meaningful design choices. In the context of deriving needs and requirements from a broader set of UCs the following paragraphs summarise the 6G-IA contribution to 3GPP [Wik24].

Immersive experiences blur the boundaries between physical and digital spaces, enabling richer, more intuitive ways to collaborate, learn, and interact. These UCs span mixed reality for remote teamwork, virtual training and operations in industry, immersive education and gaming, and real-time content creation. Together, they position 6G as a key enabler of human-centric, high-performance digital environments that are responsive, engaging, and accessible on the move.

6G will empower **collaborative robotics**, enabling machines to communicate, coordinate, and make decisions in real time. Key capabilities include cooperating mobile robots for agile industrial tasks, autonomous agents that fuse AI with network intelligence for independent action, and mesh embodied intelligence, where distributed robotic systems dynamically self-organise to solve complex challenges. Together, these advancements will enable more flexible, efficient, and resilient automation across sectors like manufacturing, construction, and logistics.

6G will enable a **digitally aware physical world** by integrating advanced sensing, precise positioning, and AI-driven analytics into the network fabric. This will support real-time 3D mobility for autonomous systems, ensure safer and more efficient operations through situational data sharing, and enhance public safety via intelligent crowd and event monitoring. With capabilities like environmental radio sensing, 6G becomes a powerful tool for monitoring and responding to conditions in the physical world supporting smarter, more responsive environments across urban, industrial, and rural settings.

Digital twins are dynamic virtual counterparts to real-world systems that enable continuous monitoring, simulation, and control. 6G technologies will enable real-time twins for managing industrial operations or entire urban infrastructures, seamless cloud-to-edge integration for scalable and responsive

performance, and smart maintenance twins that enable predictive upkeep and support public protection and disaster response. Through high-fidelity, ultra-responsive digital replicas, 6G paves the way for smarter, safer, and more resilient physical environments.

6G envisions a **fully connected world** where connectivity is universal and sustainable. It will bring resilient broadband access to underserved and remote regions, ensuring critical communication even in emergencies. By promoting digital sobriety, 6G supports responsible use of digital resources, prioritising efficiency. It supports environmental stewardship and food security through real-time monitoring and precision agriculture. Autonomous supply chains and virtualised device functions will boost logistics resilience and operational flexibility, anchoring 6G as an enabler of inclusive, sustainable digital infrastructure.

6G will be supporting the creation of **trusted environments** that place human well-being, safety, and inclusion at the forefront. It will enable human-centric networks designed for applications like personalised healthcare and intelligent safety systems at public gatherings. In industrial settings, sensor-based networks will ensure real-time monitoring to prevent accidents and enhance workplace safety. Advanced in-vehicle connectivity will support automotive safety, supporting features like predictive hazard detection and seamless communication. Collectively, these capabilities reinforce trust, reliability, and human-centred innovation across critical sectors.

From an **operational point** of view, 6G networks will act as a flexible, intelligent backbone for a diverse array of services by embedding adaptability and intelligence directly into their architecture. Key to this is the use of unified interfaces that enable seamless interoperability across cloud, communications, and application domains. With intent-based management, network operations become more automated and user-driven, while native AI/ML integration empowers real-time analytics and decision-making. Support for TN/NTN convergence ensures resilient, wide-reaching connectivity, and built-in migration tools guarantee smooth, uninterrupted transitions from 5G to 6G.

The table below summarises some of the most important key performance indicators per UC group reported by the 6G-IA (Note that some values have been omitted).

Table 6-1: Important KPIs per UC group reported by the 6G-IA

UC Family	Key KPIs	Typical Target Values
Immersive Experience	User-experienced data rate, Area traffic capacity, E2E latency, Positioning accuracy	- Data rate: 250 Mbit/s (DL/UL) - Area traffic: 20 Mbit/s/m ² - Latency: <10 ms - Positioning: <10 cm
Collaborative Robots	Data rate, Area density, Mobility, E2E latency, Reliability	- Data rate: <10 Mbit/s - Area density: <0.1-1 Mbit/s, 1 robot/m ² - Latency: <0.8 ms - Reliability: 99.999%-99.999999%
Physical Awareness	Data rate, Location accuracy, Mobility, E2E latency, Reliability, Availability, Coverage	- Data rate: 1-10 Mbit/s - Location: 1 m - Mobility: up to 300 km/h - Latency: 1-20 ms - Reliability: 99.99% - Availability: 99.9%
Digital Twins	Area density, E2E latency, Reliability, Coverage, Location accuracy	- Area density: 1-10 Mbit/s/m ² - Latency: <1 ms - Reliability: 99.99999% - Location: ≤0.1 m
Fully Connected World	Data rate, E2E latency, Reliability, Flexibility, Availability, Coverage	- Data rate: 0.1-25 Mbit/s (DL), 2 Mbit/s (UL) - Latency: 10-100 ms - Reliability: 99.9-99.999% - Availability: 98.5%
Trusted Environments	Area density, E2E latency, Reliability, Location/positioning accuracy	- Area density: 1-10 Mbit/s/m ² - Latency: <0.1-1 ms - Reliability: 99.9-99.999% - Location: <0.001-1 m

6.2 *SUSTAIN-6G vertical overview*

As industries continue to evolve through digital transformation, the role of advanced connectivity becomes increasingly critical. While 5G laid the groundwork for enterprise-grade services, many industrial sectors still face challenges in accessing the high-performance, wide-area infrastructure needed to fully realise these benefits. This is particularly true for sectors that depend on national-scale networks rather than localised private solutions.

In this context, three vertical sectors have been selected for deeper exploration: smart grids, agriculture, and telemedicine. These sectors are not only demanding in terms of connectivity requirements, but also hold immense potential to deliver societal, environmental, and economic value. They address fundamental human needs—energy, food, and healthcare—and represent areas where 6G technologies are expected to have transformative impact. Smart grids can enhance energy efficiency and resilience; agriculture can benefit from precision farming and resource optimisation; and telemedicine can expand access to quality healthcare through ultra-reliable, low-latency communication.

This section introduces each of these verticals, providing a general overview and outlining the key stakeholders involved. In the following section, we will delve into three representative UCs per vertical, selected to highlight the diverse and complementary ways in which 6G connectivity can support sustainable development and improve quality of life.

6.2.1 Agriculture

6.2.1.1 *Vertical Overview*

Agriculture is an activity that has accompanied mankind since its beginnings and has evolved over time. Like other industries, it has gone through a period of automation (cf. Figure 6-1), but this has mainly focused on physical tasks, with machines facilitating work in the field. However, it is only relatively recently that technology has been incorporated to support decision-making, allowing for more accurate and efficient crop management.

To meet the growing demand, agriculture in 2050 will need to produce nearly 50% more food, feed, and biofuel than it did in 2012. Projections for 2050 also indicate increasing pressure on agricultural land, water, forests, capture fisheries, and biodiversity. To address the rising demand for food and tackle the scarcity of natural resources, agriculture has started to adopt more efficient and sustainable approaches.

Agriculture is a critical sector in achieving sustainability goals, as it directly affects food security and has environmental impacts. The demand for sustainable agricultural practices has been growing, being driven by global challenges such as climate change and the increasing population. In this context, the use of advanced technologies such as 6G can revolutionise the agricultural sector by enhancing productivity and reducing environmental impacts. Utilising 6G technologies for agricultural applications involves leveraging resilient connectivity, low-latency communication, and cutting-edge technologies like edge computing to create more efficient, intelligent and resource-conscious agricultural practices. By enabling real-time data collection and analysis, 6G can support optimising water consumption, monitor crop health, and enable precision farming, which consequently contributes to sustainability goals.

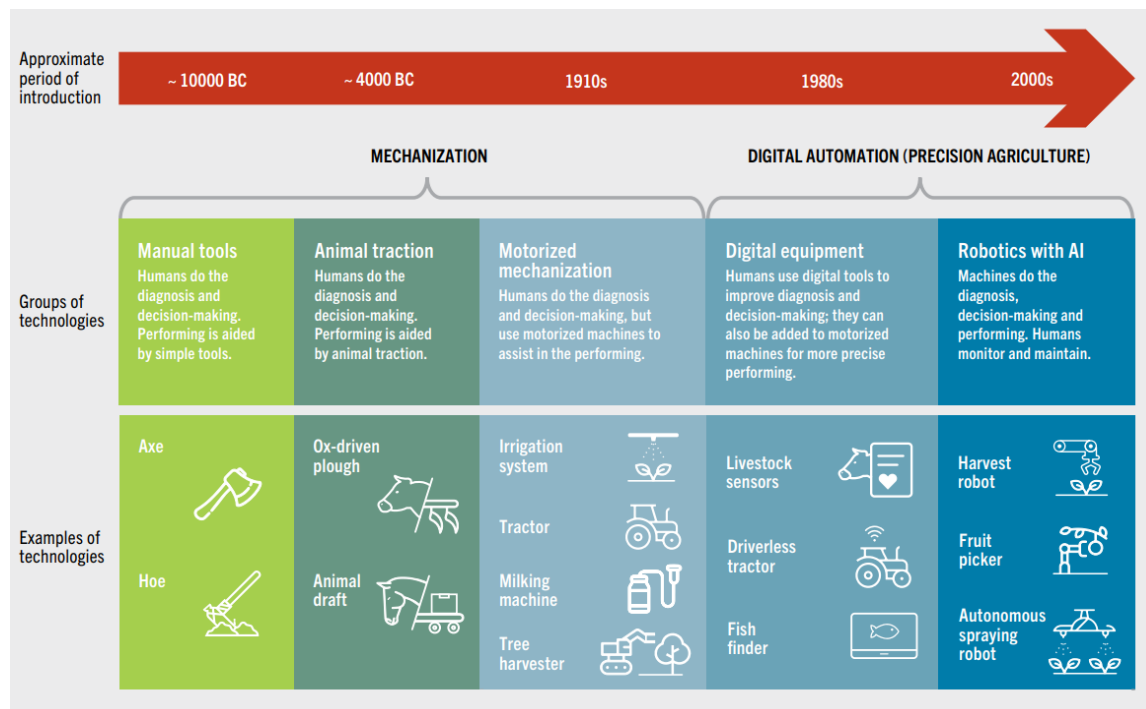


Figure 6-1: Evolution of agricultural automation (FAO22)

The ISPA provides the following definition of precision agriculture: “Precision Agriculture is a management strategy that gathers, processes and analyses temporal, spatial and individual plant and animal data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production” [Isp24]. Precision agriculture emerges as a key solution, enabling more accurate and localised crop management. Through the use of technologies such as sensors, satellite imagery and global positioning systems (GPS), farmers can monitor soil conditions, weather and crop status in real time. This information enables informed decisions to optimise the use of water, fertilisers and pesticides, reducing waste and minimising environmental impact. By combining agronomic knowledge with technological tools, precision agriculture not only improves productivity, but also contributes to more sustainable resource management, which is essential to ensure food security in a context of a growing population and increasingly limited resources.

The first iteration of precision agriculture is to collect data from sensors, which can be deployed in the field (weather or soil) or on agricultural machinery, Unmanned Aerial Vehicles (UAVs) or Earth Observation (EO) satellites. The next step is processing, turning all the data collected into useful information that can be used to take appropriate action. An available and reliable communications network, capable of both data transmission and data processing, is essential for this proposal.

Precision agriculture technologies help farmers manage inputs more effectively, resulting in improved yields while conserving resources. 6G enables real-time data collection from IoT sensors, drones, and satellites, which can help optimise irrigation, fertilisation, and usage of pesticides, hence managing consumption of resources. [AKN20] provides an overview of the potential role of 6G technologies in revolutionising sectors such as agriculture by enabling technologies like IoT, edge computing, and AI applications.

With ultra-reliable and low-latency communication enabled by 6G, agricultural robots and drones are expected to be able to support farmers in a wider scope of tasks like planting, harvesting and crop monitoring, in addition to the ability to introduce autonomous farming vehicle in a wider range, which leads to improved productivity. [SBC20] provides a vision of the 6G networks while highlighting the potential for automation in various sectors including agriculture. It also emphasises the role of 6G in supporting autonomous systems and smart agriculture through low-latency communication and enabling real-time operation of autonomous agricultural machinery.

The benefits of precision agriculture go beyond improving productivity and efficiency, smart agriculture aims at sustainably increasing food security and incomes, and adapting and building resilience to climate change, while capturing potential mitigation co-benefits. Agricultural automation is highly relevant to several Sustainable Development Goals (SDG), including SDG 1 (No Poverty) and SDG 2 (Zero Hunger). Increasing automation in agriculture globally can also help advance SDG 9 (Industry, Innovation and Infrastructure), which emphasises the need to build technological capacity, promote research and innovation, especially in low-income countries. In the same way, by overcoming the barriers to adoption, automation can help to bridge the technology divide and drive progress towards SDG 5 (Gender Equality), SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities). It can play a role in contributing to SDG3 (Good Health and Well-being) through its ability to improve working conditions and food quality. Ultimately, the effective implementation of automation solutions that promote environmental sustainability can support progress towards SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life below Water) and SDG 15 (Life on Land).

6.2.1.2 Agriculture Stakeholder Landscape

There are two main groups of stakeholders common for the UCs, both working together to improve the efficiency and sustainability of agricultural activities by leveraging the power of data and technology:

- Producers (farmers and growers)
- Researchers, data scientists, and agronomical advisors

Producers (farmers and growers): Are the main users of the UCs. The application of the technology proposed in the UCs and the knowledge of the crops will lead to improvements in the productivity and sustainability of their farming practices.

Researchers, data scientists, and agronomical advisors: This group provides research, advice and technical solutions to optimise farming practices based on data collected in the field.

6.2.1.3 Selected Use Cases

The three selected UCs address some of the current challenges and opportunities in agriculture. The limited coverage and capacity of networks in rural areas, is a challenge for automation and makes it difficult to have real-time data transmission and processing. Data collected by sensors at weather and soil stations, and the integration of sensors into agricultural machinery, enable continuous monitoring of soil, crop and environmental conditions. This enables more accurate application of inputs and proactive field management. 6G provides the right environment for real-time data exchange and advanced information processing. Technology solutions that combine connectivity with advanced processing capabilities can not only optimise use of resources like water, agrochemicals and energy, but improve machine performance, reducing waste and environmental impact. This can result in more sustainable and resilient farming practices.

UC 1: Connectivity on demand: temporary connectivity solutions in rural areas

This UC addresses the challenging connectivity conditions in rural areas, where connectivity solutions suffer from being unreliable and hence hindering the adoption of smart agricultural technologies. This UC imagines a portable solution that can provide temporary networks, enabling seamless, and timely connectivity. This allows farmers to adopt smart agricultural technologies such as connected sensors and autonomous farming which can improve their access to real-time data and market resources.

UC 2: Task offloading to the edge for critical and resource-demanding tasks

This UC addresses the challenging requirements of some agricultural UCs when it comes to computational resources, some applications such as AI-based crop analysis and predictive modelling are considered resource-demanding tasks, which makes processing them locally energy-intensive. Utilising edge computing capabilities as one of the pillars of 6G technologies to enable task offloading to the edge, where computationally heavy tasks can be processed near the data source, can contribute to lower-latency communication while reducing the consumed energy. Agricultural applications like real-time crop monitoring and predictive analysis of data can benefit from edge computing technologies.

UC 3: Agriculture data vs information

This UC addresses the challenge of providing useful, real-time information to support decision-making in crop management. With access to up-to-date data, productivity can be increased and resource use optimised. To achieve this, it combines data from various sensors and sources. This is achieved by combining data from different sensors and sources. 6G technology will enable this data to be collected and processed in real time, which is critical for tasks such as disease detection and control (where time is a key factor).

These UCs were selected because they align with the broader vision of sustainable agriculture by leveraging 6G technology to manage resources consumption, optimise production processes, and improve connectivity and data processing capabilities in rural areas. They are crucial elements for advancing the digitisation of agriculture and achieving sustainability goals in the sector.

6.2.2 Smart Grid

6.2.2.1 Vertical Overview

A smart grid is an advanced and modernised electrical distribution grid that utilises digital technologies and two-way communication to improve the efficiency, reliability, and sustainability of electricity generation and distribution. Unlike traditional grids with one-way electricity flow, smart grids actively manage energy through real-time data from both suppliers and consumers. This is essential due to the growing integration of renewables and intelligent loads that decouple supply from demand.

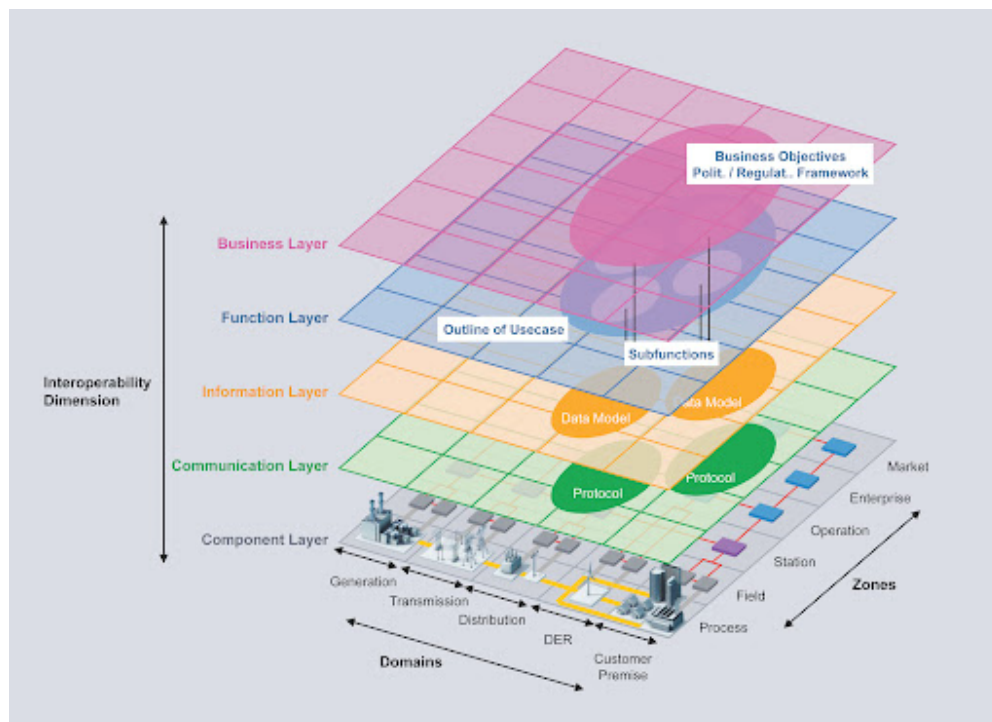


Figure 6-2: Smart Grid Architecture Model (SGAM) [Cen14]

Information and Communication Technology (ICT) is fundamental to smart grids, providing the infrastructure for two-way data exchange and control. This is illustrated in the Smart Grid Architecture Model (SGAM) developed by the CEN-CENELEC-ETSI Smart Grid Coordination Group [Cen14], shown in Figure 6-2. SGAM models interactions and information exchange among entities in the smart energy domain, helping stakeholders to coordinate effectively. The communication layer in SGAM, highlighted in green in Figure 6-2, is critical for ensuring interoperability across domains and aligning technical components with business objectives.

With the emergence of the smart grid, ICT has expanded to integrate not only high- and medium-voltage, but also low-voltage networks. Devices like smart meters, sensors, and control units now collect real-time data on energy usage and grid conditions, transmitting it securely to centralised control

centres and distributed intelligence nodes. This enables advanced analytics, automated decision-making, and coordinated control across the grid.

Smart grids rely on a wide range of communication technologies and protocols. Field devices use both wired and wireless protocols such as Modbus, Distributed Network Protocol 3 (DNP3), International Electrotechnical Commission (IEC) 61850, and IoT standards like Bluetooth Low Energy, ZigBee, Z-Wave, Wi-Fi, and Ultra-Wideband (UWB). They utilise both public and private networks including 3G, 4G, 5G, Long Range Wide Area Network (LoRaWAN), Narrowband Internet of Things (NB-IoT), and utility-owned fibre-optic and wireless backhaul systems. This diversity is essential for achieving real-time connectivity and coordination throughout the grid.

6.2.2.2 Smart Grids Stakeholder Landscape

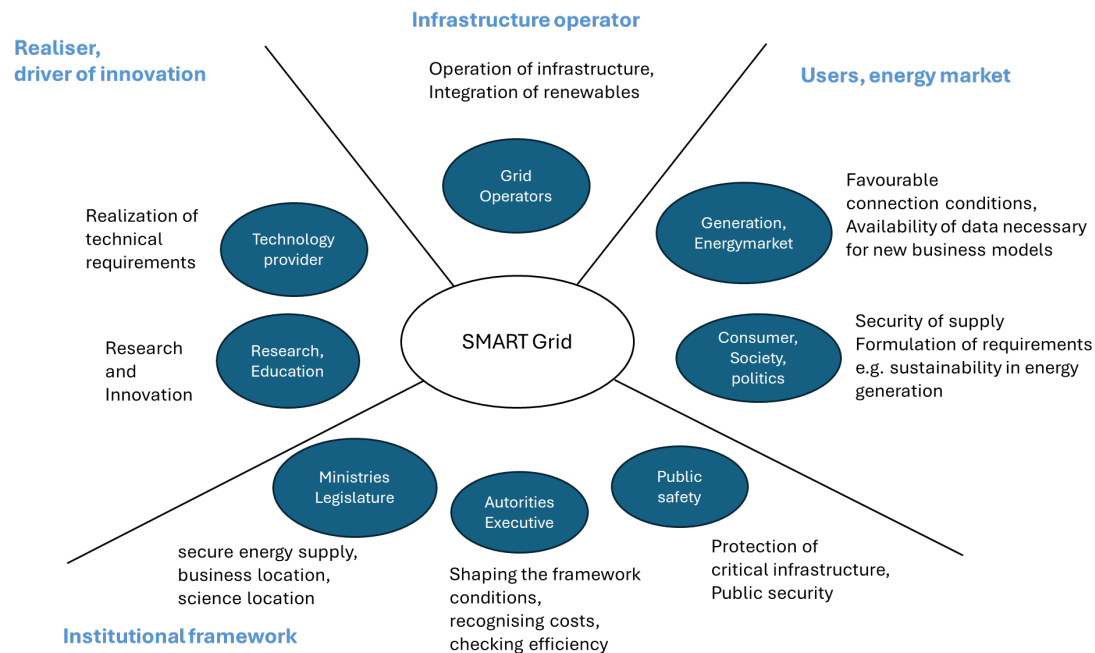


Figure 6-3: Smart Grid Stakeholder landscape (adapted from [BML+19])

According to the RASSA project [BML+19], the smart grid stakeholder landscape includes four groups, as shown in Figure 6-3:

- The **institutional framework** sets legal and regulatory conditions for grid operation and ensures the safe management of electricity as critical infrastructure.
- **Infrastructure operators**, including electricity and ICT providers, manage decentralised energy integration and represent sector interests to policymakers.
- The **users and energy market** group includes producers, traders, and increasingly prosumers, who interact with the grid and market through flexible consumption and generation.
- **Implementers and innovation drivers** consist of technology providers and research institutions that develop and advance smart grid components and solutions.

6.2.2.3 Selected Use Cases

Presented here are three UCs of 6G application in the context of future energy systems:

- **UC1: 6G-enabled grid balancing services from distribution grid assets** leverages 6G's low latency and high bandwidth to coordinate distributed energy resources in real time, enabling their participation in grid balancing and electricity markets.
- **UC2: Resilient grid section operation** enhances grid resilience by using 6G to enable real-time fault detection, adaptive reconfiguration, and stable operation during disruptions.
- **UC3: Joint planning of 6G and smart grid infrastructures** lays the foundation by ensuring both systems are developed in tandem for maximum synergy.

Together, these UCs form a strategic framework that supports innovation, improves efficiency, and ensures reliable energy system performance in the face of future demands.

6.2.3 Telemedicine

6.2.3.1 Vertical Overview

Telemedicine is a method for the provision of medical services that relies on a communication medium of any sort in order to provide alternative, remote or de-personalised services which would otherwise typically require physical co-location of the provider and recipient of that service. Early forms of this practice date back to the invention of radio, with remote diagnosis or treatment directions supplied to ships on the high sea and in battlefields since WWI. The advent of digital communication networks and widespread Internet adoption means that remote consultation and diagnosis have become widely available. The anticipated improvement of network speed and latency for 5G and 6G networks is also fuelling expectations and R&D in advanced practices, such as tele-surgery.

A strong support from the wireless network is a pre-requisite for services like remote medical consultations, diagnoses and treatments, through video calls or specific platform platforms toward rural or underserved areas. Other benefits of robust network support include the possibility to share knowledge by providing a collaborative shared platform where doctors, surgeons, specialists, and trainees can participate. This allows for allowing instances of interregional cooperation which would have been otherwise hindered by the need of mobility. The patient's treatment can be enhanced by engaging them through apps and portals where they can actively participate in treatment plans. The elimination of the need for patient mobility not only saves economic costs but also saves effort when treating patients with deambulatory restrictions. Many challenges need to be tackled: privacy and data security, lack of technology access (for the elderly, rural areas, or a lack of internet-enabled devices in the population) and the definition of a proper regulatory framework.

The telemedicine/eHealth vertical aims to provide high-quality medical services to as wide a target population as possible, circumventing accessibility barriers such as geographical distance, technology literacy and confidentiality/trust concerns by the intended user base. It also aims to exploit the power of Artificial Intelligence for the reliable and affordable development and use of medical data models, to be used as advanced consulting and diagnostic tools.

6.2.3.2 Vertical Structure

Telemedicine is structured around the various stakeholders, technologies, and services that cater to its characteristics and specific needs. Regulatory bodies, typically in the form of government and international regulatory bodies and the various products of their function are also an integral part of the vertical, mainly due to the sensitive nature of medical data and the associated challenges arising from their gathering and processing.

Stakeholders

- Healthcare Providers – Hospitals, clinics, physicians, nurses, telemedicine providers
- Payers & Insurance – Health insurance companies, public health systems, reimbursement services
- Pharmaceutical & Life Sciences – Drug manufacturers, biotech firms, research labs
- Medical Device Companies – MRI machines, wearables, diagnostic tools
- National & International Regulatory & Legislative Bodies
- Patients & Consumers – End users of healthcare services, patient advocacy groups
- Network Infrastructure Providers & Operators
- Medical SW & applications suppliers, consultants and certification agencies.

Technologies & Solutions

- Core networks and RANs, UE and network edge components
- Electronic Health Records (EHRs) – Patient data management
- Telemedicine & virtual care – Remote consultations, remote patient monitoring
- Healthcare AI & analytics – Predictive diagnostics, patient risk assessment

- Medical IoT & Wearables – Smartwatches, glucose monitors, connected pacemakers
- Cybersecurity & compliance with confidentiality regulations.

Services & Operations

- Patient Care & Hospital Management – Scheduling, workforce management
- Medical Supply Chain – Procurement, logistics for pharmaceuticals and devices
- Public Health & Research – Disease tracking, epidemiology tools
- Healthcare Marketing & Patient Engagement - Customer Relationship Management for patient outreach, chatbots

Challenges & Regulatory Considerations

- Regulatory Compliance – HIPAA (Health Insurance Portability and Accountability Act, USA), European General Data Protection Regulation (GDPR) [R2016/679], drug approvals
- Data Privacy & Security – Protection of patient health information
- Data Federation Issues – Integration across different EHR and medical systems

6.2.3.3 *Selected Use Cases*

The selected UCs address some of the current challenges and opportunities in telemedicine, such as the current lack of low-latency and guaranteed QoS that is needed for reliable telesurgery procedures. Also, they demonstrate that the current level of AI exploitation needs to expand and evolve for effective supervised patient recovery or rehabilitation and for properly supervised ML-generation and use of diagnostic models. Finally, the security and privacy of patient health records, as well as properly attested data ownership, needs to be addressed, if telemedicine applications are to gain widespread acceptance from a trusting public. The end result of addressing these challenges is wider availability of high-quality health services, overcoming location and confidence-in-technology obstacles. Economic activity that is directly or indirectly related to telemedicine is also expected to expand, increasing income and employment for the vertical's stakeholders.

The first UC (“Concurrent Preoperative Surgical/Engineering Planning”) proposes a platform for remote concurrent preoperative planning. The application involves the design and production of custom surgical tools via the use of shared medical imagery and 3D modelling. Given the high specialisation involved, the intention is to leverage the latest 3D input technologies and 3D visors for a more immersive perception and manipulation of the virtual surgical field.

The second UC (“Remote Rehabilitation Assessment”) proposes a remote rehabilitation framework leveraging on AI for tracking and evaluating the patient's motions and on XR for a more immersive perception of the rehabilitation exercise. AI will also provide counselling when problems are identified or alert a rehabilitation expert if serious or unidentified problems occur.

The third UC (“Privacy-Aware Medical Data Federation with 6G-Assisted Trust Establishment”) aims to provide a trusted execution environment for processing and management of medical data, which is based on the network instead of user applications and end devices for the supply of the components and protocols that ensure user consent, data privacy and security, data provenance. In this manner, the added value from data processing is always under control of the actors participating in telemedicine practices.

These three UCs were selected because they demonstrate how an advanced network can increase the scope, quality and economic/societal penetration of telemedicine applications, which are viewed as important for the realisation of several of UN's Sustainable Development Goals, such as good health and well-being, reduced inequalities and sustainable cities & communities.

Towards the realisation of these goals, the selected UCs make specific requirements from future digital networks. Thus, the first UC will stress a mobile network because the very specialised application requires a fluid collaboration between the participants, while the second application will also require a larger bandwidth for managing the AI application, this being more ‘market-oriented,’ toward a larger number of patients. The third UC will require direct network involvement and support towards the target of a comprehensive trusted execution environment for medical data.

6.3 SUSTAIN-6G Use Cases

In this section, we present nine UCs that explore the application of 6G technology to enhance sustainability in the selected verticals. Each UC follows a structured template to ensure consistency and comprehensiveness in documenting the state of the art, sustainability analysis and technical requirements. The template is shown in the following table:

Table 6-2: Use case template

Section Name	Content
UC overview	Description: pre-conditions, post-conditions, objectives Rationale: assumptions, values, motivations Need: benefits, why this UC Challenges: operational problems Societal Goals: Sustainable Goals, societal challenges Target Scenario: desirability, driving values and principles
State of the Art	Current Solutions: existing potential technical options Shortcomings of existing solutions Currently unachievable goals/needs
Impact and Sustainability Analysis	First and second order sustainability benefits and costs for the environmental, societal and economic plane.
Technical requirements and gaps	Technical requirements for different UC scenarios Initial gap analysis on the requirements

6.3.1 Agriculture UC1: Connectivity on Demand: Temporary Connectivity Solutions in Rural Areas

6.3.1.1 Use Case description

The agricultural sector is increasingly adopting technologies to boost productivity, efficiency, and sustainability. This shift demands reliable, high-speed, low-latency connectivity—especially in rural areas where such infrastructure is often lacking. Poor connectivity limits the potential of smart agriculture and hinders innovation.

This UC proposes a temporary, on-demand connectivity solution for areas without 4G or 5G coverage. It involves plug-and-play devices that can be integrated into agricultural machinery, operating independently of existing infrastructure. The goal is to ensure uninterrupted connectivity in remote fields, enabling continuous and efficient farming operations. Figure 6-4 schematically depicts the UC.

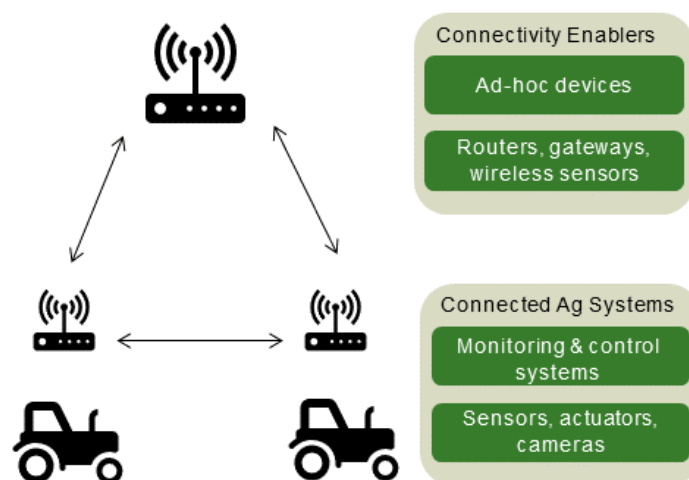


Figure 6-4: Connectivity on demand use case description

Why is this use case needed?

This UC addresses the rural connectivity gap—a major barrier to adopting smart farming technologies. By enabling reliable, on-demand connectivity, it allows farmers to use modern tools without interruption, leading to:

- Higher productivity through real-time monitoring and decision-making
- Improved efficiency by minimising downtime
- Greater sustainability via precision farming and resource optimisation

The main challenge is the lack of stable connectivity, which limits the use of IoT devices and coordinated machinery operations, such as harvesters and tractors working together. These applications require continuous communication to function effectively and pave the way for future automation.

Temporary, on-demand connectivity reduces the need for permanent infrastructure in areas where it's not always required. This approach saves energy, labor, and resources, aligning with UN SDGs 9 (industry, innovation, infrastructure) and 15 (life on land).

The targeted scenario (where we want to land)

The target is to create a scenario where farmers in rural areas have seamless access to reliable connectivity enabling them to fully utilise smart agriculture technologies, leading to uninterrupted field operations and enhanced data utilisation with the help of real-time data collection and analysis.

Table 6-3: Detailed technical scenario for Agriculture UC1

Parameter/ Scenario	Max. latency (ms)	Through put (Mbit/s)	Range (km)	Description
Coordinated unloading	50	2-8	~1	Coordinated unloading enables real-time synchronisation between harvesters and transport vehicles in the field. This minimises downtime, reduces grain loss, and ensures continuous harvesting operations.
In-field data sharing	100	2 – 8	~2	In-field data sharing allows machines and operators to exchange agronomic and operational data instantly. This improves decision-making, and enhances efficiency
Remote support over HMI	100	2- 8	Cloud	Remote support via HMI (Human-Machine Interface) enables technicians to access and troubleshoot machine systems from afar. It reduces the need for on-site visits and speeds up issue resolution, minimising equipment downtime
OTA SW updates	100	2- 8	Cloud	OTA software updates allow agricultural machines to receive the latest features, bug fixes, and performance improvements wirelessly. This keeps equipment up-to-date without interrupting field operations
Remote support over video transmission	100	25	Cloud	Video-based remote support lets technicians visually assess machine issues in real time. This enhances diagnostic accuracy and enables faster, more effective remote assistance
Live alerts over M2I	20	Up to 100	~2	Live alerts over M2I provide operators with instant notifications about machine status, performance, or faults. This proactive communication helps prevent breakdowns and ensures timely interventions

Why the future solution/scenario we aim at (with its benefit and goals) is desirable for society?

The solution is desirable for society because it empowers farmers by providing them with the tools they need to optimise their operations and increase yields. It also supports the development of rural communities by enhancing the network's resilience.

Which are the values, principles and criteria that are driving our steps forward?

- **Accessibility:** ensuring that all farmers, regardless of their location, have access to enablers of modern technologies.
- **Productivity:** enhancing agricultural gains to meet the growing food demand by staying connected and supporting uninterrupted field operations.

By focusing on these values, the proposed solution aims to create a more connected, productive, and sustainable agricultural sector.

6.3.1.2 State of the art

The shift from traditional to smart agriculture relies on stable connectivity, especially for real-time data exchange between (semi)-autonomous machines. However, rural areas often lack the infrastructure for such connectivity. While terrestrial networks (TNs) work well in cities, extending them to remote areas is costly and impractical, especially for seasonal farming.

Non-terrestrial networks (NTNs) offer a promising alternative, using satellites, High-Altitude Platforms (HAPs), and unmanned aerial vehicles (UAVs) to extend coverage without relying solely on ground infrastructure. These platforms can complement TNs to provide flexible, temporary connectivity in challenging environments.

Recent advances in satellite technology and integration into 5G standards (starting with 3GPP Release 15) have expanded NTN capabilities. Low Earth Orbit (LEO) and Geosynchronous Equatorial Orbit (GEO) satellites are now prioritised, with ongoing standardisation efforts in Releases 17–19.

HAPs, operating around 20 km altitude, offer wide coverage and low latency. They can be solar-powered and replace multiple ground stations. UAVs, though lower in altitude, are highly mobile and useful for on-demand tasks like acting as aerial base stations or data collectors. For example, drones with LoRa gateways can gather sensor data across large farms.

Despite progress, integrating NTNs with existing networks remains complex, with challenges in resource management, policy, and governance. Furthermore, a set of further challenges apply with respect to the use of NTN (ad-hoc) solutions:

- **Limited capacity:** such solutions will not be able to provide connectivity in high capacity (for high number of users) which is not considered as an issue in UCs for agriculture or construction.
- **Security concerns:** using ad-hoc solutions will eliminate the need to route the traffic through an access point; however, this can make the system prone to interference, which calls for security measures.
- **Short connectivity range:** ad-hoc solutions tend to have short connectivity range, which should be considered in scenarios like in agriculture or construction.
- **Limited capabilities:** such solutions tend to have limited data rate/speed capabilities, which needs to be considered in scenarios where there is a need for large data transmissions.

6.3.1.3 Stakeholders

- **Farmers:** they are considered the primary users of the UC described. Farmers would benefit from enhanced communication with their machinery, access to real-time data, and improved operational efficiency. They could utilise the connectivity for tasks such as monitoring equipment, receiving alerts, and making data-driven decisions.
- **Agricultural machinery operators:** These users are responsible for operating the agricultural equipment. They would rely on the connectivity solution for real-time data transmission to optimise machinery performance and ensure effective operation in the field. The farmers could also be machinery operators in some cases.
- **Field technicians:** they are responsible for maintaining and repairing agricultural machinery. This solution would enable them to access remote support, diagnostics, and troubleshooting

resources while working in the field, which enhances their ability to resolve issues in a timely manner.

- **Researchers:** researchers studying agricultural technologies might utilise the connectivity to gather data for experiments and innovation, contributing to advancements in the sector.

6.3.1.4 Impact and sustainability analysis

Table 6-4: Expected sustainability effects of Agriculture UC1

Environmental		Societal		Economic	
1 st order effects	2 nd order effects	1 st order effects	2 nd order effects	1 st order effects	2 nd order effects
More reliable connectivity in agricultural contexts	More optimised operations, fewer working hours for machines	Rural access to previously urban-only technology	Bridging the digital gap	Increased speed and efficiency of data transmission	Fewer interruptions of field work
	Lesser environmental impact	Increased coverage area	Empowering farmers		Higher agricultural productivity and efficiency
Reuse, recycling, or disposal of used ad-hoc devices		Cost of ensuring data privacy and security		Initial installation cost and ongoing maintenance costs	

6.3.1.5 Technical requirements and gaps

Besides the general challenges listed in Section 6.3.1.2, specific gaps for Agriculture UC1 have been identified:

Table 6-5: Technical requirements and gaps for Agriculture UC1

Parameter/ Scenario	Max. latency (ms)	Throughput (Mbit/s)	Range (km)	Gaps
Coordinated unloading	50	2-8	~1	Local connectivity on demand needed WiFi is not reliable
In-field data sharing	100	2 – 8	~2	Local connectivity on demand needed WiFi is not reliable
Remote support over HMI	100	2- 8	Cloud	Global Connectivity needed no service available in White spots
OTA SW updates	100	2- 8	Cloud	Global Connectivity needed no service available in White spots
Remote support over video transmission	100	25	Cloud	Global Connectivity needed no service available in White spots
Live alerts over M2I	20	Up to 100	~2	Global / local Connectivity needed no service available in White spots

6.3.2 Agriculture UC2: Task Offloading to the Edge for Critical and Resource-Demanding Tasks

6.3.2.1 Use Case description

Modern agriculture increasingly relies on advanced technologies, but processing data from sensors, drones, and machinery requires significant computing power. Equipping each vehicle with high-performance hardware is costly and energy-inefficient, especially when not used continuously.

A more efficient approach is task offloading to edge computing, where selected tasks are processed by shared edge resources instead of individual machines. This reduces energy consumption and hardware costs while still delivering the necessary performance for advanced agricultural applications. The proposed UC illustrates how vehicles, edge platforms, and cloud servers can work together to support this model. Figure 6-5 schematically depicts the UC.

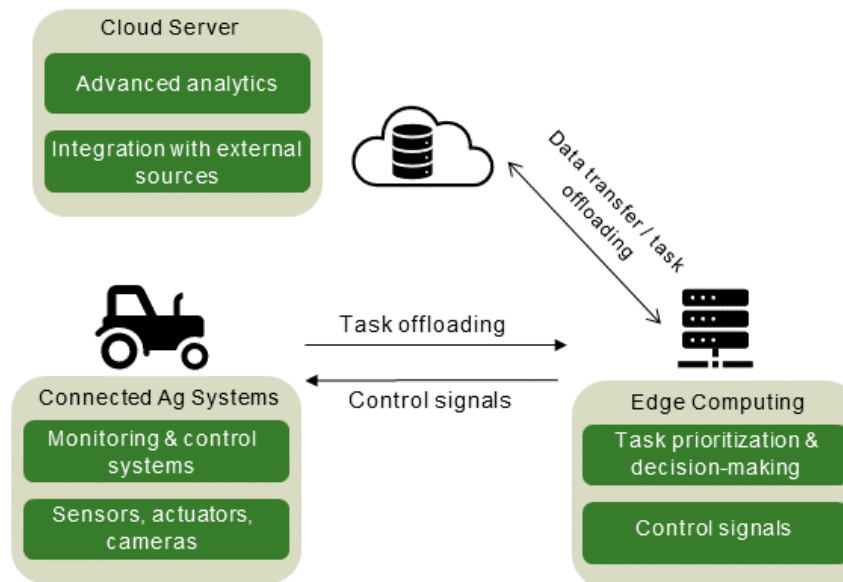


Figure 6-5: Task offloading to the edge use case description

Why is this use case needed?

This UC addresses the need for efficient and cost-effective computational resources in modern agriculture. By offloading tasks to the edge computing resources, this UC ensures that the resource-demanding tasks are handled efficiently, providing by that the necessary performance for advanced agricultural applications.

What operational problem/challenge is this use case trying to address for the target business (utility company/farm/healthcare provider)?

A key challenge in agriculture is creating scalable solutions that meet varying computational needs without constant hardware upgrades. This is especially useful for applications like image-based crop monitoring, where drones or cameras capture data, and machine learning algorithms process it to detect harmful plants. Once identified, the system can automatically instruct vehicles to take action.

This UC addresses global challenges by promoting energy-efficient, tech-driven agriculture that boosts productivity while conserving resources. It aligns with UN SDGs 7 (Affordable and Clean Energy) and 9 (Industry, Innovation, and Infrastructure).

The targeted scenario (where we want to land)

Enable seamless offloading of computational tasks to edge resources, ensuring real-time, cost-effective data processing. This enhances operational efficiency and optimises resource use in agriculture.

Table 6-6: Detailed technical scenario for Agriculture UC2

Parameter/Scenario	Max. latency (ms)	Throughput (Mbit/s)	Range (km)	Description
Remote engineering over AR	50	Up to 100	Cloud	Remote engineering over AR allows technicians to guide on-site operators through complex repairs or diagnostics using augmented visuals. This reduces downtime, eliminates travel needs, and enhances accuracy in maintenance task

Live alerts over M2I	20	Up to 100	~2	Live alerts provide real-time notifications about machine performance, environmental conditions, or system faults. These alerts help operators respond quickly to issues, improving safety and operational efficiency
Image processing over AI	50	200 - 500	Local / Cloud	AI-powered image processing analyses visual data from fields or equipment to detect patterns, anomalies, or crop health indicators. It enables smarter decision-making in areas like pest detection, yield estimation, and soil analysis.

Why is the future solution/scenario we aim at (with its benefit and goals) is desirable for society?

The future solution is desirable for society because it enables farmers to achieve higher efficiency in data processing without the need for costly hardware setup. In addition, it reduces energy consumption and promotes environmentally friendly farming practices.

Which are the values, principles and criteria that are driving our steps forward?

- *Innovation*: embracing cutting-edge technologies to transform agricultural practices and improve productivity.
- *Environmentalism*: promoting energy- efficient solutions that minimise environmental impact and promote sustainability.
- *Accessibility*: ensuring that advanced agricultural technologies and affordable and accessible to farmers, fostering inclusive growth and development.

6.3.2.2 State of the art

Edge computing is transforming modern agriculture by enabling real-time data processing and decision-making directly in the field. Low Altitude Platform Stations (LAPS) equipped with edge servers can monitor large, remote areas and analyse data on-site, reducing latency and reliance on cloud infrastructure. This supports applications like continuous crop and soil monitoring.

In **precision farming**, edge computing processes data from field sensors to optimise planting, irrigation, and fertilisation, improving productivity and reducing waste. Future autonomous machinery will also rely on edge computing, AI, and machine learning to interpret sensor data, adjust operations in real time, and ensure safe, efficient, and uninterrupted fieldwork. Figure 6-6 schematically depicts the UC.

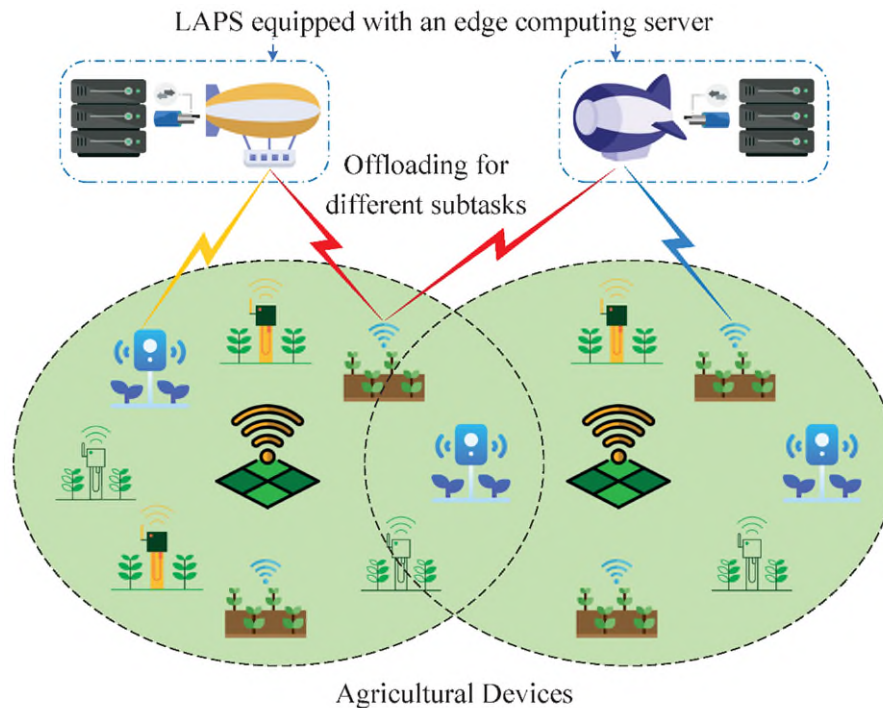


Figure 6-6: Continuous field monitoring using LAPS

6.3.2.3 Stakeholders

- **Farmers and technicians:** they are the primary users who can benefit from the enhanced productivity and efficiency brought by edge computing. They can use the technology to monitor crop health, manage resources, and make data-driven decisions.
- **Data scientists:** they can analyse the data collected from various devices and use the information to help optimise farming practices.

6.3.2.4 Impact and sustainability analysis

- **Data management and processing:** the scenario might involve handling a large amount of data from various sources such as sensors or cameras depending on the application.
- **Energy use:** While edge computing can reduce the need for high-performance hardware on each machine, the edge devices themselves still consume a considerable amount of energy.
- **Reliable network connectivity** for real-time data transmission and processing.
- **Ensuring a secure environment** among connected devices.

Table 6-7: Expected sustainability effects of Agriculture UC2

Environmental		Societal		Economic	
1 st order effects	2 nd order effects	1 st order effects	2 nd order effects	1 st order effects	2 nd order effects
More accurate application of water, fertilisers, and pesticides	Lesser environmental impact of agriculture	Enhanced efficiency and productivity in farming	Higher crop yields	Optimised resource use, reduced waste	Lower operational costs for farmers
Shorter data processing time of edge devices	Lower overall energy usage due to less time in use	Increased system uptime	Better food safety and availability		
Increased energy		Cost of maintaining		Initial installation cost and ongoing	

consumption of edge devices		privacy of the collected data		maintenance costs	
-----------------------------	--	-------------------------------	--	-------------------	--

6.3.2.5 Technical requirements and gaps

Based on the technical scenario outlined in Table 6-6, the following technical requirements and gaps have been identified:

Table 6-8: Technical requirements for Agriculture UC2

Parameter/Scenario	Max. latency (ms)	Throughput (Mbit/s)	Range (km)	Gaps
Remote engineering over AR	50	Up to 100	Cloud	Global Connectivity needed, no service available in White spots
Live alerts over M2I	20	Up to 100	~2	Global / local Connectivity needed no service available in White spots
Image processing over AI	50	200 - 500	Local / Cloud	Global Connectivity needed no service available in White spots. Current services do not provide the performance required.

6.3.3 Agriculture UC3: Agriculture Data vs. Information

6.3.3.1 Use Case description

Technology has become fundamental to the development and sustainability of agriculture. With a growing global population and the need to produce more food with fewer resources, tools such as artificial intelligence, IoT sensors, satellite remote sensing and automation are revolutionising the sector. These innovations make it possible to optimise water and fertiliser use, improve crop management, and reduce environmental impact. In addition, real-time data analytics enable more accurate decision-making, helping farmers increase productivity and profitability in an increasingly challenging environment due to climate change and market volatility.

This UC combines data from different sources like field sensors, climatic stations, soil analysis, and satellite images providing a context of the crop as shown in Figure 6-7 in real time. Real-time context enables more accurate crop management decisions, resulting in more efficient use of all resources involved in production, primarily water, energy, and agrochemicals. In addition to saving these resources, providing the plant with exactly what it needs improves production, enhancing crop quality and productivity, ultimately boosting profitability.

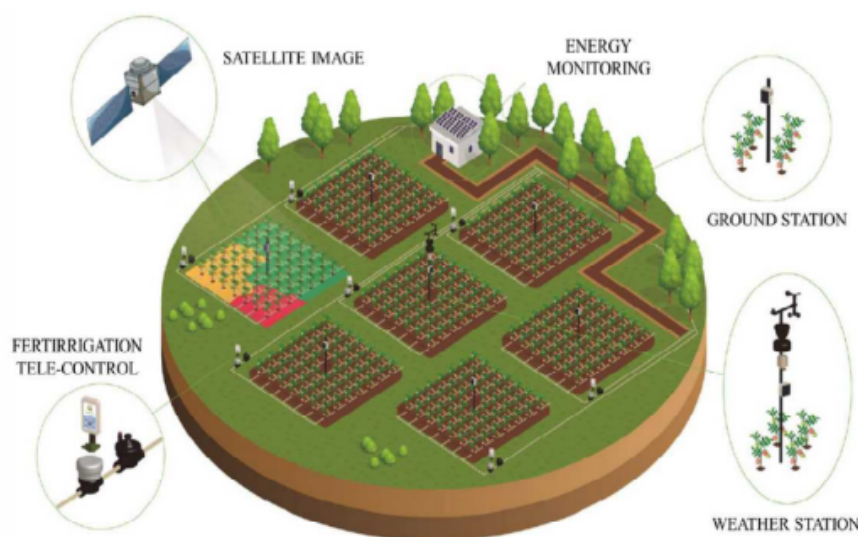


Figure 6-7: Data sources providing crop context

Environment and deployment scenarios

The environment can be a field with irrigation and a high added value crop, like avocado, berries or some types of nuts. Those crops are more delicate and much more appropriate to demonstrate the idea of the UC.

Platforms/Devices

The UC deployment would be a set composed by:

- Weather Station, see Figure 6-9
- Soil Stations (one per irrigation sector), see Figure 6-8
- Water Station in the irrigation header
- Satellite capture plan

Each station shall be composed by a wireless datalogger and a set of sensors.

Each station doesn't require any gateway or similar. Data is sent directly to the cloud.

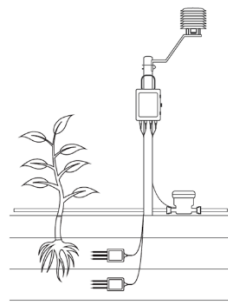


Figure 6-8: Example of basic schema of soil station

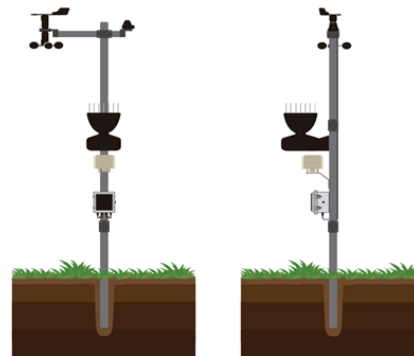


Figure 6-9: Schema of a basic weather station

Why is this use case needed? What operational problem/challenge is this use case trying to address for the target business (utility company/farm/healthcare provider)?

The challenge highlighted in this UC is the data interpretation. The limitation is not the cost of the technology, or the cost of the communications. The limitation is the cost of the data interpretation and the availability of experienced advisors. The average grower can perfectly afford the technology required. Service subscription, IoT sensors, etc. But they cannot afford the cost of a professional agronomic expert providing crop management recommendations (on a daily basis) based on the data provided by the technology. It is not possible to take crop management decisions just reviewing satellite image data, or sensor data. It is necessary to consider many context factors. And that is the reason why human experts analysing different agronomic data are required.

Now, though, the game is changing. Today, it is possible to combine both satellite image and sensor data. Through deep learning and AI, the systems can be designed to be aware of the context. Reasoning and decision-making software achieve results much closer to the decisions that a human expert might make. This opens a big opportunity to agronomic experts and growers. With these tools, agronomic experts can do their job much easier. With the same effort, they can cover x40 or x50 clients they have now. For a grower, this means a much more accessible service which is much more affordable.

In the context of decision-making systems in agriculture, data must come from two complementary sources: (1) raw, ground-level data from IoT sensors and (2) remote imagery from Earth Observation (EO) satellites. Each contributes uniquely to the generation of actionable insights.

Satellite imagery, on its own, offers global coverage and can provide valuable context on crop condition, biomass variability, and general vegetation indices. It enables a moderate level of information extraction and supports a certain degree of automated decision-making and trust in agronomic recommendations. However, these insights are limited in temporal resolution (frequency of updates), depth of ground-level understanding, and susceptibility to environmental interference (e.g., cloud cover).

On the other hand, IoT sensor data—capturing real-time (understanding real time in minute-level), high-resolution measurements of variables like soil moisture, temperature, humidity, and electrical

conductivity—offers deeper, localised insights. Systems based solely on this ground data are one step ahead in terms of decision-making accuracy and automation. They provide better trustability and contextual relevance by being rooted in the specific conditions of each plot.

Combining both data sources—EO imagery and IoT sensor data—unlocks a step-change in decision support capabilities. It's not merely additive; the synergy between them leads to exponentially improved insights, with enhanced precision, reliability, and adaptability. This fusion enables a richer understanding of crop status and a more robust decision-making framework than using either source independently.

However, while satellite imagery is globally accessible due to the nature of orbital coverage, the deployment of IoT sensors is hindered by limitations in communication infrastructure. Connectivity gaps, particularly in rural and remote areas, represent a significant barrier to collecting and transmitting real-time sensor data. This communication bottleneck is one of the critical challenges that must be addressed to scale the benefits of integrated agronomic intelligence.

What societal challenge(s) and goals is this use case trying to address considered global societal challenges and Sustainable Development Goals (SDGs)?

The UC is relevant to various SDGs, including SDG 1 (No Poverty) and SDG 2 (Zero Hunger). By integrating technology into the sector: SDG 9 (Industry, Innovation and Infrastructure). By improving working conditions and food quality, it can contribute to SDG 3 (Good Health and Well-being), SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities). And the outcome of the practices driven by the information and advice outcomes of the UC will contribute to SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate action), SDG 14 (Life below Water) and SDG 15 (Life on land) through the efficient use of resources, reduced waste and environmental impact.

The targeted scenario (where we want to land)

The targeted scenario involves a fully monitored crop. In this scenario, data from various technologies are integrated and processed in real time. The network plays a crucial role in enabling this real-time data flow, particularly by facilitating the acquisition and processing of images in real time. This approach ensures that resources are optimised, and actions are taken in the most efficient manner, based on the needs of the crop for sustainable performance.

Why is the future solution/scenario we aim at (with its benefit and goals) desirable for society?

The first step in being able to act sustainably is to know the current state, adapt and act in response to the environment. In agriculture, this means knowing the state of the crop, the type of soil, the weather, etc. Several agronomic variables can provide us with the knowledge to understand our study environment. The demand for food and the lack of certain resources force us to make decisions in order to optimise them; no real decision can be made without the necessary data and information about them. If we were in a scenario where most farmers were using precision agriculture techniques, it would mean that we would be in a scenario where most of the SDGs would be achieved, starting with food security, which implies SDG 1 (no poverty) and SDG 2 (zero hunger). Of course, the efficient use to resources is a driver to SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate action), SDG 14 (Life below Water) and SDG 15 (Life on land). And the working conditions and the food quality obtained with SDG 9 (Industry, Innovation and Infrastructure) provide an environment for achieving SDG 3 (Good Health and Well-being), SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities). It could be said, therefore, that it is in fact desirable for society as a whole.

Which are the values, principles and criteria that are driving our steps forward?

The principles and values driving this UC focus on promoting agricultural practices that are both efficient and sustainable. Key principles such as *efficiency* and *sustainability* aim to maximise production through the use of technology, while minimising environmental impact and optimising resource usage.

The values that support these principles are *inclusiveness*, ensuring services lower entry barriers for end customers to adopt AgriTech solutions, and *ecology*, reducing productivity risks and agrochemical

usage. *Collaboration* is also a core value, as Qampo views collectives as a solution to equalise opportunities for small growers in a market dominated by large landowners. *Food security* is another essential value, where producing more with fewer resources addresses the growing global population in the face of diminishing natural resources. *Profitability* remains a key consideration, ensuring that the technology provides a return on investment, especially in the current economic context where it is not yet planned as a public service.

Moreover, these principles are grounded in *environmental responsibility*, which focuses on preserving resources and biodiversity while minimising agriculture's impact on the environment. *Equal opportunities and worker well-being* are also important, ensuring that access to new technologies improves working conditions for all involved. Key criteria include *resource efficiency*, measuring consumption and quality, *environmental impact*, and ensuring *accessibility and scalability* of technology that can be adapted to various contexts.

Ultimately, these principles, values, and criteria guide the objective of ensuring that improvements in agricultural productivity are driven by both societal and environmental well-being.

6.3.3.2 *State of the art*

In the context of precision agriculture, digital transformation has enabled significant advances in data collection and analysis for decision-making. Technologies such as sensors, drones and satellites generate large amounts of information, facilitating crop monitoring and resource optimisation. However, the effectiveness of these solutions is limited by the ability to transform data into useful and actionable information. This challenge, combined with the need for sustainable management of resources such as water, fuel and agrochemicals, is driving the search for more advanced solutions.

Despite progress, current solutions have significant shortcomings. Real-time data transmission and processing remains a challenge due to limited connectivity in rural areas. These limitations mean that image acquisition, transmission and processing, and the resulting information, are not available in real time, limiting certain decisions. In addition, the large amount of information generated by technological systems requires the intervention of agronomists to translate it into practical recommendations, which makes it difficult for producers to make effective use of it.

In this UC, the application of 6G networks in precision agriculture aims to address these shortcomings by enabling faster and more accurate analysis of data obtained from satellite imagery, UAVs and sensors. This real-time processing capability facilitates the generation of actionable information for disease prediction and detection, as well as efficient irrigation and agrochemical management. Optimising the use of resources not only improves agricultural productivity, but also reduces environmental impact, contributing to the sustainability of the sector. End-users also benefit from easier access to clear and practical information.

To date, various technical solutions have been considered to meet the challenges of precision farming. The use of IoT networks has made it possible to connect devices and sensors for real-time monitoring. In addition, remote sensing systems and artificial intelligence-based data analysis platforms have proven effective in detecting anomalies and predicting yields. However, these solutions often face problems of latency, processing capacity and connectivity, especially in rural areas. A network that provides a more robust and efficient communications infrastructure opens up new possibilities for the development of smart farming solutions, transforming data into useful and actionable information quickly and accurately.

6.3.3.3 *Specific policy or regulation aspects (and their impact on sustainability aspects)*

- Global G.A.P. [Glo18]
- European Commission Common Agricultural Policy (CAP)⁷
- EU Regulation of organic production and labelling [R2018/848]
- Water use regulations. Specific for each country / area and crop.

Based on EU water regulations and CAP sustainability requirements, specific restrictions have been established to monitor and control groundwater use and improve irrigation efficiency. These policies introduce new rules that require the monitoring and hourly reporting of water volumes and water flow

⁷ https://agriculture.ec.europa.eu/common-agricultural-policy_en

rates to ensure proper control of extractions. Traditionally, measurements were taken manually once a month, and the measures were just about water volumes but not flow rates.

Now it is necessary to install flow meters that can record and transmit hourly data. However, the implementation of connected monitoring devices is heavily dependent on reliable network coverage. These regulations are not compatible with traditional methods. A connected device is required, and if there is no network coverage in the area to enable this technology, it is not possible to comply with the regulations.

6.3.3.4 Stakeholders

- **Network providers:** Provide the necessary connectivity infrastructure for data transmission and communication between sensors, weather stations, drones, satellites and cloud platforms.
- **UAVs and EO satellite providers:** Supply Earth Observation (EO) data and imagery through satellites and Unmanned Aerial Vehicles (UAVs) for crop and environmental monitoring.
- **Data platform Providers:** Provide an integrated service that includes field data collection, cloud processing with AI-driven analytics, and user-friendly data visualisation for informed decision-making. This encompasses three key areas:
 - *Sensor and Environmental Data Provider:* Collect field data, providing key information on ambient humidity and temperature, soil humidity and temperature, electrical conductivity, and other agronomic variables.
 - *Cloud Processing and Data Analytics Platform:* Process data collected applying analytical models and AI to generate real-time insights that support decision-making.
 - *Data Visualisation and Decision Support App Provider:* Provide an application that presents data in an accessible way for end users, enabling visualisation and action based on the insights obtained.
- **Growers:** Farmers and agro-alimentary companies that use processed data to improve irrigation efficiency, optimise agrochemical application, and enhance decision-making in the field.
- **Agronomic Advisors:** Experts who analyse data and provide recommendations to the growers optimising crop management, resource usage, and yield improvement.
- **Agrochemical and Agricultural Machinery Companies:** Suppliers of agricultural inputs and machinery that facilitate actions derived from data analysis, such as the precise application of fertilisers or pesticides and the efficient use of machinery in the field.

The priorities of this UC reflect the priorities of which actor or stakeholder group?

This UC reflects the priorities of the agricultural growers and agronomic advisors, who are the primary beneficiaries of the service. With the integrated data and insights, they can prioritise optimised crop management, efficient use of resources and increased productivity.

The problems and societal challenges the UC addresses are direct expressions of the needs of the target business / service / final user?

The societal problems and challenges addressed by the UC are a direct reflection of the needs of the end users, whose primary goal is to maximise agricultural production, especially agricultural producers and agronomic advisors. These users need access to accurate, real-time data to optimise crop and resource management. The ability to transform this information into actionable insights depends on technical expertise. The UC addresses this need by providing a solution that not only makes the technology accessible but also supports users to interpret and apply the data effectively.

6.3.3.5 Impact and sustainability analysis

What is the benefit/gain/value when we arrive at the targeted scenario (qualitative description)?

We survive. As Humankind.

At the current population increment rate, we won't be able to feed all of us in 2050. Climate change is modifying the arable land quickly. We have new growing techniques but most of them are intensive in terms of agrochemical products usage. We produce food but with a high CO₂ footprint and with cross contamination of other ecosystems. irrigation water and drinkable water contamination, oxygen

deprivation in water ecosystems, soil empowerment which is creating a derived global nutritional problem in the population because of the lack of vitamins and minerals that have the plants produced in an empowered soil...

Arriving at the target scenario means food guaranteed for the whole population, without killing hundreds of other species in the way, or even ourselves.

Current “cost”/impact of the problem

If one third (33.3%) of global agricultural land adopted precision agriculture techniques, the potential water savings could be estimated at approximately 350 km³ per year, considering only blue water use (i.e., irrigation). This figure is based on global estimates that agriculture withdraws about 3,500 km³ of freshwater annually for irrigation purposes [Unf22]. Precision agriculture practices—such as variable rate irrigation, soil moisture sensors, and satellite-based crop monitoring—can reduce irrigation water use by 20% to 50%, depending on crop type, climate, and management [EFA17]. Assuming a moderate savings rate of 30%, the potential global water saving would be 1,050 km³ per year if applied universally. Limiting this to one third of agricultural land, the annual saving would amount to approximately 350 km³.

To illustrate the scale of this figure, the average domestic water consumption in Europe is 144 litres per person per day, according to the European Environment Agency and the Made Blue Foundation [Eea14]. With an estimated 744.6 million inhabitants in Europe [WP-EU], this results in an annual domestic water use of approximately 39.1 km³.

Therefore, the projected 350 km³ of annual water savings would be enough to supply the entire population of Europe with domestic water for nearly 9 years. This demonstrates the massive potential of targeted precision agriculture practices to alleviate water scarcity and support sustainable freshwater management on a global scale—even when deployed in just a portion of total agricultural land.

Table 6-9: Expected sustainability effects of Agriculture UC3

Environmental		Societal		Economic	
1 st order effects	2 nd order effects	1 st order effects	2 nd order effects	1 st order effects	2 nd order effects
Optimised application of water and agrochemical products	Overall sustainability improvement through optimised resource use.	Inclusiveness; increased number of small growers with access to AgroTech solutions	Rural population fixation and generational renewal. Instead of population moving to cities to change business	Increase crop quality, meaning more price per kg. Increase production meaning more kg to sell. Net increment of profitability per hectare	Reduction of overall costs: Cost of water, cost of energy to pump the water, cost of fertilisers and agrochemical treatments
Lower CO ₂ emissions and pollution due to reduced machinery operations.	Savings in energy and water offset increased energy use	Access to education and advisory services enabling growers to apply new techniques and monitor crops remotely.	Improved knowledge dissemination and capacity building, leading to enhanced farm management and productivity over time.	Initial investment and recurring maintenance costs.	New business opportunities in digital services.
Energy consumption for communication	Technological obsolescence and generation of e-waste.	Improved labor safety (less exposure to chemicals)	Social exclusion of users lacking the skills or		Increased competitiveness of the agricultural sector.

and data processing.			access to adopt the technology.		
		Dependence on external technical knowledge.	More accessible and affordable agronomic knowledge through digital tools and advisory services.		Displacement of less digitised farms.

Table 6-10: Cost and benefit analysis of Agriculture UC3

Sustainability Benefits		
	IMPACT	POTENTIAL KPIS/KVIS
Environmental	IoT and precision agriculture optimise the use of natural resources (water, energy, agrochemicals), reducing resource consumption per hectare.	- Liters of water saved/kg of product - kWh/kg of product saved - kg/kg of product of fertilisers saved - CO₂eq avoided
Societal	Agricultural digitalisation enhances inclusion and access to technical knowledge, enabling rural population retention, generational renewal, and better quality of life in rural areas.	- % reduction in rural migration- Number of young people entering the sector - % decrease in agrochemical application frequency and quantity
Economic	Agricultural technology improves profitability and reduces operational costs, increasing competitiveness and long-term viability.	- €/ha increased profitability - % reduction in operational costs
Sustainability Costs		
	IMPACT	POTENTIAL KPIS/KVIS
Environmental	Additional energy consumption required for sensors, communication, and processing, and generation of electronic waste due to device replacement.	- Number of obsolete devices/year - Wh for data storage and processing - Wh for IoT devices communication
Societal	Digitalisation may lead to social exclusion for farmers lacking access or skills and raises concerns over data ownership and privacy.	- % adoption of available technology in an area - Number of data security incidents

Economic	Initial investment and recurring maintenance costs.	- €/ha initial investment- €/ha maintenance costs - Return on Investment
-----------------	---	---

6.3.3.6 Technical requirements and gaps

Use Case requirements for 6G

- Real ubiquity
- Satellite global provision
- Different operational modes with different energy consumption levels

The reason is that there are different situations over the year in which crops have different monitoring needs.

- *General Stations*. Low bitrate, low reliability, high latency. Very low power consumption.
- *Control Stations* (eg.: remote switch on a pump). Low bitrate, high reliability, high latency. Very low power consumption.
- *Real Time Image Processing*. High bitrate, High reliability, low latency. High power consumption.

Geographic setting for the UC as well as typical volume of users/end devices”

- One Soil Station each 5ha - 10ha. Between 5 and 15 sensor measurements per monitoring point. Measuring every 5 - 15 minutes and sending data every hour.
- One Weather Station each 500 - 1000 ha. 7 sensor measurements per monitoring point. Measuring every 5- 15 minutes and sending data every hour.

Average data volume = 5Mb per month per station.

Device lifetime:

- Battery-powered and recharged daily via an integrated solar panel.
- Ultra-low power consumption → up to 15 days of operation without sunlight.
- The batteries and solar panels are recycled every 5 years.

Table 6-11: Technical requirements for Agriculture UC3

Instantiation Parameters	Sensing time	Sending rate	Throughput (Mbit/s)	Max. latency (ms)	Frame length
General sensing mode	15 minutes	Every 4 samples = 1 hour	0.01	1000	2 kbits per sample; 8 kbits sent
Irrigation event sensing mode	5 minutes	Every 1 sample = 1 minute	0.01	1000	2 kbits per sample; 2 kbits sent
Hydroponics Irrigation event sensing mode	1 minutes	Every 1 sample = 1 minute	0.01	1000	2 kbits per sample; 2 kbits sent
Energy saving sensing mode	1 hour	Every 12 samples = 12 hour	0.01	1000	2 kbits per sample 96 kbits sent
Drone Communication operational mode	15 minutes	Every 48 samples = 12 hour	0.01	1000	2 kbits per sample 96 kbits sent

6.3.4 Smart Grid UC1: 6G enabled grid balancing services from distribution grid assets

6.3.4.1 Use Case description

This UC focus is on enabling Distributed Energy Resources (DERs), such as home batteries, electric vehicles, and smart appliances, to actively participate in grid balancing and frequency response services, in real time, and by leveraging 6G capabilities [BAP+22]. Traditional grid control systems lack the flexibility and response time to manage the increasing complexity and the growing instability from the integration of DERs, in parallel to the decentralisation of power generation.

Preconditions include the availability of wireless connectivity with edge nodes deployed near DERs, functional DER control units (e.g., microcontrollers), and an energy market framework that allows Distribution System Operators (DSOs) and Transmission System Operators (TSOs) requesting services.

Post-conditions entail successful DER dispatch, measurable frequency stabilisation, logged activation events, and market validation. The **objective** is to demonstrate that a distributed, latency-sensitive, AI-supported grid balancing service orchestration, with high reliability and scalability in the number of DERs, enabling a sustainable and decentralised power grid.

Further technical assumptions include DERs that can be controlled via standardised APIs and network protocols, edge nodes and AI-based decision support systems are present, while wireless connectivity features beyond 5G can accelerate the subject grid balancing services. **Values** guiding the UC include system resilience, sustainability, prosumer empowerment and digital inclusion. The **motivation** stems from the need to replace centralised, fossil-fuelled assets with localised, clean, and intelligent alternatives.

This UC is addressing critical needs of future energy systems:

- Grid stability through fast-acting flexibility from DERs
- Economic efficiency with the utilisation of available DERs and reduction in power storage costs
- Economic and societal inclusion of small asset owners in energy markets
- Positive environmental impact by enabling higher Renewable Energy Sources (RES) penetration and emissions reduction

Operational challenges being addressed by the UC:

- Ensuring sub-second response times for control signals
- Controlling a wide range of heterogeneous DER types-capabilities
- Interoperability across grid platforms of DER owners, DSOs and TSOs
- Availability of grid balancing services during failures in cloud-edge infrastructure
- Securing data flows and control commands across network slices

These challenges necessitate a robust, programmable, and AI-supported communication-control infrastructure, to be supported by 6G features.

This UC is supporting multiple United Nations Sustainable Development Goals (UN SDGs):

- 7: Affordable and Clean Energy: by improving the grid resilience upon integrating renewables
- 9: Industry, Innovation & Infrastructure: through innovation in distributed grid management
- 10: Reduced Inequalities: by enabling the fair participation of all DER owners in energy markets
- 13: Climate Action: through emissions reduction, due to the real-time integration of renewables

On societal terms, the UC is supporting a broader engagement of citizens in sustainability efforts. The envisioned future is one where DERs automatically respond to the grid needs in near real-time, under the coordination of an intelligent cloud-edge communication platform.

This target scenario is desirable for the:

- System resilience and service continuity despite partial system failures
- Decentralised orchestration, empowering regional control nodes to act autonomously
- Transparency and trust through validated feedback loops and market oversight

In that direction, the associated values can be the hallmarks of the future energy systems.

6.3.4.2 *State of the art*

The increasing decentralisation of power systems and the integration of renewables have made the role of DERs critical in achieving real-time grid stability. Technological developments have set the baselines, but limitations remain to meeting the requirements of fast grid balancing services. Existing technologies and their limitations are outlined in the following paragraphs, while the potential future capabilities are described.

Existing power and communication infrastructures partially support DER-based balancing services. 5G networks offer Ultra-Reliable Low-Latency Communication (URLLC), which has been piloted in some industrial and energy applications. These networks can provide radio interface latency below 1 millisecond and support network slicing for fine-tuning of application requirements. However, further improvements are expected on edge intelligence and dynamic adaptation at scale.

Traditional Supervisory Control and Data Acquisition (SCADA) systems and Advanced Distribution Management Systems (ADMS) are widely used for centralised grid control. These tools are suitable for high- and medium-voltage systems but are insufficient for real-time control at the distribution level. More recently, DER Management Systems (DERMS) have emerged to help aggregate and dispatch flexibility. While effective at a tactical level, these systems are typically centralised, often operate in slow time cycles (15-minute intervals or longer), and do not support sub-second response needed for frequency containment.

At the edge of the network, early deployments of computing platforms—such as Raspberry Pi, Jetson Nano, or x86-based servers—enable localised analytics and decision-making. These systems can execute Machine Learning (ML) models for forecasting and DER dispatch, but they are not yet standardised, and their orchestration at scale remains a challenge. IoT communication protocols can facilitate device-level integration between DERs and grid controllers, but they still depend heavily on backend cloud services, which introduce latency and vulnerability.

Despite these developments, current systems fall short in certain areas. First, 5G networks with their centralised architecture, limit the real-time, autonomous control of distributed DERs at the edge. Moreover, their network slicing capabilities lack the flexibility and AI-assisted orchestration that can be beneficial to the grid balancing services.

Second, the control and orchestration of DERs are not yet aligned with real-time operational timelines. Most DERMS platforms are designed for day-ahead optimisation, rather than responding to contingency events within seconds or milliseconds, which is required by services like frequency response to achieve grid stability. In addition, the interoperability between DER controllers, aggregators, DSOs, and TSOs is limited by proprietary architectures, differing standards, and lack of unified interfaces.

Furthermore, cloud dependency introduces both latency and resilience risks. In the event of connectivity loss or overload, cloud-centric architectures cannot maintain real-time control. While edge computing offers a partial solution, mechanisms for seamless edge-cloud failover and distributed edge-to-edge coordination are still underdeveloped. Finally, current solutions lack robust, end-to-end security models necessary for critical infrastructure service provision.

Still, several requirements for the UC successful deployment remain to be fulfilled. The reliable and high-speed control of geographically distributed DERs requires sub-700 milliseconds end-to-end communication, AI-supported decision-making, and seamless device coordination. Decentralised orchestration across multiple actors, including DSOs, Aggregators, LEM Operators is also required. The ability to perform real-time, multi-actor coordination using distributed edge intelligence and cross-domain communication remains a challenge. AI-driven predictive dispatch, where ML models anticipate grid contingencies and pre-emptively mobilise DERs, is still at pilot stages. These models require massive data ingestion, real-time inference, and dynamic actuation, with none of them are currently feasible at scale in grid environments. Finally, the dynamic network slicing support seems relevant to the need for real-time, context-aware prioritisation of grid services, possibly based on AI-driven policies.

6.3.4.3 *Stakeholders*

The following table (Table 6-12) outlines the specific priorities and needs for each stakeholder relevant to the UC.

Table 6-12: Stakeholder needs and benefits for Smart Grid UC1

Stakeholder	Needs and Benefits
TSOs and DSOs	- Reliable real-time DER response - Compliance with regulatory timelines (<1s response) - Service validation and traceability - Seamless ICT-grid integration
Prosumers & DER Owners	- Fair compensation for flexibility - Simple and secure onboarding - Privacy and control over asset participation - Transparent market rules
Aggregators / Local Energy Market (LEM) Operators	- Ability to bundle small assets efficiently - Low-latency coordination across regions - Accurate forecasting and dispatch tools
ICT & 6G Providers	- Support for cloud computing at the edge of the network - QoS guarantees for grid applications - Sufficient network slicing granularity
Regulators	- Resilient system architecture - Traceability of decisions (who acted, when, and why) - Inclusiveness and non-discrimination
Vendors / Research Institutes	- Open APIs and interoperable architectures - Platforms that scale to millions of devices - Proof of impact on SDGs (climate, inclusion, cost reduction)

6.3.4.4 Impact and sustainability analysis

Sustainability first and second order effects of the particular UC, are being analysed under the 3 pillars (environmental, societal, economic). Relevant topics are mentioned in UC description, while associated KPIs and KVIIs have been identified, and they will be utilised in following SUSTAIN-6G activities:

- WP 4 “6G Solutions for Sustainable Applications” on the vertical UCs implementing 6G technology
- The interworking between WPs 3 and 4 towards implementing a recursive approach (following the methodology outlined in Section 5.6) for optimising the E2E sustainability effects
- WP 5 “Proof-of-Concept and E2E integration testing” on proving the sustainability effects of the developed 6G enablers and their integration to vertical UCs.

Table 6-13: Expected sustainability effects of Smart Grid UC1

Environmental		Societal		Economic	
1st order effects	2nd order effects	1st order effects	2nd order effects	1st order effects	2nd order effects
Increased share of renewables in the energy markets by the grid balancing services	Reduction of CO ₂ emissions due to integration of renewables, through the grid balancing services	Enhanced energy accessibility for prosumers from the inclusion even of the small asset owners in the energy market		Increased participation of small-scale asset owners in energy markets	Lower operational costs for system operators (TSOs), including the power storage costs, with the utilisation of available DERs
	GHG emissions from the production of new infrastructure equipment & their use	Security and privacy on data flow and control signals of the grid balancing services. Any breaches can lead to services mis-function and		Increased grid reliability and resilience due to the flexibility from DERs integration	Potential job losses in traditional energy sectors from the automated grid balancing services

		credibility loss, including financial & environmental side effects			
	Increased energy consumption due to the deployment & operation of the 6G infrastructure and/or the grid application services				Increased costs due to the deployment & operation of the 6G infrastructure and/or the grid application services, including costs for the infrastructure upgrades & new spectrum acquisition

6.3.4.5 Technical requirements and gaps

From the list of the identified functional (and non-functional) requirements, for the UC pilot system to enable the real-time orchestration of grid balancing and frequency response services, the subset relevant to the wireless connectivity requirements is presented in Table 6-14. For reference purposes, the requirement numbering is kept in brackets. Specific communication parameters are declared under the second column, to facilitate the comparison with 5G/6G capabilities.

Table 6-14: Technical requirements for Smart Grid UC1

UC Functional Requirements	Connectivity Requirements / Parameters§
Real-Time DER Control & Optimisation [FR1.1]	Support for real-time data transmission from DER to edge/cloud with sub-700ms latency (end-to-end, including processing)
Sub-Second Response for Frequency Balancing [FR1.2]	The same as the above
URLLC communication [FR2.1]	Packet loss $<10^{-5}$; latency jitter <10 ms; reliability $\geq 99.999\%$
Network Slicing for Critical Energy Applications [FR2.3]	Dynamic 6G network slicing per application (e.g., balancing, forecasting)
Edge-Based DER Control [FR3.2]	Resilient edge connectivity with failover support (<200 ms failover time)

6.3.5 Smart Grid UC2: Resilient Grid Section Operation

6.3.5.1 Use Case description

Traditional power grids rely on fossil fuels which contribute to emissions and environmental challenges. The integration of renewable energy sources can lessen this effect and reduce the dependence on limited resources as renewables are naturally replenished. Energy providers are motivated to transition to renewables due to emission targets set by governments and international agreements, which aim to reduce greenhouse gas emissions, as well as by increasing consumer demand for cleaner energy. The increased integration of renewables and novel and proactive loads such as E-Chargers, as well as the implementation of new business models such as renewable energy communities in the European distribution system, require the active control of distribution systems which have traditionally been operated passively, i.e., with little to no monitoring/control equipment installed in the low-voltage tiers. ICT plays a major role in this context as it allows for gathering and processing sensor information as well as controlling the distribution system according to the available information.

Nowadays, distribution systems themselves can already contain participants (load/generation) which could exhibit flexibility by shifting their consumption/production. As an example, a building containing a PV battery system can reduce its consumption (load) from the grid and continue to operate on the energy stored in the battery (previously produced by the PV system or obtained from the grid), thus reducing the load requirements for the distribution system for a significant period of time.

While potential flexibility is already available in the grids to a certain extent, it is not yet utilised by Distribution System Operators (DSOs). DSOs can use this flexibility in the form of ancillary services, to achieve a more resilient grid operation, i.e., to mitigate congestions of the grid equipment and allow for an operation of their distribution system according to the regulatory specification. Even in the case of a fault, such flexibilities can be used to keep critical infrastructure supplied for longer, thus delaying a blackout and avoiding compensation payouts or productivity losses. It is important to note that the utilisation of grid flexibility may differ between countries within the EU due to varying regulatory frameworks and market conditions. This UC focuses specifically on the Austrian situation.

The distribution system is structured hierarchically: a medium voltage (MV) network connects and supplies several low voltage (LV) networks with energy. Flexibility can be used when coordinating the MV operation. This UC aims for implementing and demonstrating a 6G enabled resilient grid operation strategy given an MV grid and its underlying LV grids shown in Figure 6-10.

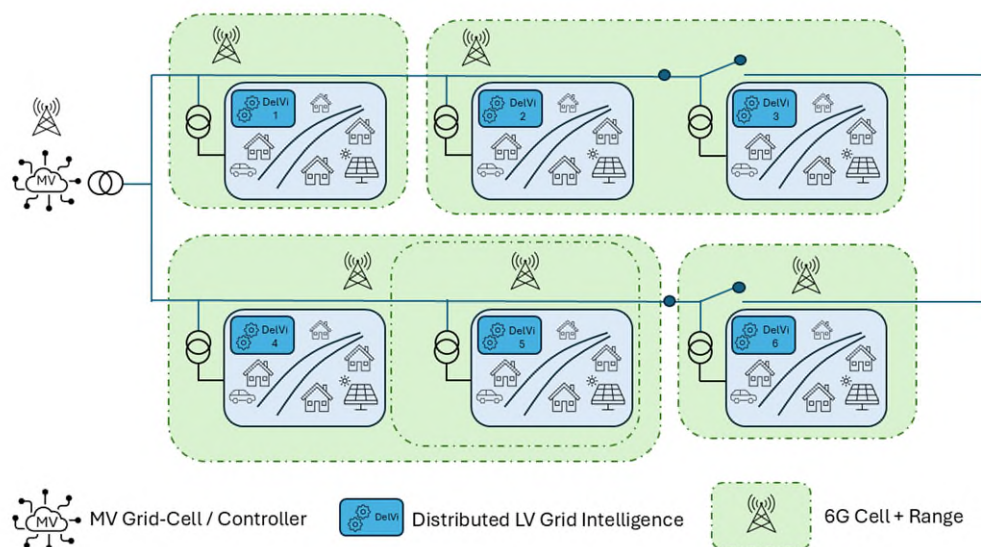


Figure 6-10: UC Overview

In the UC, each LV grid and its flexibilities are controlled by an intelligent Distributed LV Grid intelligence (DeLVi). Each DeLVi has a 6G communication interface which allows it to communicate to its neighbouring substations as well as the MV controller. Each DeLVi is aware of its flexibilities and receives a certain demand from the MV controller which it required to adhere to. However, DeLVIs are able to coordinate among each other to exchange flexibility. As an example, if one DeLVi does not require the full grid capacity which was initially reserved for the next hour, this capacity could be used by a DeLVi whose consumption would exceed the specification of the MV controller.

This mechanism should be resilient against fault scenarios. One such scenario can be derived from Figure 6-10: If the communication to the MV controller or other DeLVIs fails (due to a blackout, device failure, cyber-attack, etc.), the 6G cells can still be used to have at least some DeLVIs connected to each other (= cluster) using one or multiple active 6G cells. In this case, DeLVIs can coordinate their demands and flexibility to balance the operation of the respective LV grids and-higher level MV grid sections, thus preventing or at least delaying the outage of its participants. Clusters/cell reconfiguration should happen automatically, thus enabling seamless reconfiguration and underlying ICT communication.

The main values driving this UC are:

- **Efficient Use of Smart Grid Infrastructure:** Optimises the use of smart grid technologies and ICT for real-time data gathering, processing, and control, leading to more efficient energy management and reduced operational costs.

- *Supply Security and Resilient Grid Operation:* Ensures a stable and reliable energy supply by enhancing the grid's ability to withstand faults and automatically reconfigure in the event of a fault. This resilience supports economic stability, reduces the risk of outages, and ensures uninterrupted energy supply for communities, which is crucial for both economic stability and social well-being.
- *Integration of Renewables:* Facilitates the integration of renewable energy sources like solar and wind power, promoting a cleaner, more sustainable energy mix and reducing reliance on fossil fuels.
- *Reduction of CO₂ Footprint:* Contributes to significant reductions in CO₂ emissions by increasing the use of renewable energy and improving energy efficiency, supporting environmental sustainability and climate change mitigation.

6.3.5.2 State of the art

Several communication technologies have been evaluated for supporting smart grids, each with its own strengths and shortcomings. There are applications where they alone are sufficient, but also others where none of them offer an optimal solution. This section should give a short overview.

Power Line Communication (PLC) uses the existing electrical power lines to transmit data. It modulates data signals onto the electrical wiring, allowing for communication over the same infrastructure used for power distribution. As it is used in most of the Smart Meter rollouts, the technology is suitable for smart metering, home automation, and non-real-time grid monitoring. It is naturally cost-effective as it leverages existing infrastructure, reducing the need for new communication infrastructure. Downsides include susceptibility to noise and interference from electrical appliances (inverters, power electronics, etc.), which can degrade signal quality and reliability, as well as limited bandwidth and data rates.

LoRaWAN (Long Range Wide Area Network) is a low-power network protocol designed for wireless battery-operated devices. It operates in the sub-GHz frequency bands. It is used by municipalities for basic remote monitoring, smart metering (e.g. for monthly billing), and environmental sensing. The advantages lie in long-range communication (up to 15 km in rural areas), low power consumption, and good penetration through obstacles. The weaknesses include the limited data rate (up to 50 kbps) and payload size, which may be insufficient for applications requiring high data throughput or SW updates.

NB-IoT (Narrowband Internet of Things) is a cellular communication technology which operates in the licensed spectrum. It is designed for low-power, wide-area applications like smart metering, asset tracking, and environmental monitoring and is therefore comparable with LoRaWAN. It also achieves good coverage, long battery life, and low interference. Its main feature are the lower data rates compared to other cellular technologies, though it may incur higher costs due to licensing fees. Moreover, it may increase the dependency of critical supply infrastructure on the public telecommunication network.

The **450 MHz Band (LTE450)** is used for wireless communication, offering good propagation characteristics. Regarding the proposed UC, it is especially suitable for rural and remote area coverage, as well as smart metering and near-real-time grid monitoring. The better coverage in rural and remote areas is a result of the utilisation of a lower frequency, which allows signals to travel longer distances and penetrate obstacles more effectively. But the limited bandwidth availability, which can restrict the number of devices, data rates and making SW updates difficult, is a weakness.

Fiber Optics communication is ideal for backbone networks, high-speed internet, and data centre. Fiber optics can support extremely high data rates, making them suitable for applications requiring large bandwidth. Because they are less susceptible to electromagnetic interference, their main advantage is stable and consistent performance; for this reason, they are also used for redundant communication in high-voltage transmission networks. The initial setup and installation of fibre optic networks are expensive due to the need for specialised equipment and infrastructure. Preexisting fibre optics may be used for smart grid applications, though changing or expanding the network may be difficult and costly.

Cellular Networks (e.g., 4G, 5G) use radio waves to transmit data between mobile devices and base stations. 4G and 5G are the latest generations, offering improved speed and capacity suitable for mobile communication, IoT devices, and remote monitoring. SW updates and real-time monitoring are made possible by high-speed data transmission, supporting applications that require a large bandwidth. Cellular networks have extensive coverage across both urban and rural areas. They fulfil the needs of

the proposed UC but risk a dependency of DSOs on other infrastructure providers. Also, cellular networks can be expensive to operate due to various fees for bandwidth and data volume. Moreover, mobile devices/receivers and base stations require a significant amount of power, which can present a constraint for battery-operated IoT devices and have a negative impact on sustainability goals.

Each technology has its own set of advantages and limitations, making it suitable for different aspects of smart grid communication. The choice of technology often depends on the specific requirements of the application, such as range, data rate, power consumption, and cost. We have deliberately proposed a UC that cannot be implemented at all, or only with very high costs and energy requirements, using the previously mentioned technologies. A section-oriented distribution network operation scenario is currently the subject of research but will gain importance due to developments related to the energy transition. The proposed UC thus places rather high demands on the communication infrastructure; regardless, simpler UCs can be implemented using these technologies as well.

6.3.5.3 Impact and sustainability analysis

Table 6-15: Expected sustainability effects of Smart Grid UC2

Environmental		Societal		Economic	
1 st order effects	2 nd order effects	1 st order effects	2 nd order effects	1 st order effects	2 nd order effects
More local energy generation and consumption, including self-consumption	Higher density of sustainable assets	Cheaper energy	Greater satisfaction in industries and the general population	Reduced need for grid replanning	Less financial burden on low-income households
Efficient hardware usage	Minimised infrastructure needs	Sense of doing good	Increased GDP	Lower CAPEX/OPEX	Avoidance of blackouts
Higher % of renewables		Social safety	Community empowerment		
Less CO ₂ emissions					
Higher density of PV, chargers, heat pumps					
Increased energy consumption from 6G	GHG emissions from production/maintenance	User adoption barriers	Digital divide	High deployment and maintenance costs	Potential job losses in traditional energy sectors
Use of rare materials	E-waste from outdated components	Privacy concerns	Need for education and retraining		

6.3.5.4 Technical requirements and gaps

Table 6-16: Technical requirements for Smart Grid UC2

Scenario	Description	Technical Requirements	Gaps/Challenges
Normal Operation	Normal Grid operation where all LV cells have full communication with the MV grid controller. The MV grid controller will then collect all LV measurement data and calculate the optimal setpoints.	Low energy consumption: Support for energy-harvesting sensors. Coverage: 100% area coverage, including hard-to-reach locations (e.g., basements). Bandwidth: ~10 Mbit/s; Time synchronisation: < 1 ms E2E Interoperability: Standardised onboarding, firmware updates. Maintenance: Long-term QoS, automated software updates.	Lack of standardised protocols for automated sensor onboarding and firmware updates. Coverage assurance in underground or shielded environments.

		Cluster Mode: Flexible cluster formation if backbone fails. Guaranteed QoS: Bandwidth and service levels must be maintained.	
Cluster Mode (Backbone Network Unavailable)	MV grid controller (backbone) is not available, and therefore all DelVi sensors try to form local clusters using available 6G cells for cluster-wise optimisations.	Flexible cluster formation across substations. Guaranteed bandwidth/service level. Cluster-local communication with minimal latency.	Ultra-precise time sync ($< 2 \mu\text{s}$) in decentralised clusters is challenging Dynamic cluster management protocols are underdeveloped in the Smart Grid domain.
3. Failure Mode (Grid Failure Scenario)	A failure affects the operation of one LV cells leading to a blackout. Failure protocols and high-res measurements should be transmitted for root cause analysis.	Time synchronisation: $< 2 \mu\text{s}$ for PMUs/differential protection E2E Backup power: 30 min UPS for communication systems. High bandwidth: $> 100 \text{ Mbit/s}$ for high-res data. Spontaneous high data transmission with guaranteed latency. Dynamic power adaptation of 6G transmitters.	Energy-efficient ICT operation Latency guarantees under failure conditions are difficult to maintain.
6G Sensing – Weather	Using 6G sensors to get information on local weather (e.g. rain) can improve the MV/LV optimisation algorithms, as they highly rely on coarse forecasts.	Local weather detection (sunshine, rain, temperature).	6G-native weather sensing capabilities are still experimental.
6G Sensing – Sensor Location	Using 6G to localise all sensors can be additionally used to find wrongly placed sensors and simplify sensor onboarding.	Sensor localisation without GPS $\leq 1\text{m}$	High-accuracy indoor localisation via 5/6G is still in early research.

6.3.6 Smart Grid UC3: Joint Planning of 6G / Smart Grid Infrastructures

6.3.6.1 Use Case description

The joint planning of 6G and smart grid infrastructures is vital to achieving cost-effective, resilient, and sustainable ICT systems. As 6G scales with dense small cells, edge computing, and a surge in connected devices, energy demands will rise sharply, exceeding the capacity of traditional centralised grids. To meet this challenge, localised micro-grids powered by renewables and managed by AI-driven EMS

offer adaptive, low-carbon energy provisioning. This enables intelligent energy allocation to 6G nodes, aligning infrastructure sustainability with operational efficiency.

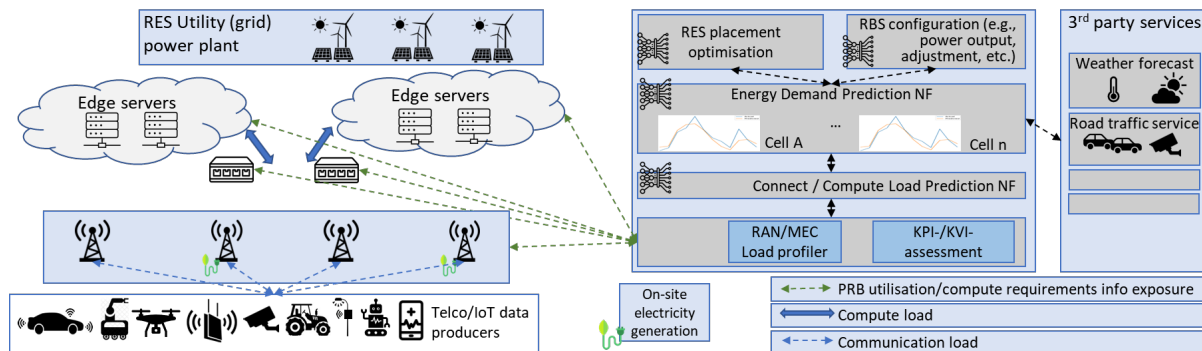


Figure 6-11: Illustration of the ecosystem involving matching the system operation to the energy supply

Integrating solar, wind, and storage systems—advanced batteries and/or hydrogen storage—will be essential to mitigate RES intermittency and ensure network stability. AI-based optimisation will guide the siting of 6G components near energy hubs and reduce transmission losses. In urban areas, rooftop solar on telco infrastructure can partially power nodes, while rural deployments may rely on community-based RES and storage for energy autonomy.

Advanced EMS will forecast demand, balance load, and coordinate DERs, ensuring 6G components adapt to real-time energy availability and constraints. AI-based prediction and adaptive slicing will prioritise critical services under limited power conditions. To enhance resilience, intelligent control of hybrid storage—including long-duration hydrogen solutions—will optimise efficiency and continuity across varied deployment scenarios.

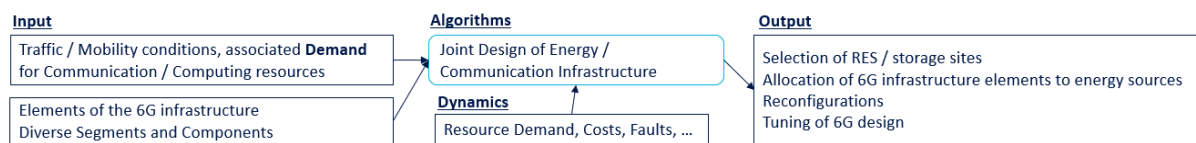


Figure 6-12: AI-driven joint planning of energy and communication infrastructure in 6G networks

As 6G energy demands grow, joint planning must address cost-efficiency, regulation, and standardisation. Regional factors—like RES cost, interconnection, and microgrid scalability—guide optimal placement of energy and storage assets. AI-driven trade-off analysis supports balanced CAPEX/OPEX decisions, maximising RES usage while ensuring financial viability. Resilience metrics are integrated into the optimisation loop, enabling autonomous reconfiguration of network elements and continuous tuning of 6G infrastructure under varying energy conditions.

This approach depends on close collaboration between TSOs, DSOs, FSPs, LEM operators, and telecom providers, enabling coordinated control of DERs and energy-aware 6G operation. It responds to rising telecom energy needs, EU policies, and the shift toward decentralised sustainability. Through AI-driven joint planning, SUSTAIN-6G enables low-carbon, cost-effective, and resilient 6G deployments with uninterrupted service continuity.

Environment and deployment scenarios

The following environment and deployment scenarios are relevant for this UC:

- Urban deployments (integrated into smart city energy grids, supporting resilient emergency services)
- Industrial/campus microgrids (factories, data centres, logistics hubs, etc.)
- Remote / off-grid areas.

Platforms/Devices

The following platforms and devices are relevant for the implementation of the UC:

- wi.SENSE platform [Win22] (energy metering & anomaly detection, smart energy infrastructure monitoring, AI-based energy management and optimisation, RES integration and production forecasting capabilities, etc.)
- Various devices comprising power meters, voltage sensors, environmental sensors, controllers, etc.
- Emulated smart grid including the power grid network, the power suppliers, as well as the corresponding consumers.

6.3.6.2 *State of the art*

AI-driven energy management for microgrids has been widely studied in both academic research and industry, with key advancements in renewable energy integration, predictive optimisation, and intelligent control frameworks. Research has explored renewable-powered small cell base stations, leveraging traffic-aware load balancing and sleep mode operations to improve energy efficiency in mobile networks [IYI23]. Other works apply game-theoretic optimisation, particularly Stackelberg models, to optimise demand-response mechanisms in distribution networks and 5G infrastructures, dynamically adjusting energy pricing and load balancing.

Beyond network-energy interactions, AI-driven microgrid optimisation has been explored using reinforcement learning (RL) and adaptive controllers to minimise DER costs while optimising battery and hydrogen-based storage [RHK+21]. These approaches rely on real-time load data to make autonomous energy storage dispatch decisions, ensuring battery longevity and optimal renewable energy utilisation. In addition, Deep Reinforcement Learning (DRL) techniques have demonstrated the potential for self-optimising microgrids, enabling dynamic energy allocation and grid reconfiguration based on real-time renewable generation fluctuations [NT21].

Despite these advances, existing solutions still face limitations in real-time adaptability, multi-source energy coordination, and large-scale microgrid scalability. Many AI-based energy management systems depend on static models, which struggle to handle sudden grid fluctuations, renewable intermittency, and unpredictable demand spikes. While hydrogen storage is emerging as a long-duration solution, its integration with AI-driven microgrid control remains limited, leaving gaps in large-scale energy balancing and resilience optimisation.

Beyond the State of the Art

SUSTAIN-6G introduces real-time AI-based microgrid reconfiguration, shifting from rule-based models to adaptive, event-driven energy distribution. By continuously monitoring grid conditions, renewable output, and network demand, the system enables dynamic energy reallocation, improving efficiency and resilience during fluctuations or outages. Unlike static dispatch, AI optimisation supports rapid, informed responses to changing energy needs.

The project will also evaluate diverse storage options—lithium-ion, hydrogen, and emerging alternatives—using AI to select the best fit per UC based on cost, efficiency, and scalability. Rather than relying on a fixed model, storage strategies will adapt dynamically to real-time needs, balancing short-term and long-duration requirements.

Finally, SUSTAIN-6G will develop decentralised coordination across microgrids, enabling surplus energy exchange and reducing reliance on central grids. This forms the foundation for resilient, flexible energy ecosystems aligned with the needs of 6G-powered infrastructure in diverse deployment contexts.

6.3.6.3 *Specific policy or regulation aspects (and their impact on sustainability aspects)*

The UC aligns with key EU energy and digital infrastructure regulations, ensuring cost-effective, resilient, and sustainable deployments. The Renewable Energy Directive (RED II [D2018/2001] and RED III [D2023/2413]) mandates increased renewable energy integration, impacting the planning and allocation of energy resources for 6G networks. This requires AI-driven joint optimisation of power distribution and network slicing, ensuring that 6G small cells and edge nodes are efficiently powered by renewables while maintaining grid stability.

The EU Electricity Market Design framework [D2024/1711] and the Network Code on Demand Response (NC DR) [Eur25] set the foundation for energy flexibility and grid balancing, enabling dynamic resource allocation between the grid, microgrids, and distributed energy resources (DERs). This ensures that 6G network components can adjust energy consumption in real time, participating in

demand-response programs and energy market trading where applicable. Moreover, EU microgrid regulations provide the legal basis for integrating localised renewable generation and storage, allowing 6G-powered sites to operate autonomously or in coordination with the main grid.

6.3.6.4 Stakeholders

The table below outlines the key Stakeholders involved in the UC and the specific benefits they derive from SUSTAIN-6G's advanced energy and communication infrastructure:

Table 6-17: Stakeholder needs and benefits for Smart Grid UC3

Stakeholders	Needs and Benefits
Transmission System Operators	Procure grid flexibility services from DERs via AI-driven coordination, ensuring grid stability and frequency regulation.
Distribution System Operators	Utilise AI-assisted DER management to enhance local voltage regulation, congestion management, and demand-response mechanisms.
LEM (Local Energy Market) Operators	Act as market facilitators, enabling real-time trading of energy flexibility across TSOs, DSOs, and decentralised energy resources.
FSPs (Flexibility Service Providers)	Aggregate DERs and optimise their participation in wholesale markets, ancillary services, and demand-side response programs using AI-driven market insights.
DER Owners (Microgrid Operators, Prosumers, and Industrial Sites)	Maximise energy efficiency through AI-driven orchestration of batteries, solar, hydrogen storage, demand response, and EV charging.
Telecom Operators & 6G Network Providers	Enable ultra-low latency communication for real-time DER coordination using 6G network slicing, edge computing, and AI-powered data analytics.
Cloud & Edge Computing Providers	Host AI-driven energy management, digital twins, and multi-microgrid coordination algorithms in a distributed cloud-edge computing architecture.
Regulatory Authorities & Energy Market Operators	Ensure compliance with EU energy regulations, grid codes, and interoperability standards, fostering a secure and standardised energy-trading ecosystem.
End Users / Energy Consumers (Households, Businesses, Industries)	Benefit from lower electricity costs, improved power reliability, and participation in demand-side response programs.

6.3.6.5 Impact and sustainability analysis

This SUSTAIN-6G UC is grounded in three sustainability pillars—environmental, societal, and economic—guiding the development of resilient and cost-efficient energy systems for 6G networks.

Environmental: By integrating renewables like solar and wind into microgrids, and using AI to optimise energy flow and minimise curtailment, the system reduces reliance on fossil fuels and cuts CO₂ emissions from conventional grid and diesel operations.

Social: Reliable, autonomous energy provisioning ensures continuous operation of critical 6G services—such as emergency systems and remote infrastructure—while promoting local energy independence and resilience in underserved or remote areas.

Economic: AI-driven planning lowers operational costs by enabling efficient use of distributed energy and storage, reducing dependence on costly centralised grid power and ensuring the long-term economic viability of 6G deployments.

The points above are summarised in the following table:

Table 6-18: Expected sustainability effects of Smart Grid UC3

Environmental		Societal		Economic	
1 st order effects	2 nd order effects	1 st order effects	2 nd order effects	1 st order effects	2 nd order effects
Use of recyclable and modular 6G	More renewable energy use (solar, wind, storage)	Empowerment of local communities	Reliable power for telecom, emergency		Lower OPEX for telecom/grid operators

infrastructure components		through energy independence	services, smart cities		
	Lower CO ₂ emissions via AI-optimised energy use		Energy independence via decentralised grids		Cheaper electricity for users via smart energy trading
	Less energy waste through demand-response and load balancing		Fewer outages, better service stability		6G cost savings with localised power
	Higher efficiency in 6G energy consumption		Local energy market participation for prosumers		New business models in energy services
Manufacturing footprint of 6G/grid hardware		User adoption barriers, need for education		High CAPEX for AI-based grid monitoring	
Disposal / recycling of outdated equipment.		Data privacy risks in AI-driven monitoring		Maintenance costs for AI / communication networks	
Battery / hydrogen storage impact if not sustainably sourced.		High initial cost for microgrid adoption		Regulatory changes needed for grid integration	

6.3.6.6 Technical requirements and gaps

The following technical -functional and non-functional- requirements have been identified.

- Minimum information set: sensors must capture power flow (import/export) at the node/microgrid level, voltage/current for anomaly detection, frequency for grid imbalance detection, real-time and forecasted renewable energy availability (e.g., solar irradiance, wind speed), energy storage status including state of charge, charging/discharging rates, capacity limits for batteries, load consumption profiles reflecting active and reactive power usage, (optional) environmental conditions such as temperature and weather forecasts to support AI models, (optionally) communication and computing demand forecasts via APIs
- The system must support joint forecasting of a) energy-side variables: RES production, storage status, load curves; b) network-side variables: traffic demand, service mobility patterns, UE density, and application-layer profiles (e.g., video, AR/XR, etc.).
- Sensor density/coverage: the deployment must ensure a minimum density of 50-200 sensors / km². More granular energy management (e.g., balancing with real-time AI control) may require higher densities (e.g., 200-500 sensors / km²).
- Data transmission frequency: near real-time sensor data collection is required for critical power adjustments, frequency regulation, DER dispatch, etc., while non-time-sensitive data (e.g., historical load patterns, system diagnostics) can be transmitted hourly or daily to reduce network congestion.
- Information reception and actuation: AI-driven energy dispatch and reconfiguration commands must be delivered with low-latency communication (typically <100 ms for fast response scenarios, up to 1-5 seconds for load balancing and grid reconfiguration).
- The platform must support interoperable APIs and protocols (e.g., IEC 61850 for substation and DER communication, OpenADR for automated demand-response events, OPC-UA as

platform-independent communication between industrial devices, MQTT, etc.) to interface with DER controllers, energy storage systems, 6G network orchestration components, etc.

- Cloud-native orchestration (Docker, Kubernetes, microservices architecture) must enable dynamic redeployment of forecasting, optimisation, and control logic based on energy/network state.

6.3.7 Telemedicine UC1: Concurrent Preoperative Surgical/Engineering Planning

6.3.7.1 Use Case description

Many surgical fields benefit from 3D preplanning analyses consisting of two tasks:

- analysis of 2D medical images (segmentation, i.e. identification of the areas pertaining to the organ/structure under examination) and the development of a 3D model of the anatomical structure,
- further processing of the 3D model (design of custom implants or resection guides, validation),

with the goal of deploying the surgical steps to be operated on the patient.

The existing certified medical software used for the first task is intended for being used by an engineer that will support a surgeon to deploy the 3D geometry and the planning of the intervention. Two professional figures are required: one engineer, that knows how to operate the complexity of the specific software and a Surgeon that has the clinical knowledge required to plan the operation.

The goal is to deploy a Remote Concurrent Preoperative Planning Framework (RCPPF) intended to:

- permit of an effective communication of medical and topological data and the operative intents between surgeon and engineer through the sharing of screen, keyboard, mouse and webcams,
- implement lossless screen sharing for ensuring that medical data based on grayscale and colours are not altered and facilitating the certification of the framework as medical device,
- be an open framework that permits to use a wide spectrum medical software that can be used for different highly specialised surgical fields,
- augment the processing of the 3D model through a collaborative 3D environment, operated with 3D input/output devices and represented by means of VR headsets,
- be multiuser, to permit collaboration with external expert surgeons for providing a counselling service, or with technical advisors for providing guidance on how to use and secure a specific implant, or with specialising students for training purposes,
- overcome the barriers of geographical, national and international borders.
- The framework will benefit greatly from a mobile network in the cases of:
 - emergency planning: enabling the engineering and surgical specialised personnel to design the planning from anywhere at any time, guaranteeing a service 24h / 7 days;
 - early planning and disaster medicine: by equipping onboard ambulances or the advanced points of care with portable medical imaging devices (CT for head injuries, 3D echography...) and by transmitting them to the hospital in advance.

The demonstrator intends to show a positive impact on medical practice by providing augmented remote preplanning capabilities through the integration of the latest 3D technologies, with the aim of increasing the number of operations carried out with this methodology, to the benefit of the patients.

Two barriers prevent a widespread usage of preplanning techniques: the issues related to the mobility of the engineering service providers for in-person preplanning sessions and the usage of limited videoconferencing solutions that isolate and discourage the surgeon. As a result, the burden of an intervention is all on the surgeon that must operate in a traditional free-hand practice, without having familiarised with a 3D preceding study and without patient-customised supporting tools.

The RCPPF is expected to reduce the need for mobility of the engineering service providers, by substituting in-person meetings with effective remote sessions and to extend the practice of 3D remote preplanning to a larger range of practitioners, regardless of their geographical positioning and serving peripheral health establishments. The possibility of connecting multiple users is expected to spread the

medical practices across borders and can be used for the training of specialising personnel that could join the sessions. A RAN connection is mandatory to extend the practice to the cases of emergency and disaster medicine.

The benefits deriving from the application of RCPFF will be manifold. For the surgeon: a more prepared, less stressful, simpler and shorter intervention and a reduced risk of complications; for the patient: a more precise intervention, shorter anaesthesia time and possibly a shorter recovery time; for the hospital: reduced operating room costs and insurance costs. Being multiuser, the RCPFF can also promote the sharing of national and international surgical knowledge or can be used for training specialising students.

To be effective for emergency medicine this proposed RCPFF requires improved support from mobile connections, because the data exchange here envisioned is larger than what currently implemented as it envisions lossless screen sharing, multiple users support and a fluid and synchronised manipulation of the medical images and 3D models, therefore the mobile connection should provide appropriate data-rate, latency, reserved bandwidth and a performant routing. Data reliability is required to protect the medical information that underlies the diagnosis and engineering analyses. Checksum data will be implemented to verify if medical images are altered during transmission so to notify the users.

Medical data protection is required because of the private sensible data managed as addressed in UC3. The RCPFF framework is intended to increase the usage of preoperative planning customised to the patient's specific needs, particularly in emergency medicine and because it is not subjected to geographical limitations it makes the access to quality health services more inclusive toward underserved areas accordingly to SDG3.8. The possibility of inviting trainees is intended for promoting knowledge exchange among the best practitioners, accordingly to SDG4.3. SDG 8.5 will be also addressed because the surgeon already familiarised with the 3D anatomy of the patient and with the support of custom 3D-printed surgical aids will have a less stressful intervention with positive impact over his well-being.

The UC is intended to fulfil a set of values including:

Sustainability: a functional digital service of pre-planning will have a positive impact over mobility because it will not be required for surgeon and engineer to physically move to a specific place for holding a planning session. Patients could be operated also in peripheral hospitals with all the best practices provided. As a result, environmental sustainability will be improved by reducing the need for mobility.

Inclusive digital health service: surgeons and engineers will have a framework into which develop a precise preplanning of a customised intervention to the benefit of the patient regardless of their geographical position. The possibility of accessing virtually everywhere the best medical practices will be granted to a wider set of patients, including the less wealthy ones. This is coherent with the goal of developing 'smart' hospitals and ensuring health equity.

Medical competences growth: RPPCF would enable a closer medical interconnection among major hospitals and peripheral hospitals inside a nation and stimulate transnational cooperation and practice exchange. Possibility of connecting external personnel for consultancy or for training purposes, regardless of the geographical area; spreading the excellency practices on the territory toward a growth of the medical competencies. This is coherent with the delivery of a proactive, personalised and precise health service with a participatory approach.

The RPPCF can be used on wired network or wireless network for routine hospital interventions properly scheduled. The accessibility to a RAN network is the enabler *Emergency medicine* cases, because it allows the design the surgical 3D pre-planning from anywhere, guaranteeing a service 24h / 7 days.

6.3.7.2 Stakeholders

The UC is intended for **healthcare providers**, with **professional surgeons** working in hospitals or clinics as the final customer, and for **biomedical engineering providers**, that produce surgical devices, implants or prostheses customised on the patient specific 3D morphology, acting as the supplier of the service. **Medical software companies** could be involved by developing new solutions for different surgical scenarios regarding different anatomical districts and different surgical methodologies. **Network Infrastructure Providers and Operators** have an interest in providing cloud hosting

services for secure data hosting, conferencing systems and 3D collaborative virtual environment in the medical field. **Certification agencies** should be involved the development of the complex certification protocol for medical purposes accordingly to the EU Medical Device Regulation (MDR) 2017/745 [R2017/745]. **Health insurance companies** and public health systems should promote the usage of the methodology proposed in order to obtain better patient outcomes and lower reimbursement costs. **Patients** will benefit from a better outcome being able to return to their productive life in a shorter time.

6.3.7.3 *State of the art*

On the market are available certified medical software (Materialise Mimics Innovation Suite, Planmeca Romexis, Dolphin 3D, NemoStudio, Realguide) that can manage 2D CT slices and through a manual segmentation process are able to build the 3D model of an anatomical district. Some programs have on-demand modules able to design resection or drilling guides for specific CMF applications. Otherwise, the 3D model will be exported to other more capable design software (Solidworks, Siemens NX, Rhino, etc.) for the design phase.

Because existing software are intended to be used by technical personnel (supplier) guided by a specialised surgeon (client) it is mandatory that the two figures can interact concurrently, but the software do not provide support in this sense. The rigid workflow of the design of surgical aids can be criticised by surgeon when it is incompatible with his personal practice or patient's specific needs, in some cases discouraging the usage such tools.

The lack of remote collaborative support on the side of the medical software is partially overcome through the usage of videoconferencing, but Surgeons report difficulties in instructing verbally the engineer for executing some activities that requires 2D or 3D actions like selecting a specific CT image, a proper contour of an anatomical structure, a specific landmark or rotating the 3D view of the model and making a section over it at a specific point and orientation. The complexity of the 2D/3D geometry requires a verbose description that in the end results exhausting, being the two participants able to interact by video and voice only but are otherwise isolated. Advanced devices lack a proper integration, like the space mouse used for 3D view manipulation, the 3D haptic mouse used for 3D modelling on mesh models. 3D models display by means of VR/AR headset is of limited diffusion (Mimics, Dolphin, Planmeca) and it is intended for a single user usage.

The videoconferencing is an uncertified application that introduces a vulnerability in the diagnosis and the design of a surgical aid that accordingly to the EU MDR [R2017/745] must ensure a higher level of safety and health protection for patients

The RCPPF demonstrator needs to be implemented by a professional software house and undergo the demanding certification as medical device accordingly to the EU MDR [R2017/745].

6.3.7.4 *Impact and sustainability analysis*

The discussion of impact, sustainability and KPI/KVIs is integrated into a single table presented at the end of Telemedicine UC2.

6.3.7.5 *Technical requirements and gaps*

This framework requires continuous, bidirectional transmission of high-resolution video with lossless compression and data between patients and servers. To ensure real-time performance, the network should support high data rates, ultra-low latency for the updating of the 3D concurrent environment, and reliable connectivity. Technical requirements are integrated into the table presented below for Telemedicine UC2.

6.3.8 Telemedicine UC2: Remote Rehabilitation Assessment

6.3.8.1 *Use Case description*

Rehabilitation frequently necessitates patients returning to hospitals or clinics to perform therapeutic exercises under physician supervision. This entails physical, psychological, and economic costs, particularly for people with limited mobility or who live in underserved or rural areas. The UC provides a unique framework for home-based rehabilitation that adheres to the principles of personalised medicine, which aim to optimise treatment outcomes while reducing undesirable consequences. This method allows patients to execute recommended workouts at home, guided by a real-time camera feed, eliminating the need for wearable sensors and reducing setup complexity. AI models examine video

streams to determine motion correctness and deliver individualised feedback. When deviations are noticed, the system can either recommend corrective actions or inform an on-duty healthcare expert, who can conduct a video consultation. The visual tracking approach ensures high accuracy and responsiveness without compromising user comfort, while enhancing the scalability and inclusiveness of rehabilitation services. Data from previously unknown irregularities can be saved to expand the medical dataset and assist in future neural network retraining.

The system combines Extended Reality (XR) with an immersive, intuitive exercise experience with AI for continuous, real-time motion assessment and feedback. By integrating these technologies, it delivers clear, personalised visual cues through head-mounted displays (HMDs), reinforcing motor learning and promoting faster functional recovery. The goal is not to replace medical experts, but to provide them with a useful tool that improves patient monitoring and enables remote adaptation of therapy programs. This reduces logistical and operational costs, streamlines clinical workflows through automation, and allows medical professionals to prioritise critical cases.

Beyond comfort and accessibility, the societal impact is significant. According to WHO data, nearly 2.4 billion individuals have health issues that could benefit from rehabilitation, and future projections indicate that demand will continue to rise. However, global rehabilitation programs lack skilled experts, equipment, assistive technology, and extensive waiting lists. This UC directly tackles these gaps by providing scalable, high-quality rehabilitation access across geographies, while alleviating pressure on healthcare facilities and freeing up resources for in-person treatment when truly necessary.

The proposed case study targets upper limb rehabilitation, focusing on patients experiencing phantom limb pain, a condition in which sensations persist in a limb after amputation. Building on the principles of mirror therapy, the system introduces an advanced alternative using augmented reality (AR) and deep learning (DL) to deliver personalised digital therapies remotely. Through AR, a virtual prosthesis is superimposed on the amputated limb, offering patients a first-person view that simulates natural limb presence and movement. Movements of the healthy limb are tracked and mirrored in real time onto the virtual counterpart, creating the illusion of bilateral motion. This immersive setup enables patients to engage in prescribed therapeutic exercises at home, with automated real-time assessment of execution quality via deep learning. Clinicians can remotely monitor progress, update treatment plans, or intervene as needed, providing a flexible, cost-effective, and engaging telemedicine solution.

The Proof of Concept (PoC) will be structured into four main phases: data acquisition, implementation of the deep learning (DL) model, including training and testing, and deployment of the extended reality (XR) application. During data acquisition, patients will perform rehabilitation exercises in front of a camera. The recorded video will be reviewed by clinical experts, who will label each exercise and provide qualitative feedback. This annotated dataset will then be used to train the DL model. Once the model achieves satisfactory performance, it will be integrated into an XR application, deployed on a HMD for AR. In the final deployment, the HMD captures the patient's movements and streams the video to an external processing unit, where the DL model analyses the exercise and sends real-time feedback to the HMD.

The rehabilitation application proposed in this UC will leverage the following driving values:

- *Inclusive health service*: the patient will benefit from personalised care at his home,
- *Sustainability*: the patient will be saved the inconvenience of mobility: the time, effort and costs related, particularly when they are unable to move autonomously. Also improves environmental sustainability/impact.
- *Growth*: the extension of the approach to other anatomical districts could be the enabler of new business opportunities for medical societies (data acquisition, labelling, training, testing, maintaining, updating, retraining) and wireless, data storage, and cloud computing service providers. By inviting the rehab sessions' expert physicians or specialised personnel, it will be possible to pursue knowledge transfer and improve knowledge accessibility.

6.3.8.2 Stakeholders

This technique has the potential to support:

- Medical personnel: physiotherapists and orthopaedists
- Public and commercial healthcare facilities

- Medical and engineering societies
- Patients
- Software corporations

The suggested case focuses on designing an application framework that will be supplied remotely by healthcare experts, intending to improve patient care at home while lowering mobility difficulties. Simultaneously, it provides major economic benefits by cutting hardware, logistical, and labour expenses, as well as optimising clinical resource allocation through automation, allowing healthcare staff to focus on complicated, high-priority patients while routinely monitoring them.

6.3.8.3 State of the art

In the area of remote rehabilitation, there are existing studies on the rehabilitation of articulations such as fingers and knees, as well as gait monitoring, which use AI approaches for joint identification. The goal of this UCS is to propose a framework that outperforms the current state of the art by incorporating Extended Reality, which provides a more natural and immersive perception of the rehab exercise, and AI, which estimates the exercise outcome and reports non-conformities either to patients or even to the physician.

6.3.8.4 Impact and sustainability analysis

First and second order sustainability benefits (green) and costs (red) for the environmental, societal and economic aspects are summarised in the following table, integrating those of ID2.3 UC1.

Table 6-19: Expected sustainability effects of Telemedicine UC1 & UC2

Environmental sustainability		Social Sustainability		Economic Sustainability	
1) eHealth workload can be directed to cloud computing allowing the patient/user to reuse low specs PC/Laptop devices.	5) eHealth services remove geographic and mobility restrictions and avoid mobility energy waste	8) Enable the development of advanced telemedicine solutions, reducing geographical barriers	13) Quick response and personalised medicine solutions provided to surgeons/patients. Emergency medicine enabler.	18) Business opportunities for provision of new remote health services in different medical branches	22) Reduced hospitalisation costs, insurance costs, burden reduction over healthcare institutions and personnel
2) E-Waste production for network infrastructure update	6) Device turnover (3D controllers, XR devices, GPUs for AI training)	9) Development of new eHealth infrastructure and services	14) Medical and technical competences sharing and transfer for training purposes	19) New cloud services related to medical purposes	23) Operational efficiency, reduced clinician workload, improved schedule flexibility
3) Energy consumption at network/components level	7) Energy consumption by devices used for eHealth services or deep learning models training and tuning	10) Emergency medicine enabler	15) Digital inclusion by extending Health services to underserved areas.	20) Creation of new technical figures in eHealth domain	24) Deployment of new eHealth services covering a larger range of customers
4) Resource consumption for producing new medical devices for eHealth applications		11) Data security measures are required to assure privacy of medical data, clinical input, annotated	16) Decentralised quality care delivered to patients' homes. Boosts scalability and accessibility.	21) Large investments required for infrastructure upgrade	25) Investments for updating the hardware with new 3D and XR devices and training

		datasets toward users			
		12) Data integrity: medical data must be protected from loss and corruption	17) Improved patient engagement through immersive AR experience, providing interactive and tailored feedback		26) Complex certification procedure of new medical devices

The following table summarises the expected impacts and the potential indicators for their evaluation.

Table 6-20: Impact analysis for Telemedicine UC1 & UC2

Sustainability benefits		
	IMPACT	POTENTIAL KPIS/KVIS
Environmental	Remote eHealth services are intended to practice a medical field without the need for mobility saving the cost, the pollution and the related physical effort (for rehabilitation patients)	5) Number of cases with successful remote treatment (each one avoids a mobility), number of cases developed between structures localised in different territories (national and international level)
Societal	Remote eHealth services pursue an inclusive purpose and contribute to the acceptance of 6G through the positive impact on the health and quality of life of citizens	13) Diagnosis to surgery lead time 14) Number of planning session with specialising surgeons 15) Evolution of the remote concurrent preplanning cases during time 16) Evolution of the home rehab cases during time 17) User experience survey of patients
Economic	Remote eHealth services with the goal can reduce hospital costs and risks and create new business opportunities by health service providers	22) Surgical room time reduction, insurance fee reduction 23) Number of home rehab cases 24) Number of software/hardware frameworks implemented, number of eHealth supporting network services, number of anatomical districts that benefits for remote rehab or remote planning, turnover generated by companies
Sustainability costs		
	IMPACT	Potential KPI/KVIS
Environmental	Remote eHealth services require new hardware and can anticipate obsolescence of other	6) Number of electronic wastes generated 7) AI training energy expenditure
Societal	Citizens could express worries about privacy and integrity of medical data	11) Public opinion surveys, healthcare facilities surveys, compliance with EU Regulation (GDPR, MDR, ...)
Economic	Large investments are required for implementing eHealth services	25) Return On Investment 26) Number successful certification

6.3.8.5 Technical requirements and gaps

This process requires continuous, bidirectional transmission of high-resolution video and data between patients, servers, and cloud-based DL systems. To ensure real-time performance, the network must support high data rates, ultra-low latency between patient movement and system response, and reliable connectivity. These requirements underline the critical role of future 6G infrastructure, which is expected to provide the necessary bandwidth, responsiveness, and nationwide coverage to enable seamless interaction, timely feedback, and data integrity essential for clinical use.

Table 6-21: Technical requirements for Telemedicine UC1 & UC2

Scenario Parameters	Max. latency [ms]	Throughput [Mbit/s]	Description
Remote Concurrent Preoperative Planning	10	100 – 400 UL Depends on frame rate and resolution.	Real latency 10–20ms is difficult to reach outside controlled environments and results too high for real-time feedback in concurrent VR and XR for motor tasks analysis. Effective uplink is often <1 Gbit/s in most home networks but high throughput required to reliably stream high-resolution video with lossless compression. 6G should ensure reduced real latency even in variable environments, enabling natural and immersive interactions and provide sufficient uplink rates to enable high-fidelity real-time visual processing.
Remote Rehabilitation Assessment	10	20	

The additional capabilities of Bandwidth reservation and Fixed routing are required for eHealth applications where reliable, stable, and uninterrupted communication is necessary.

6.3.9 Telemedicine UC3: Privacy-Aware Medical Data Federation with 6G-Assisted Trust Establishment

6.3.9.1 Use Case description

Qualtek's UC focuses on an e-Health/Telemedicine platform that features two key points:

The first point is about controlled utilisation of federated medical data on the grounds of trusted code to data patterns. Medical data may include patient records gathered and managed by institutions such as Hospitals, diagnostic centres or even doctors' offices. The data concept expands also to AI-developed diagnostic models due to the protection requirement against inference attacks. In principle the UC aims at demonstrating adequate sovereignty over personal or owned information and the value potential of it.

The second point is the provision of a trusted environment for data access and processing, that ensures protection (including confidentiality) in the management of medical information (which is considered sensitive personal data, as per GDPR [R2016/679]). This trust shall be provided by technical enforcement of the consent options of the individual, as stipulated by policies regarding provisions and prohibitions. The concept of the trusted environment expands to cater for protection requirements relating to data products (e.g. AI models) and credible attribution of data provenance and ownership to the providers of data and developers of AI models.

The UC focuses on exploiting data without the need for centralised architectures and data movement/duplication. This is achieved by introducing a data plane dimension that is integrated with and across the network (data-aware slices) and makes possible the utilisation of assets in various workflows and scenarios. The data plane dimension supports advertisement, discovery, usage negotiation and orchestration of trusted artifacts for the envisaged usage scenarios.

Data Utilisation Slice

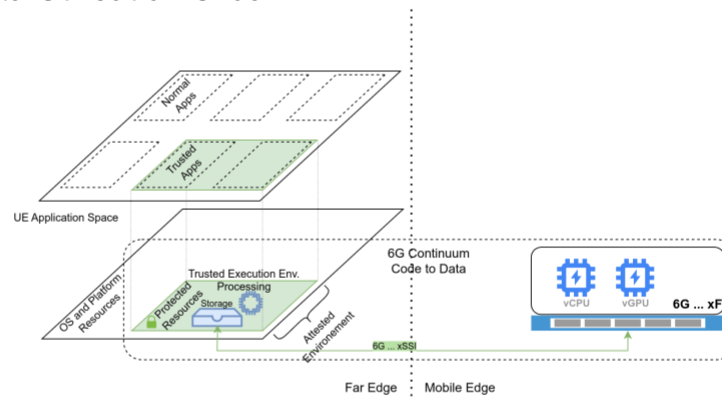


Figure 6-13: Illustration of the trusted execution network slice concept

Policy or regulation aspects (And Their Impact on Sustainability).

Medical data are primarily regulated by the GDPR [R2016/679] in the EU. In addition to the basic legal framework furnished by GDPR, a number of European Acts and Directives further refine aspects of use and dissemination of medical data, such as the NIS2 Directive, the ePrivacy directive, directive 2011/24/EU (data protection for patients seeking healthcare in other EU countries), EU MDR [R2017/745] and In Vitro Diagnostic Regulation (IVDR) 2017/746, (safety and performance of medical devices and diagnostic tools), the European Data Governance Act [R2022/868], the Digital Markets Act [R2022/1925] and Digital Services Act [R2022/2065] and others.

In addition to the state-imposed framework, there are numerous self-regulation initiatives for secure and ethical personal data use, such as AHIP⁸, HIMSS⁹ and ACT-IAC¹⁰ in the US, the international ISO/IEC 27701 standard for medical data privacy, or the *Partnership on AI* initiative.

Environment and deployment scenarios

The UC environment for the project will be based on emulated medical nodes holding personal data. These nodes should be possible to be attested for their integrity and their adherence to the envisaged operation. To this end, a software bill of materials signed by Hardware Root of Trust can be employed. The node attestation machinery can be developed independently of any network stack and can adapt to what will be available as a 6G stack in the course of the project. Applications built in the above concept will apply zero trust principles before any interaction. Regarding user space applications, we have to devise mechanisms to display reliability and integrity assurances that will support user awareness.

Qualtek has a prototype architecture that is based on a Fast Healthcare Interoperability Resources (FHIR) compliant server (that can be populated with synthetic data) integrated with a Data Space Connector (per domain) and custom integration software. The overall setup shall form the basis for elaborating and proving automated attestation practices.

Platforms/Devices

Requirements include ARM-based embedded boards, chipsets and Software Development Kits (SDKs) for development of 5G network software (6G-supporting material not expected during the project's lifetime), APIs and SDKs for development of, or ready-made APIs for mobile phones and finally simulated medical equipment/devices/data for integration with the trust stack.

⁸ <https://www.ahip.org/>

⁹ <https://www.himss.org/>

¹⁰ <https://www.actiac.org/>

6.3.9.2 State of the art

Currently, data federation and utilisation of data is mainly addressed by negotiated data transfers (Data Spaces, EU Health Data Space) among stakeholders that are certified within relevant ecosystems through manual processes.

The medical domain in particular is quite complex and is not completely addressed in current Data Spaces, because the roles of Stakeholders (i.e. the federation participants) as Data Controllers and Processors (according to GDPR) do not entitle unconditional data usage, but only what is foreseen by data subject consent.

6.3.9.3 Why this use case?

The UC challenges this pattern by introducing requirements aiming at automating enforcement of policies as well as guaranteeing that the overall data management is limited to what is foreseen by the will of the individual. Additionally, the UC invests significantly on the preservation of data value by ensuring that any exploitation of the primary or secondary products can trace back to the contributors, thus ensuring a proper share (claim of such share is not the subject of this UC however).

The UC aims for data to remain where they are created, with the 6G network adopting of the trusted-code- to data paradigm. It also aims to turn the use of AI-generated diagnostic models into a collaborative task with all participating nodes retaining fundamental rights, such as in/out opting and value share. Processing and training workflows not only shall address connectivity but also require active and trusted participation of the network in the processing plane. A new secure network slice pattern is to be created, which is enabling the individual to exploit/combine network connectivity capabilities with built-in privacy protection (e2e slice between owner's assets, e.g. phone or home camera). The envisaged components and patterns may allow for future intelligence orchestration by the network, instead of the participating business/application/service.

6.3.9.4 Stakeholders

The stakeholder group for the UC includes:

- **Healthcare infrastructure** such as hospitals and clinics, that may need to adapt for E2E telemedicine services, or to update existing infrastructure towards 6G-oriented services
- **Healthcare personnel** such as physicians, nurses and support personnel, that will have an interest/need to train in telemedicine applications and also to be instructed in the societal and psychological aspects of telemedicine practice
- **Insurance companies** and reimbursement services will also need to adapt existing policies involving more extensive use of ICT for issues such as transaction recording and verification
- **National and international regulatory & legislative bodies** shall need to account for the novel handling and management mechanisms proposed for 6G networks
- **Patients, consumers and advocacy groups** will also need to be updated on rights and legal recourse mechanisms for dispute settlement
- **Medical equipment companies** may see an expanded market for the supply of diagnostic/monitor aids tailored to telemedicine
- **Network infrastructure providers & operators**, must supply the novel 6G components to support telemedicine and will therefore need to update access and billing mechanisms
- **Companies** active in the telemedicine will also have impact on their business model.

6.3.9.5 Impact and sustainability analysis

The following table summarises the expected effects as headlines:

Table 6-22: Expected sustainability effects of Telemedicine UC3

Environmental sustainability		Social Sustainability		Economic Sustainability	
1st order effects	2nd order effects	1st order effects	2nd order effects	1st order effects	2nd order effects
Centralisation of data processing and	Physical transport and	Guaranteed privacy of	Increased public acceptance.	Delegation of data security to the network	Entry barrier lowered for new business.

network infrastructure	travel reduction.	access to health care.		and accordingly relief of end applications from this requirement.	
Reduction in power consumption.	Reduction in carbon emissions.				
Cost of energy & resources for network support of trusted execution.			Lack of trust in non-physical patient/health-professional interaction.	Revenue reduction and pressure onto business models built around end-point data security.	

6.3.9.6 Technical requirements and gaps

New functions need to be defined in the context of 6G networks, such as

- Network Slice Selection Function (NSSF)
- User Plane Function (UPF)
- Session Management function (SMF)
- Mobile Edge Computing (MEC).

For the 6G network's far edge we shall need items like a NAS (Non-Access Stratum) Protocol, to handle Session Management, etc. Mobile Applications that will communicate with the network shall include items such as e-Wallets and Trusted Applications, (routed onto an ARM-based Trusted Execution Environment).

6.3.9.7 A Demonstration Scenario

A plausible outline of our UC in action is as follows:

1. A patient visits a medical centre for a prescribed exam.
2. The infrastructure (e.g. CT scanner or data acquisition workflow) and the citizen (wallet app) ensure the identity of each other and agree to initiate a data collection session.
3. The data collected are directly encrypted and stored (the infrastructure is verified for adhering with this approach and this is assured in the previous handshake step).
4. The data remains inaccessible, and citizens have to supply consent options.
5. The stored options lead to metadata advertisement about types of available data but not the actual data.
6. The advertisement may be subject to query resolution about availability of data by a data engineer for the purposes of ML training.
7. Depending on the consent options data may be directly utilisable, or specific interest can be expressed to the data subject for inspection and approval.
8. Consolidated negotiations allow processing tasks to be sent close to data for performing the training phase, instead of the data being copied or otherwise accessed by the processing site.
9. The data subject (i.e. the patient) is always in a position to inspect usages of their data and the relation to newly created models.

7 Strategic recommendations

This document outlines the sustainability baseline and associated requirements, along with UC expectations, derived from an analysis of current 5G technologies and anticipated 6G developments, considering the evolving nature of 6G UC definitions. This chapter outlines strategic recommendations for the future work of SUSTAIN-6G project and are considered generally valid for the whole industry.

7.1 Strategic recommendations in the global context

Sustainability must be treated not as an afterthought but as a guiding principle in the design and deployment of 6G technologies. From the earliest stages of concept development to full-scale network operation, every component and system should be shaped by values such as energy efficiency, trust in AI-driven functions, climate resilience, and resource-conscious engineering. Practices like life cycle assessment, modular design, and clean production methods are critical enablers—not as stand-alone goals, but as part of a broader, integrated strategy for building technology that is not only high-performing, but also responsible, inclusive, and future-ready. This recommendation is formulated such that the industry must ***mandate sustainability-by-design (SbD) from inception***.

To ensure that sustainability is meaningfully embedded in the development of 6G, a multi-dimensional KPI/KVI framework must be introduced, which captures and balances environmental, economic, and societal priorities against technical performance advancements. Rather than optimising in isolation, this approach enables stakeholders to visualise and navigate complex trade-offs transparently. By integrating participatory processes, the framework empowers diverse actors to make informed, value-driven decisions that reflect shared objectives and competing constraints. It is essential to ***clearly present trade-offs in a transparent and understandable way***.

Driving sustainability in 6G requires careful focus on technologies that offer measurable sustainability benefits. By prioritising enabling solutions, we lay the groundwork for resilient and efficient networks. Creating an evolving catalogue of potential enabling technologies helps steer current research efforts, laying the groundwork for continuous innovation as these solutions mature. From a supply side perspective this approach ***accelerates the development of high impact enabling technologies***.

Achieving sustainability in 6G requires embedding intelligence into every phase of the network lifecycle. From site construction and equipment manufacturing and deployment to day-to-day operations, sustainability follows an active and adaptive process. For the operational phase networks can continuously optimise energy consumption, emissions, and resource allocation in response to dynamic conditions, by leveraging emerging technologies such as AI-driven orchestration, digital twins, and real-time monitoring. ***Integrating a sustainability mindset into the entire network lifecycle*** enables a responsive infrastructure, capable of balancing performance and efficiency, as well as meeting sustainability targets as an operational priority. For the design phase, and with sustainability in mind, we must plan also for end-of-life. Devices, components and systems must be built to be easily disassembled, reused, or recycled, reducing resource consumption. This forward-looking approach requires early integration of decommissioning strategies that align with international standards such as RoHS [D2002/95], the WEEE directive [D2012/19], or ISO 14006 [14006], ensuring that ***application of circular economy principles to end-of-life management*** becomes an operational norm.

So far mainly environmental considerations were in the focus. Following the separation of the overall sustainability topic into three pillars (environment, societal and economic), mandates an expansion of our perspective. Bridging the digital divide must become a design priority for the future 6G system. Beyond technical performance, 6G should actively promote digital equity, particularly in underserved and remote regions. This implies to design 6G with people in mind, creating pathways for local employment, investing in digital skills development, and respecting cultural contexts. By engaging communities early and transparently, 6G networks can become tools of empowerment enabling inclusive growth, co-creation of value, and long-term trust between technology providers, operators and the society they aim to serve. The design of 6G systems must ***ensure societal and economic inclusion***. Achieving sustainability in 6G requires global coordination and measurable accountability. By contributing proactively to the development of international standards the industry can ensure that environmental and societal responsibility are built into the specifications of next-generation networks.

These efforts should be closely aligned with broader policy frameworks, such as the UN Sustainable Development Goals, the EU Green Deal, and evolving climate regulations, to **shape standards and policies for coherent impact**. At the same time, it is necessary to define clear, robust sustainability KVIs tailored to the needs of society inducing societal acceptability, as well as KPIs tailored to 6G infrastructure and services, which can induce compelling economic incentives for vendors and operators to deliver and operate 6G systems.

7.2 Strategic recommendations related to the MNO perspective

To navigate the complex demands of sustainability, MNOs must adopt **holistic decision-support frameworks** that cover the full landscape of trade-offs, balancing economic performance, environmental responsibility, and social inclusion. Such frameworks must help assess outcomes across multiple KVIs, enabling smarter, more adaptive planning. This approach will allow MNOs to make decisions, which are financially viable as well as environmentally conscious and societally acceptable. To achieve long-term sustainability, **MNOs must evolve their business models** and embrace value-driven strategies that align profitability with environmental responsibility by offering modular service plans that reward efficient usage, through environmental performance metrics such as energy-aware service-level agreements. By collaborating on areas like shared infrastructure, operators can reduce both capital expenditure and environmental impact.

MNOs must implement **lifecycle-oriented network planning**, to strategically synchronise equipment lifecycles with decarbonisation targets. Offer and supply should match demand, ensuring that densification brings societal value without unnecessary environmental impact. By embedding circular economy principles from the outset operators can move from linear consumption to sustainable, lifecycle-wide network management.

Towards Sustainable 6G, **MNOs are committed to aligning with key values** across the three sustainability pillars: (i) Environmental: Minimising GHG emissions, energy use, e-waste, and natural resource depletion—supported by circular economy practices and efficient infrastructure design (supporting SDG #13), (ii) Economic: Ensuring the telecom sector’s long-term viability through affordability, cost optimisation, inclusive value creation and acceptability (supporting SDGs #8, #9), and (iii) Societal: Promoting decent work, digital inclusion, human rights, and trust (supporting SDGs #8, #9, #16).

7.3 Recommendations from a sustainable 6G technology perspective

To ensure a sustainable foundation for 6G networks, the access segment must consider technologies that are high-performing and environmentally conscious and infrastructure-efficient. **Wi-Fi technology** will continue playing an important role in indoor and dense urban scenarios, where intelligent spectrum sharing and energy-saving mechanisms like AI-optimised sleep cycles can drastically cut power consumption. Next-generation standards such as Wi-Fi 7 and beyond must be designed with energy-aware protocol stacks and seamless integration with other radio technologies to avoid redundant coverage. **LiFi technology** emerges as a compelling candidate for energy-efficient, high-bandwidth indoor communication, leveraging the existing lighting infrastructure. **Optical Camera Communication** enables data transmission via existing LEDs and cameras and presents a strong case for low-power, circular-economy-aligned innovation, allowing integration into consumer electronics. **Free Space Optics** offers high-capacity, fibre-like backhaul in hard-to-reach areas potentially without spectrum licensing. Together, these technologies represent a broader shift toward low-energy, spectrum-efficient, and infrastructure-light solutions, aligning performance objectives with the global sustainability mandate of 6G.

In the fixed access, **Passive Optical Network** technologies offer a compelling opportunity to balance ultra-high bandwidth with environmental responsibility. Gigabit Passive Optical Network minimises energy consumption by eliminating the need for powered components between core network components and data centres and end users, but its further extensions must be designed using technologies for intelligent power management (e.g., Wavelength Division Multiplexing) as well as with applying a strategy for coexistence and backward compatibility to reduce the need for new infrastructure and extending the life of existing assets.

The Radio Access Network (RAN) must evolve into an intelligent, energy-aware fabric that dynamically adapts to traffic, topology, and environmental conditions. From a standardisation perspective, **energy-saving enablers** are being embedded into 3GPP releases, promoting features like advanced sleep modes, symbol-level deactivation, and carrier aggregation management. These mechanisms enable time-domain power savings by aligning transmission activity with actual traffic demand, while frequency-domain techniques such as bandwidth part adaptation and carrier switching reduce active spectrum usage during low-load periods. In the spatial domain, innovations like massive MIMO beamforming and antenna muting allow for precise energy targeting, minimising unnecessary radiation. Meanwhile, power-domain strategies include dynamic voltage scaling and amplifier shutdown, thereby optimising hardware-level energy consumption. AI and ML are emerging as enablers for **RAN energy optimisation**. Operators are deploying AI-driven orchestration platforms that learn traffic patterns and environmental variables to activate energy-saving features without compromising user experience. Academic research is pushing this further, exploring explainable AI models that correlate RAN parameters like airtime, throughput, and buffer status with energy footprints. The ambition of achieving **zero-watt at zero load** is driving the development of granular energy consumption models that inform real-time decisions on cell activation, sleep scheduling, and load balancing. These models support the transition from reactive to predictive energy management. On the hardware front, sustainable massive connectivity hinges on the adoption of **low-power radio frequency technologies** and **eco-managed base stations** that autonomously regulate cooling, power supply, and component usage. Integrating renewable energy powered micro-grids into RAN sites further decouples energy consumption from carbon emissions, and can be further supported by liquid cooling technology. In the metro and core network segments, sustainability centres around **agile, high-capacity, and energy-aware infrastructures** that can scale with 6G demands while minimising impact. Segment Routing over MPLS and Optical Add-Drop Multiplexers (OADM) are elements of efficient traffic engineering and optical layer flexibility. SR-MPLS simplifies routing and reduces signalling overhead, enabling more deterministic paths and lower energy use across the transport layer. OADM allows dynamic wavelength management, reducing the need for full signal regeneration and thus conserving power. For backhauling, Free Space Optics (FSO) and mmWave RF offer high-throughput, license-free alternatives to fibre, especially in dense urban or hard-to-reach areas. Metro and core networks must embrace converged IP-optical architectures that reduce equipment layers and power draw. Core routers and edge devices should be optimised, e.g. through AI-driven load balancing to dynamically adapt to traffic patterns. Data centres should transition to liquid cooling and modular designs that support granular power management. Integrating energy harvesting technologies, can further decouple operations from carbon-intensive grids.

To build a sustainable 6G, generic technologies like AI/ML, cloud-native systems, and edge computing must be designed with environmental, societal, and economic considerations in mind. **AI/ML** must evolve beyond performance metrics to embrace sustainability as a guiding principle. Environmentally, this means reducing the first order effects of training and inference through model compression, federated learning, and energy-aware scheduling. Socially, AI must be inclusive, explainable, fair, and that its decisions are transparent and accountable. Economically, open-source ecosystems and modular AI architectures can democratise innovation, and lower barriers to entry. **Virtualised and cloud-native technologies** like containerisation and serverless computing offer a path to leaner, more efficient infrastructure, potentially reducing idle energy consumption and supporting elastic scaling. Green data centres, powered by renewables and cooled through advanced techniques like liquid immersion, form the physical backbone of this transformation. The **cloud/edge continuum** introduces new challenges and opportunities. At the far edge, where devices are resource-constrained and often off-grid, lightweight AI models, energy harvesting, and tamper-resistant hardware are essential.

Eco-design principles must be embedded into the design, including life cycle thinking to reduce impact from raw material sourcing to disposal. Systems should be resource-efficient, using less energy and fewer materials, favouring recyclables and low-energy components. Products must be durable and modular, easy to repair, disassemble, and recycle, while clean production techniques reduce emissions and toxicity. Packaging should be minimalist and recyclable, and devices must be energy-efficient, supporting low-power modes. Planning for end-of-life with clear labelling supports a circular economy. Avoiding hazardous substances ensures compliance and safer recycling. Finally, aligning with

environmental regulations like ISO 14006 and the EU EcoDesign Directive ensures designs meet future sustainability standards.

7.4 Recommendations from a 6G for sustainability perspective

While 5G has opened the door to enterprise innovation, many sectors still struggle to access the scale and performance required for truly transformative change. Against this backdrop, three verticals, **smart grids**, **agriculture**, and **telemedicine** stand out as critical arenas for 6G impact. These sectors are connectivity-intensive and central to societal well-being, environmental relevance, and economic resilience. Each addresses a core human need: energy, food, and health, and offers a unique opportunity for 6G to drive sustainable progress.

In the context of **sustainable agriculture**, 6G technologies promise to transform the sector by enabling smarter, more efficient, and environmentally conscious practices. With ultra-reliable, low-latency connectivity and native AI/edge integration, 6G will empower stakeholders in the industry to make real-time, data-driven decisions that optimise resource use and reduce environmental impact. **On-demand connectivity** in rural and remote areas will bridge the digital divide, allowing farmers to access precision tools and cloud services during critical periods like planting or harvesting. **Offloading to edge computing** supports intensive tasks directly to local nodes, reducing latency and energy consumption. Furthermore, 6G will help transform raw **agricultural data into actionable information**, enabling predictive insights into soil health, crop performance, and climate adaptation. This shift from data collection to intelligent interpretation will be key to meeting key values in the sector.

In the transition to a sustainable energy future, the 6G system offers a strategic enabler for the evolution of **smart grids**. By delivering ultra-low latency, high reliability, and pervasive connectivity, 6G can support real-time coordination of distributed energy resources, empowering prosumers and grid operators alike. Key stakeholders, such as institutional regulators, infrastructure providers and technology innovators, must collaborate to ensure that 6G and smart grid infrastructures are co-designed for maximum efficiency and resilience. UCs such as **grid balancing through distributed assets**, **resilient grid section operation**, and **joint infrastructure planning** illustrate how 6G can enhance flexibility, fault tolerance, and system-wide optimisation. Strategically, 6G should be positioned as a foundational layer for smart grids, enabling dynamic, data-driven energy ecosystems that are more efficient as well as sustainable and secure.

In the context of **telemedicine**, the 6G system is becoming a cornerstone for delivering equitable, high-quality healthcare at scale. With ultra-reliable, low-latency communication and native support for AI and edge computing, 6G can address critical challenges in remote diagnostics, patient monitoring, and data security. Strategically, 6G should be leveraged to support **real-time** collaboration in complex medical procedures, such as remote surgical planning, by enabling immersive, high-fidelity data exchange. It can also empower **AI-driven rehabilitation services**, allowing continuous patient assessment and adaptive care delivery. Furthermore, 6G's trusted network capabilities can underpin **privacy-aware data federation**, ensuring secure, consent-based sharing of sensitive health information across systems and stakeholders. To realise these benefits, collaboration among healthcare providers, regulators, infrastructure operators, and technology developers is essential. Together, they can shape a telemedicine ecosystem that is accessible, affordable, efficient, inclusive, and resilient.

8 Conclusions and future outlook

Deliverable D2.1 establishes a robust knowledge baseline and vision for sustainability in the 6G era—spanning technological enablers, and vertical UC potentials for assessing sustainability impact. By consolidating comprehensive findings from work on sustainable 6G concepts and technologies, as well as 6G for sustainability and UCs, this document provides clarity on *1st order effects* of 6G networks as well as *2nd order effect* across transformative application domains.

This deliverable maps out a trajectory for 6G development in which sustainability serves as a driver of innovation. It illustrates how principles like **sustainability-by-design**, **multi-KVI planning** approaches, **lifecycle-oriented MNO strategies**, and advances in technologies such as **RAN**, **PON**, and **AI-powered orchestration** can converge to enable 6G systems that are technically advanced as well as societally and environmentally responsible.

It highlights how 6G technologies can support sustainability objectives across key verticals. In agriculture, this includes enabling more data-driven and adaptive farming practices. In energy systems, 6G can facilitate improved coordination and efficiency in smart grid operations. In healthcare, it offers potential for enhanced remote care and monitoring. These examples illustrate the relevance of 6G as an enabler for sector-specific digitalisation aligned with broader sustainability goals.

This foundational synthesis directly supports the next phases of the project. In WP4, selected vertical UCs undergo detailed analysis to identify technical limitations, sustainability opportunities, and lifecycle-embedded requirements. deliverable D4.1, building on the outputs of D2.1, will detail the KPI and KVI expectations, current technology gaps, and the initial requirements for practical implementation of sustainable UCs.

In parallel, WP3 focuses on consolidating and assessing 6G technology solutions, performing a systematic sustainability-focused inventory and gap analysis. This work will yield deliverable D3.1, which captures the identification of relevant technologies and their sustainability impacts, laying the groundwork for deeper technical development in WP3 and contributing to implementation and validation strategies in WP5 and WP6. These efforts are tightly linked to the outputs of WP2 and exemplify the iterative, cross-cutting methodology of SUSTAIN-6G.

As the project progresses, Deliverable D2.1 will serve as both a reference and a directional guide, ensuring that sustainability remains a central design parameter in shaping the 6G systems of tomorrow. The insights consolidated here provide a shared vision and foundation for ongoing research, aligning technological ambition with societal needs and sustainability objectives.

9 References

[14006]	ISO 14006:2020, “Environmental management systems — Guidelines for incorporating ecodesign”, [online] available at https://www.iso.org/standard/72644.html [Accessed 22 July 2025]
[22.870]	3GPP TR 22.870, “Study on 6G Use Cases and Service Requirements”, V0.3.1, 23 June 2025
[28.908]	3GPP TR 28.908, “Study on Artificial Intelligence/Machine Learning (AI/ ML)”, V18.1.0, 2024
[33.501]	3GPP TS 33.501, “Security architecture and procedures for 5G System (Release 17)”, V 17.14.0, 2024
[3gp25]	3GPP News, “Overview of AI/ML related Work in 3GPP,” 16 February 2025. [online] available at https://www.3gpp.org/news-events/3gpp-news/ai-ml-2025
[6GCLOUD25]	6G Cloud project, website, [online] available at https://www.6g-cloud.eu/ [Accessed: 25 February 2025]
[6gs25]	6GSNS Smart Networks and Services Joint Undertaking, “AI/ML as a Key Enabler of 6G Networks”, whitepaper, 2025, [online] available at https://smart-networks.europa.eu/wp-content/uploads/2025/02/ai_ml_white-paper-sns_tb_v1.0.pdf
[6gw24]	6GWorld, “ Immersion, AI and reliability: Next G alliance details roadmap to 6G, 6GWorld”, [online] available at https://www.6gworld.com/exclusives/immersion-ai-and-reliability-next-g-alliance-details-roadmap-to-6g/ (Accessed: 25 February 2025).
[ACH+22]	A. E. Amine, J. -P. Chaiban, H. A. H. Hassan, P. Dini, L. Nuaymi and R. Achkar, "Energy Optimisation With Multi-Sleeping Control in 5G Heterogeneous Networks Using Reinforcement Learning," in IEEE Transactions on Network and Service Management, vol. 19, no. 4, pp. 4310-4322, Dec. 2022, doi:10.1109/TNSM.2022.3157650.
[ADN20]	A. E. Amine, P. Dini and L. Nuaymi, "Reinforcement Learning for Delay-Constrained Energy-Aware Small Cells with Multi-Sleeping Control," 2020 IEEE International Conference on Communications Workshops (ICC Workshops), Dublin, Ireland, 2020, pp. 1-6, doi:10.1109/ICCWorkshops49005.2020.9145431.
[AKN20]	I. Akyildiz, A. Kak and S. Nie, “6G and Beyond: The Future of Wireless Communications Systems,” IEEE Access, vol. 8, pp. 133995-134030, 2020.
[Alp25]	Alp Consulting, “The Possible Effects of 6G Transition on the Labour Market”, blog post, [online] available at https://alp.consulting/6g-impacts-on-labour-market/ [Accessed 28 July 2025]
[AMO+25]	A. I. Abubakar, M. S. Mollel, M. Ozturk, N. Ramzan, “FAMAC: A Federated Assisted Modified Actor-Critic Framework for Secured Energy Saving in 5G and Beyond Networks”, arXiv:2311.14509 [eess.SY]
[Arc25]	ARCEP, “Digital Device Ownership and Usage Digital Market Barometer: 2024 edition”, March 19, 2025, [online] available at https://en.arcep.fr/news/press-releases/view/n/digital-device-ownership-and-usage-190325.html
[ASB24]	Azmy, S.B. et al., “Extreme edge computing challenges on the edge-cloud continuum”, 2024 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), pp. 99–100. doi:10.1109/ccece59415.2024.10667328.
[AYY+17]	J. An, K. Yang, N. Ye, et al., “Achieve Sustainable Ultra-Dense Heterogeneous Networks for 5G”, arXiv:1711.05044 [cs.NI]
[BAP+22]	A. Bachoumis, N. Andriopoulos, K. Plakas, A. Magklaras, P. Alefragis and G. Goulas, “Cloud-Edge Interoperability for Demand Response-Enabled Fast

	Frequency Response Service Provision”, IEEE Transactions on Cloud Computing, vol. 10, no. 1, pp. 123-133, 2022
[BCB+11]	Pankaj Bhatia et.al., “Corporate Value Chain (Scope 3) Accounting and Reporting Standard”, Supplement to the Green House Gas Protocol Corporate Accounting and Reporting Standard, World Resources Institute and World Business Council for Sustainable Development, September 2011, ISBN 978-1-56973-772-9, [online] available at https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporting-Standard_041613_2.pdf
[Ber17]	S. Bergen, “Design Considerations for a 5G Network Architecture”, arXiv:1705.02902 [cs.NI]
[Ber22]	BEREC (Body of European Regulators for Electronic Communications), “BEREC Report on Sustainability: Assessing BEREC’s contribution to limiting the impact of the digital sector on the environment”, 9 June 2022.
[BMB+24]	F. Binucci, M. Merluzzi, P. Banelli, E. C. Strinati and P. Di Lorenzo, “Enabling Edge Artificial Intelligence via Goal-oriented Deep Neural Network Splitting”, 2024 19th International Symposium on Wireless Communication Systems (ISWCS), Rio de Janeiro, Brazil, 2024, pp. 1-6, doi:10.1109/ISWCS61526.2024.10639178.
[BML+19]	A. Berger, M. Meisel, L. Langer, M. Litzlbauer and M. Usler, “Stakeholderprozess der Initiative 'Referenzarchitektur für sichere Smart Grids in Österreich”, Berichte aus Energie- und Umweltforschung, vol. 33, 2019.
[Bru23]	Rogers Brubaker, “Hyperconnectivity and Its Discontent”, Hoboken, NJ: Polity, 2023, December 2024. Antropologicheskij forum 20(63):223-237. doi:10.31250/1815-8870-2024-20-63-223-237.
[Bru87]	G. Brundtland, “Our common future”, World Commission on Environment and Development, United Nations, 1987.
[BS20]	R. Brondolin and M. D. Santambrogio, “PRESTO: a latency-aware power-capping orchestrator for cloud-native microservices,” in 2020 IEEE International Conference on Autonomic Computing and Self-Organising Systems (ACSOS), Washington, DC, USA, Aug. 2020, pp. 11–20. doi:10.1109/ACSOS49614.2020.00021.
[Cap25]	Capgemini, “Developing sustainable Gen AI”, Report, 2025, [online] available at https://www.capgemini.com/insights/research-library/sustainable-gen-ai/
[Car09]	John B. Carter, “A look inside IBM's green data centre research”, In Proceedings of the 2009 ACM/IEEE international symposium on Low power electronics and design (ISLPED '09). Association for Computing Machinery, New York, NY, USA, 153–154, [online] available at https://doi.org/10.1145/1594233.1594270
[CDS+24]	E. C. Strinati et al., “Goal-Oriented and Semantic Communication in 6G AI-Native Networks: The 6G-GOALS Approach”, 2024 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Antwerp, Belgium, 2024, pp. 1-6, doi:10.1109/EuCNC/6GSummit60053.2024.10597087.
[Cen14]	CEN-CENELEC-ETSI Smart Grid Coordination Group, “SGAM User Manual - Applying, testing & refining the Smart Grid Architecture Model”, version 3.0, November 2014
[Chi24]	J. Childres, “The Rise of the 6G Network: What to Expect,” HP Tech Takes, 7 March 2024, [online] available at https://www.hp.com/us-en/shop/tech-takes/what-to-expect-from-6g-networks [Accessed 24 March 2025].
[CJL+24]	Mauro Cazzaniga, Florence Jaumotte, Longji Li, Giovanni Melina, Augustus J Pantan, Carlo Pizzinelli, Emma J Rockall, and Marina Mendes Tavares, “Gen-AI:

	Artificial Intelligence and the Future of Work”, Staff Discussion Notes 2024, 001 (2024), https://doi.org/10.5089/9798400262548.006
[CNC24]	CNCF TAG Environmental Sustainability, “Cloud Native Sustainability Landscape”, June 2024
[CV+25]	Chido Mpemba, Vivel Murthy et al., “Who Commission on Social Connection, Flagship report”, World Health Organisation. June 30, 2025. https://www.who.int/groups/commission-on-social-connection
[D2002/95]	European Union, “Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment”, Official Journal of the European Union, 13. February 2003, [online] available at https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:037:0019:0023:en:PDF
[D2012/19]	European Union, “Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast)”, Official Journal of the European Union, 24 July 2012, [online] available at https://eur-lex.europa.eu/eli/dir/2012/19/oj/eng
[D2018/2001]	European Union, “Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)”, Official Journal of the European Union, 21. December 2018, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001
[D2023/2413]	European Union, “Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652”, Official Journal of the European Union, 31. October 2023, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302413
[D2024/1711]	European Union, “Directive (EU) 2024/1711 of the European Parliament and of the Council of 13 June 2024 amending Directives (EU) 2018/2001 and (EU) 2019/944 as regards improving the Union’s electricity market design”, Official Journal of the European Union, 26. June 2024, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401711
[Das25]	S. Dash, “Green AI: Enhancing Sustainability and Energy Efficiency in AI-Integrated Enterprise Systems”, in IEEE Access, vol. 13, pp. 21216-21228, 2025, doi:10.1109/ACCESS.2025.3532838
[Dav25]	N. Davis, “Free online virtual reality tool helps people tackle public speaking nerves,” The Guardian, 15 March 2025, [online] available at https://www.theguardian.com/technology/2025/mar/15/online-vr-tool-virtual-reality-public-speaking-nerves-anxiety [Accessed 24 March 2025].
[DDL14]	C. Desset, B. Debaillie and F. Louagie, “Modeling the hardware power consumption of large scale antenna systems,” 2014 IEEE Online Conference on Green Communications (OnlineGreenComm), AZ, USA, 2014, pp. 1-6, doi:10.1109/OnlineGreenCom.2014.7114430.
[DDL15]	B. Debaillie, C. Desset and F. Louagie, “A Flexible and Future Proof Power Model for Cellular Base Stations”, 2015 IEEE 81 st Vehicular Technology Conference (VTC Spring). Glasgow, UK, 2015, pp. 1-7, doi:10.1109/VTCSpring.2015.7145603
[Den22]	Denkstatt GmbH, “Pathway to Net Zero”, factsheet, December 2022, [online] available at https://denkstatt.at/wp-content/uploads/2023/05/Decarbonization-and-Neutrality_denkstatt.pdf

[Des12]	C. Desset et al., "Flexible power modeling of LTE base stations," in Proc. IEEE Wirel. Commun. Netw. Conf. (WCNC), Paris, France, 2012, pp. 2858-2862, doi: 10.1109/WCNC.2012.6214289
[DR02]	Daemen, J., & Rijmen, V. (2002). The Design of Rijndael: AES - The Advanced Encryption Standard. Springer
[DS22]	R. L. Devi and V. Saminadan, "Machine Learning Based Traffic Prediction System in Green Cellular Networks," 2022 1st International Conference on Computational Science and Technology (ICCST), CHENNAI, India, 2022, pp. 593-596, doi:10.1109/ICCST55948.2022.10040347
[DT225]	Derek Thomson, "The Antisocial Century", The Atlantic, January 8, 2025, [online] available at https://www.theatlantic.com/magazine/archive/2025/02/american-loneliness-personality-politics/681091/
[Dua25]	Fabio Duarte, "Time Spent Using Smartphones (2025 Statistics)", June 5, 2025, [online] available at https://explodingtopics.com/blog/smartphone-usage-stats
[Dwo08]	C. Dwork, "Differential privacy: A survey of results," in International Conference on Theory and Applications of Models of Computation. Springer, 2008, pp. 1–19.
[EB24]	H. Edquist and P. Bergmark, "How is mobile broadband intensity affecting CO ₂ emissions? – A macro analysis," Telecommunications Policy, vol. 48, no. 2, March 2024, [online] available at https://doi.org/10.1016/j.telpol.2023.102668
[Edg24]	Edge Impulse, "The Ultimate Guide to Edge AI," blog post, December 2024, [online] available at https://www.edgeimpulse.com/blog/the-ultimate-guide-to-edge-ai/
[Eea14]	European Environment Agency, "Water use in Europe in 2014," EEA Signals 2014, [online] available at https://www.eea.europa.eu/signals-archived/signals-2018-content-list/articles/water-use-in-europe-2014
[EF23]	Rania El-Khattab and Salma Fathy, "Energy-Efficient Computing: Innovations in Hardware and Software for Sustainable Advanced Computing Systems", JACS, Vol. 3, N° 11, 2023, [online] available at https://scipublication.com/index.php/JACS/article/view/38
[EFA17]	G. Egea, J. E. Fernandez, F. Alcon, "Financial assessment of adopting irrigation technology for plant-based regulated deficit irrigation scheduling in super high-density olive orchards", Agricultural Water Management, vol. 187, 2017, pp. 47-56, [online] available at https://doi.org/10.1016/j.agwat.2017.03.008 .
[EHA24]	M. Al-Emran, B. Abu-Hijleh and A. A. Alsewari, "Exploring the Effect of Generative AI on Social Sustainability Through Integrating AI Attributes, TPB, and T-EESST: A Deep Learning-Based Hybrid SEM-ANN Approach," in IEEE Transactions on Engineering Management, vol. 71, pp. 14512-14524, 2024, doi: 10.1109/TEM.2024.3454169.
[EIH+19a]	A. El-Amine, M. Iturralde, H. A. Haj Hassan and L. Nuaymi, "A Distributed Q-Learning Approach for Adaptive Sleep Modes in 5G Networks," 2019 IEEE Wireless Communications and Networking Conference (WCNC), Marrakesh, Morocco, 2019, pp. 1-6, doi: 10.1109/WCNC.2019.8885818.
[EIH+19b]	A. El-Amine, H. A. Haj Hassan, M. Iturralde and L. Nuaymi, "Location-Aware Sleep Strategy for Energy-Delay Tradeoffs in 5G with Reinforcement Learning," 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Istanbul, Turkey, 2019, pp. 1-6, doi: 10.1109/PIMRC.2019.8904155.
[Eri24]	Ericsson, "Digital transformation of industries to enable Net Zero," 2024. [online] available at https://www.ericsson.com/en/about-us/sustainability-and-corporate-

	responsibility/environment/climate-action/decarbonising-industries [Accessed 11 March 2025].
[Ets25]	ETSI, “ETSI AI Conference - How Standardisation is Shaping the Future of AI”, February 2025, [online] available at https://www.etsi.org/events/2451-etsi-ai-conference-2025
[Eur19a]	European Commission, “The European Green Deal – Striving to be the first climate-neutral continent”, November 2019, [online] available at https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en [Accessed 28 July 2025]
[Eur19b]	European Commission: Directorate-General for Climate Action, “Going climate-neutral by 2050 – A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy”, Publications Office, 2019, [online] available at https://data.europa.eu/doi/10.2834/02074 [Accessed 28 July 2025]
[Eur23]	European Commission, “Artificial Intelligence: Economic Impact, Opportunities, Challenges, Implications for Policy,” Directorate-General for Economic and Financial Affairs, Brussels, 2024.
[Eur25]	European Union Agency for the Cooperation of Energy Regulators (ACER), “Recommendation 01/2025 (...) on reasoned proposal for the establishment of the Network Code on Demand Response according to Article 59(1)(e) of Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast)”, 7. March 2015, [online] available at https://www.acer.europa.eu/sites/default/files/documents/Recommendations/ACER_Recommendation_01-2025_Demand_Response_Network_Code.pdf
[Fft20]	Forum for the Future, “The Five Capitals - a framework for sustainability”, 2020, [online] available at https://www.forumforthefuture.org/the-five-capitals
[FMF+23]	H. Fourati, R. Maaloul, L. Fourati and M. Jmaiel, “An Efficient Energy-Saving Scheme Using Genetic Algorithm for 5G Heterogeneous Networks”, in IEEE Systems Journal, vol. 17, no. 1, pp. 589-600, March 2023, doi:10.1109/JSYST.2022.3166228.
[GAR+24]	L. Golard, Y. Agram, F. Rottenberg, F. Quitin, D. Bol and J. Louveaux, “A Parametric Power Model of Multi-Band Sub-6 GHz Cellular Base Stations Using On-Site Measurements”, 2024 IEEE 35th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Valencia, Spain, 2024, pp. 1-7, doi:10.1109/PIMRC59610.2024.10817448.
[GB23]	D. Ghosh and S. H. Bharathi, “Energy Consumption Saving in 5G Network Based on Artificial Intelligence”, 2023 International Conference for Advancement in Technology (ICONAT), Goa, India, 2023, pp. 1-6, doi:10.1109/ICONAT57137.2023.10080476.
[GCL+20]	Y. Gao, J. Chen, Z. Liu, B. Zhang, Y. Ke and R. Liu, “Machine Learning based Energy Saving Scheme in Wireless Access Networks”, 2020 International Wireless Communications and Mobile Computing (IWCMC), Limassol, Cyprus, 2020, pp. 1573-1578, doi:10.1109/IWCMC48107.2020.9148536.
[Ges15]	Global e-Sustainability Initiative, “Smarter2030 Opportunity: ICT Solutions for 21st Century Challenges”, 2018, [online] available at SMARTer2030_Full_report_Status_2015-06-07_v04 . [Accessed June 3 2025]
[Git25]	GitHub, “Container Level Energy-efficient VPA Recommender”, [online] available at GitHub - sustainable-computing-io/clever: Container Level Energy-efficient VPA Recommender
[Glo25]	GlobalG.A.P., “Global smart farm assurance solutions”, website, [online] available at https://www.globalgap.org/ [Accessed July 28, 2025]

[Gsm25]	GSMA, “The Mobile Economy 2025”, 2025, [online] available at https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-economy/wp-content/uploads/2025/02/030325-The-Mobile-Economy-2025.pdf [Accessed July 23rd 2025]
[GSQ+16]	Ariel Gomez, Kai Shi, Crisanto Quintana, Grahame Faulkner, Benn C. Thomsen, and Dominic O’Brien, “A 50 Gb/s Transparent Indoor Optical Wireless Communications Link With an Integrated Localisation and Tracking System.” <i>Journal of Lightwave Technology</i> 34, no. 10 (May 15, 2016): 2510–17.
[HEX21-D12]	Hexa-X, “Deliverable D1.2: Expanded 6G vision, use cases and societal values – including aspects of sustainability, security and spectrum (extension of D1.1)”, April 2021.
[HEX22-D13]	Hexa-X, “Deliverable D1.3: Targets and requirements for 6G - initial E2E architecture,” April 2022.
[HEX23-D14]	Hexa-X, “Deliverable D1.4: Hexa-X architecture for B5G/6G networks – final release,” July 2023.
[HEXAX21]	Hexa-X (2021) Hexa-X. Available at: https://hexa-x.eu/ (Accessed: 25 February 2025).
[HEXII23-D11]	Hexa-X-II, “Deliverable D1.1: Environmental, social, and economic drivers and goals for 6G,” June 2023
[HEXII25-D14]	Hexa-X-II, “Deliverable D1.4: 6G Value, Requirements and Ecosystem”, April 2025
[HLL+20]	X. Hou, C. Li, J. Liu, L. Zhang, Y. Hu, and M. Guo, “ANT-Man: Towards Agile Power Management in the Microservice Era,” in <i>SC20: International Conference for High Performance Computing, Networking, Storage and Analysis</i> , Atlanta, GA, USA: IEEE, Nov. 2020, pp. 1–14. doi:10.1109/SC41405.2020.00082.
[Hnr24]	HNR, “5G vs 6G: What’s the Difference and What Should You Expect?”, blog post, 9. September 2024, [online] available at https://thehnr.com/5g-vs-6g-whats-the-difference-and-what-should-you-expect/
[Hug25]	Hugging Face, “Announcing AI Energy Score: Evaluating AI models on energy efficiency”, [online] available at https://huggingface.co/blog/sasha/announcing-ai-energy-score
[Imf24]	International Monetary Fund, “Gen-AI: Artificial Intelligence and the Future of Work,” IMF Staff Discussion Note, Washington, D.C., 2024
[Int18]	Intergovernmental Panel on Climate Change (IPCC), “Annex I: Glossary”, In: <i>Global Warming of 1.5°C. An IPCC Special Report</i> , 2018, Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-562, [online] available at https://doi.org/10.1017/9781009157940.008
[Int22]	Intel, “Technology guide power manager – kubernetes operator, Kubernetes Power Manager”, 2022, [online] Available at: https://builders.intel.com/docs/networkbuilders/power-manager-kubernetes-operator-technology-guide-1669984380.pdf (Accessed: 25 February 2025).
[Isp24]	International Society of Precision Agriculture (ISPA), “Precision Ag Definition”, January 2024, [online] available at https://ispag.org/about/definition [Accessed 26 March 2025].
[IYI23]	A. Israr, Q. Yang and A. Israr, “Renewable Energy Provision and Energy-Efficient Operational Management for Sustainable 5G Infrastructures”, in <i>IEEE Transactions on Network and Service Management</i> , vol. 20, no. 3, pp. 2698-2710, Sept. 2023, doi:10.1109/TNSM.2023.3244618.
[JBY+20]	Chaoqiang Jin, Xuelian Bai, Chao Yang, Wangxin Mao, and Xin Xu, “A review of power consumption models of servers in data centres”, <i>Applied Energy</i> 265, 2020, [online] available at https://doi.org/10.1016/j.apenergy.2020.114806

[JHS24]	Leif Johansson, Per Holmberg and Robert Skog, “Designing energy-efficient cloud-native mobile networks”, Ericsson Technology Review - Charting the future of innovation #2, February 2024
[JKK+20]	H. Ju, S. Kim, Y. Kim, H. Lee and B. Shim, “Energy-Efficient Ultra-Dense Network using Deep Reinforcement Learning”, 2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Atlanta, GA, USA, 2020, pp. 1-5, doi:10.1109/SPAWC48557.2020.9154261.
[Kal24]	S. Kallio, “A transparent and methodical framework to assess the sustainability impact of AI”, blog post, September 2024, [online] available at https://www.nokia.com/blog/a-transparent-and-methodical-framework-to-assess-the-sustainability-impact-of-ai/
[Kal24]	Susanna Kallio, “A transparent and standards-based way to assess the environmental impact of AI systems”, Nokia blog post, September 2024, [online] available at https://www.nokia.com/blog/a-transparent-and-methodical-framework-to-assess-the-sustainability-impact-of-ai
[Kar25]	Karunanithi, V., “Techno-Feudalism: The New Digital Serfdom”, LinkedIn Pulse, [online] available at https://www.linkedin.com/pulse/techno-feudalism-new-digital-serfdom-varshini-karunanithi-ftguc/ [Accessed 28 July 2025]
[KPR23]	A. Khoshsirat, G. Perin and M. Rossi, “Divide and Save: Splitting Workload Among Containers in an Edge Device to Save Energy and Time”, 2023 IEEE International Conference on Communications Workshops (ICC Workshops), Rome, Italy, 2023, pp. 134-138, doi:10.1109/ICCWorkshops57953.2023.10283807
[KPR24]	A. Khoshsirat, G. Perin, M. Rossi, “Decentralised LLM Inference over Edge Networks with Energy Harvesting,” 2024, [online] available at https://arxiv.org/abs/2408.15907
[Kub24]	Kubernetes, “Horizontal pod autoscaling”, 2024, [online] available at: https://kubernetes.io/docs/tasks/run-application/horizontal-pod-autoscale/ [Accessed: 25 February 2025]
[Kub24]	Kubernetes, “Production-grade container orchestration”, 2024, [online] available at https://kubernetes.io/ [Accessed 25 February 2025]
[Kub25]	Kubernetes, “Autoscaling workloads”, [online] available at https://kubernetes.io/docs/concepts/workloads/autoscaling/ [Accessed 25 February 2025]
[L.1410]	International Telecommunication Union, Recommendation ITU-T L.1410, “Methodology for environmental life cycle assessments of information and communication technology goods, networks and services”, November 2024
[L.1480]	International Telecommunication Union, Recommendation ITU-T L.1480, “Enabling the Net Zero transition: Assessing how the use of information and communication technology solutions impact greenhouse gas emissions of other sectors”, December 2022
[LCG+14]	D. Lo, L. Cheng, R. Govindaraju, L. A. Barroso, and C. Kozyrakis, “Towards energy proportionality for large-scale latency-critical workloads,” ACM SIGARCH Comput. Archit. News, vol. 42, no. 3, pp. 301–312, Jun. 2014, doi:10.1145/2678373.2665718.
[Lif25]	LiFi Group Connectivity, “LiFi Companies”, [online] available at https://lifi.co/lifi-companies/
[LLW+23]	Y. Li, Y. Lin, Y. Wang, K. Ye and C. Xu, “Serverless Computing: State-of-the-Art, Challenges and Opportunities”, in IEEE Transactions on Services Computing, vol. 16, no. 2, pp. 1522-1539, 1 March-April 2023, doi:10.1109/TSC.2022.3166553

[LSL+22]	K. B. Letaief, Y. Shi, J. Lu and J. Lu, “Edge Artificial Intelligence for 6G: Vision, Enabling Technologies, and Applications”, in IEEE Journal on Selected Areas in Communications, vol. 40, no. 1, pp. 5-36, Jan. 2022, doi:10.1109/JSAC.2021.3126076.
[LSZ+24]	T. Lv, Q. Sun, L. Zhang, Y. Wu and J. Zhang, “An Intelligent Energy Saving Strategy Recommendation Method of 5G Base Station Based on GBDT+FM”, 2024 IEEE 21st International Conference on Mobile Ad-Hoc and Smart Systems (MASS), Seoul, Korea, Republic of, 2024, pp. 520-526, doi:10.1109/MASS62177.2024.00082.
[M.2160]	ITU-R Recommendation M.2160, “Framework and overall objectives of the future development of IMT for 2030 and beyond”, November 2023.
[MAA+20]	Matinmikko-Blue, M., Aalto, S., Asghar, M. I., Berndt, H., & Chen, Y., “6G Drivers and the UN SDGs”, whitepaper, 2020, University of Oulu: 6G Flagship Program, [online] available at https://arxiv.org/abs/2004.14695
[Mal24]	Malmio, I., “Artificial intelligence and the social dimension of sustainable development: through a security perspective”, Discov Sustain 5, 466, 2024, [online] available at https://doi.org/10.1007/s43621-024-00677-6
[Mck20]	McKinsey & Company, “Connected world: An evolution in connectivity beyond the 5G revolution”, discussion paper, 20 February 2020, [online] available at https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/connected-world-an-evolution-in-connectivity-beyond-the-5g-revolution
[Mck25]	McKinsey & Company, “AI in the workplace: A report for 2025”, McKinsey & Company, 2025, [online] available at https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/superagency-in-the-workplace-empowering-people-to-unlock-ais-full-potential-at-work
[MHC+19]	Shahjalal, Md., Moh. Khalid Hasan, Mostafa Zaman Chowdhury, and Yeong Min Jang, “Smartphone Camera-Based Optical Wireless Communication System: Requirements and Implementation Challenges”, Electronics 8, no. 8, August 19, 2019
[MLR22]	Y. Matsubara, M. Levorato, and F. Restuccia, “Split computing and early exiting for deep learning applications: Survey and research challenges,” ACM Comput. Surv., March 2022, [online] available at https://doi.org/10.1145/3527155
[MLZ+24]	Y. Ma, T. Li, Y. Zhou, L. Yu and D. Jin, “Mitigating Energy Consumption in Heterogeneous Mobile Networks Through Data-Driven Optimisation”, in IEEE Transactions on Network and Service Management, vol. 21, no. 4, pp. 4369-4382, Aug. 2024, doi:10.1109/TNSM.2024.3416947.
[MMC+23]	L. Maggi et al., “Energy Savings under Performance Constraints via Carrier Shutdown with Bayesian Learning”, 2023 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Gothenburg, Sweden, 2023, pp. 1-6, doi:10.1109/EuCNC/6GSummit58263.2023.10188338.
[MPF23]	S. Malta, P. Pinto and M. Fernández-Veiga, “Using Reinforcement Learning to Reduce Energy Consumption of Ultra-Dense Networks With 5G Use Cases Requirements”, in IEEE Access, vol. 11, pp. 5417-5428, 2023, doi:10.1109/ACCESS.2023.3236980.
[MS24]	N. Movahedkor and R. Shahbazian, “Decentralised Federated Deep Reinforcement Learning Framework for Energy-Efficient Base Station Switching Control”, 2024 11th International Symposium on Telecommunications (IST), Tehran, Iran, Islamic Republic of, 2024, pp. 455-460, doi:10.1109/IST64061.2024.10843518,

[MUA+23]	L. Marques, P. Uchida, F. Aguiar, G. Kadri, R. Santos and S. Barbosa, “Escaping through virtual gaming—what is the association with emotional, social, and mental health? A systematic review,” <i>Frontiers in Psychiatry</i> , vol. 14, p. 1257685, 2023.
[MYH+24]	Y. Mao, X. Yu, K. Huang, Y. -J. Angela Zhang and J. Zhang, “Green Edge AI: A Contemporary Survey”, in <i>Proceedings of the IEEE</i> , vol. 112, no. 7, pp. 880-911, July 2024, doi:10.1109/JPROC.2024.3437365
[MZZ+23]	H. Ma, Z. Zhou, X. Zhang and X. Chen, “Toward Carbon-Neutral Edge Computing: Greening Edge AI by Harnessing Spot and Future Carbon Markets”, in <i>IEEE Internet of Things Journal</i> , vol. 10, no. 18, pp. 16637-16649, 15 Sept.15, 2023, doi:10.1109/JIOT.2023.3268339
[Nat25]	National Institute of Standards and Technology, “Post-Quantum Cryptography”, Computer Security Resource Centre, [online] available at https://csrc.nist.gov/projects/post-quantum-cryptography [Accessed 28 July 2025]
[Nex25]	Next G Alliance, “Sustainable AI in Telecom: Promises and Challenges in 6G,” Report, February 2025, [online] available at https://nextgalliance.org/white_papers/sustainable-ai-in-telecompromises-and-challenges-in-6g/
[Nex25]	NextG Alliance, “Sustainable AI in Telecom: Promises and Challenges in 6G. February 2025”, report, February 2025, [online] available at https://nextgalliance.org/white_papers/sustainable-ai-in-telecompromises-and-challenges-in-6g/
[Nic18]	Jones Nicolas, “How to stop data centres from gobbling up the world’s electricity”, <i>Nature</i> , 2018.
[Nok25]	Nokia, “KDDI energy efficiency case study”, [online] available at https://www.nokia.com/ai-and-analytics/ava-energy-efficiency/kddi-ai-ran-energy-case-study/
[NS24]	Dabok Noh and Mi-So Shim, “Factors influencing smartphone overdependence among adolescents. Scientific reports. April 2, 2024. https://doi.org/10.1038/s41598-024-58152-1
[NT21]	Nakabi, T., and Toivanen, P., “Deep reinforcement learning for energy management in a microgrid with flexible demand”, <i>Sustainable Energy, Grids and Networks</i> , 25, 100413, 2021
[Nvi17]	NVIDIA, “NVIDIA V100 GPU Architecture”, 2017, [online] available at https://images.nvidia.com/content/volta-architecture/pdf/volta-architecture-whitepaper.pdf
[Org23]	Organisation for Economic Co-operation and Development (OECD), “Measuring the environmental impacts of artificial intelligence: Compute and applications”, Report, 2023, [online] available at https://www.oecd.org/en/publications/measuring-the-environmental-impacts-of-artificial-intelligence-compute-and-applications_7babf571-en.html
[PBE+22]	G. Perin, M. Berno, T. Erseghe and M. Rossi, "Towards Sustainable Edge Computing Through Renewable Energy Resources and Online, Distributed and Predictive Scheduling," in <i>IEEE Transactions on Network and Service Management</i> , vol. 19, no. 1, pp. 306-321, March 2022, doi:10.1109/TNSM.2021.3112796
[PDB+21]	N. Piovesan et al., “Forecasting Mobile Traffic to Achieve Greener 5G Networks: When Machine Learning is Key”, 2021 IEEE 22nd International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Lucca, Italy, 2021, pp. 276-280, doi:10.1109/SPAWC51858.2021.9593102.

[PDL+21]	N. Piovesan et al., “Mobile Traffic Forecasting for Green 5G Networks”, 2021 IEEE Global Communications Conference (GLOBECOM), Madrid, Spain, 2021, pp. 1-6, doi:10.1109/GLOBECOM46510.2021.9685639.
[PMD+24]	Jary Pomponi, Mattia Merluzzi, Alessio Devoto, Mateus Pontes Mota, Paolo Di Lorenzo, Simone Scardapane, “Goal-oriented Communications based on Recursive Early Exit Neural Networks”, in proceedings of IEEE Asilomar 2024, [online] available at https://arxiv.org/abs/2412.19587
[PR25]	David Patterson and Parthasarathy Ranganathan, “Designing sustainable AI: A deep dive into TPU efficiency and lifecycle emissions”, [online] available at https://cloud.google.com/blog/topics/sustainability/tpus-improved-carbon-efficiency-of-ai-workloads-by-3x
[PSA23]	Paes, V.M., Silveira, F.F., Akkari, A.C.S., “Social Impacts of Artificial Intelligence and Mitigation Recommendations: An Exploratory Study”, In: Iano, Y., Saotome, O., Kemper Vásquez, G.L., Cotrim Pezzuto, C., Arthur, R., Gomes de Oliveira, G. (eds), Proceedings of the 7th Brazilian Technology Symposium (BTSym’21). BTSym 2021. Smart Innovation, Systems and Technologies, vol 207. Springer, Cham. [online] available at https://doi.org/10.1007/978-3-031-04435-9_54
[PTS+24]	Yashwant Singh Patel, Paul Townsend, Anil Singh and Per-Olov Ostberg, “Modelling the Green Cloud Continuum: integrating energy considerations into Cloud–Edge models”, Cluster Computing, Volume 27, pages 4095-4125, April 2024
[R2016/679]	European Union, “Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation)”, Official Journal of the European Union, 4 May 2016, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0679
[R2017/745]	European Union, “Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices, amending Directive 2001/83/EC, Regulation (EC) No 178/2002 and Regulation (EC) No 1223/2009 and repealing Council Directives 90/385/EEC and 93/42/EEC”, Official Journal of the European Union, 5 May 2017, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R0745
[R2018/848]	European Union, “Regulation (EU) 2018/848 of the European Parliament and the Council on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007”, Official Journal of the European Union, 14 June 2018, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R0848
[R2021/1119]	European Union, “Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’), Official Journal of the European Union, 9 July 2021, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119
[R2022/868]	European Union, “Regulation (EU) 2022/868 of the European Parliament and of the Council of 30 May 2022 on European data governance and amending Regulation (EU) 2018/1724 (Data Governance Act)”, Official Journal of the European Union, 3 June 2022, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R0868
[R2022/1925]	European Union, “Regulation (EU) 2022/1925 of the European Parliament and of the Council of 14 September 2022 on contestable and fair markets in the digital sector and amending Directives (EU) 2019/1937 and (EU) 2020/1828 (Digital

	Markets Act)”, Official Journal of the European Union, 12 October 2022, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R1925
[R2022/2065]	European Union, “Regulation (EU) 2022/2065 of the European Parliament and of the Council of 19 October 2022 on a Single Market For Digital Services and amending Directive 2000/31/EC (Digital Services Act)”, Official Journal of the European Union, 27 October 2022, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R2065
[R2024/1689]	European Union, “Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144 and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828 (Artificial Intelligence Act)”, Official Journal of the European Union, 12 July 2024, [online] available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401689
[RHK+21]	Roslan, M. F., Hannan, M. A., Ker, P. Muttaqi, K. M., & Mahlia, T. M., “Optimisation algorithms for energy storage integrated microgrid performance enhancement”, Journal of Energy Storage, 43, 103182, November 2021
[RR24]	Ritchie Hannah and Rosado Pablo, “Electricity mix: Explore data on where our electricity comes from and how this is changing”, 2024, [online] available at https://ourworldindata.org/electricity-mix
[RSA78]	Rivest, R. L., Shamir, A., & Adleman, L., “A method for obtaining digital signatures and public-key cryptosystems”, Communications of the ACM, 21(2), 120–126.
[RSR24]	F. Rossi, M. Schoenstein and S. Russell, “AI’s potential futures: Mitigating risks, harnessing opportunities”, OECD.AI Policy Observatory, 19 December 2024, [online] available at https://oecd.ai/en/wonk/ai-potential-futures [Accessed 11 March 2025].
[RTY+21]	T. Rumeng, W. Tong, S. Ying and H. Yanpu, “Intelligent Energy Saving Solution of 5G Base Station Based on Artificial Intelligence Technologies”, 2021 IEEE International Joint EMC/SI/PI and EMC Europe Symposium, Raleigh, NC, USA, 2021, pp. 739-742, doi:10.1109/EMC/SI/PI/EMCEurope52599.2021.9559261.
[RWM+24]	Friederike Rohde et. al., “Broadening the perspective for sustainable artificial intelligence: sustainability criteria and indicators for Artificial Intelligence systems”, Current Opinion in Environmental Sustainability, Volume 66, 2024, 101411, ISSN 1877-3435
[SAG+18]	F. E. Salem, Z. Altman, A. Gati, T. Chahed and E. Altman, “Reinforcement Learning Approach for Advanced Sleep Modes Management in 5G Networks”, 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), Chicago, IL, USA, 2018, pp. 1-5, doi:10.1109/VTCFall.2018.8690555.
[Sam25]	Samsung Electronics, “AI-Native & Sustainable Communication”, February 2025, [online] available at https://research.samsung.com/next-generation-communications
[SBC20]	W. Saad, M. Bennis and M. Chen, “A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems”, IEEE Network, vol. 34, no. 3, pp. 134-142, 2020.
[SCA+19]	F. E. Salem, T. Chahed, Z. Altman, & Gati, A., “Traffic-aware advanced sleep modes management in 5G networks”, In 2019 IEEE wireless communications and networking conference (WCNC) (pp. 1-6), 2019

[Sci25]	Science Based Target initiative, Standards and Guidance, website, [online] available at https://sciencebasedtargets.org/standards-and-guidance [Accessed 28 July 2025]
[SDK23]	A. Samorzewski, M. Deruyck and A. Kliks, "Energy Consumption in RES-Aware 5G Networks", GLOBECOM 2023 - 2023 IEEE Global Communications Conference, Kuala Lumpur, Malaysia, 2023, pp. 1024-1029, doi:10.1109/GLOBECOM54140.2023.10437451
[Sen24]	Sensor Tower, "State of Mobile 2024", The Industry's Leading Report, 2024, [online] available at https://sensortower.com/state-of-mobile-2024
[SGA+17]	F. E. Salem, A. Gati, Z. Altman and T. Chahed, "Advanced Sleep Modes and Their Impact on Flow-Level Performance of 5G Networks", 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), Toronto, ON, Canada, 2017, pp. 1-7, doi:10.1109/VTCFall.2017.8288125.
[SGH+25]	Selva, E. et al., "Towards a 6G embedding sustainability", 2023 IEEE International Conference on Communications Workshops (ICC Workshops), Rome, Italy, May 2023, [online] available at https://doi.org/10.48550/arXiv.2307.06636 [Accessed 25 February 2025]
[SGM22]	V. Singh, M. Gupta and C. Maciocco, "Intelligent RAN Power Saving using Balanced Model Training in Cellular Networks", 2022 20th International Symposium on Modeling and Optimisation in Mobile, Ad hoc, and Wireless Networks (WiOpt), Torino, Italy, 2022, pp. 357-364, doi:10.23919/WiOpt56218.2022.9930603.
[Sil22]	Silicom, "Silicom's eASIC ACC100 FEC Accelerator", documentation, 2022, [online] available at https://www.silicom-usa.com/wp-content/uploads/2022/10/LisbonACC100-FEC-Accelerator-Extended-temp-Server-Adapter.pdf
[SIX+24]	J. Stojkovic, N. Iliakopoulou, T. Xu, H. Franke and J. Torrellas, "EcoFaaS: Rethinking the Design of Serverless Environments for Energy Efficiency," 2024 ACM/IEEE 51st Annual International Symposium on Computer Architecture (ISCA), Buenos Aires, Argentina, 2024, pp. 471-486, doi:10.1109/ISCA59077.2024.00042.
[SJR22]	Kateryna Savelieva, Markus Jokela and Anna Rotkirch, "Reasons to Postpone Childbearing during Fertility Decline in Finland", June 2022, [online] available at https://www.tandfonline.com/doi/full/10.1080/01494929.2022.2083283
[SS23]	S. Sinha and K. Sengupta, "Examining the Impact of 6G Telecommunications on Society: What to consider before the next generation of connectivity," IEEE Spectrum, 10 January 2023. [online] available at https://spectrum.ieee.org/examining-the-impact-of-6g-telecommunications-on-society [Accessed 24 March 2025].
[STP+23]	M. Sarajlić, N. Tervo, A. Pärssinen et al., "Waveforms for sub-THz 6G: Design Guidelines", 2023 European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Gothenburg, Sweden, June 6-9, 2023
[The24]	The Shift Project, "Lean Networks for Resilient Connected Uses", report, March 2024, [online] available at https://theshiftproject.org/app/uploads/2025/02/The-Shift-Project-Lean-networks-for-resilient-connected-uses-Final-report-March-2024.pdf [Accessed 28 July 2025]
[TMF+24]	N. Trabelsi, R. Maaloul, L. C. Fourati and W. Jaafar, "Deep Reinforcement Learning for Sleep Control in 5G and Beyond Radio Access Networks: An Overview", 2024 International Wireless Communications and Mobile Computing (IWCMC), Ayia Napa, Cyprus, 2024, pp. 1404-1411, doi:10.1109/IWCMC61514.2024.10592464.

[TPK23]	M. Tsenos, A. Peri and V. Kalogeraki, “Energy Efficient Scheduling for Serverless Systems”, 2023 IEEE International Conference on Autonomic Computing and Self-Organising Systems (ACSOS), Toronto, ON, Canada, 2023, pp. 27-36, doi:10.1109/ACSOS58161.2023.00020.
[TSF+22]	R. Tan, Y. Shi, Y. Fan, W. Zhu and T. Wu, “Energy Saving Technologies and Best Practices for 5G Radio Access Network”, in IEEE Access, vol. 10, pp. 51747-51756, 2022, doi:10.1109/ACCESS.2022.3174089.
[Une21]	UNESCO, “Recommendation on the Ethics of Artificial Intelligence”, 2021, [online] available at https://www.unesco.org/en/articles/recommendation-ethics-artificial-intelligence
[Unf22]	United Nations Food and Agriculture Organisation (FAO), “AQUASTAT: Global irrigation water withdrawals are estimated at approximately 3,500 km ³ /year (blue water only)”, https://www.fao.org/aquastat/en/overview/methodology/water-use [Accessed 23 July 2025]
[Uni15]	United Nations, Department of Economic and Social Affairs, “Sustainable Development Goals”, New York, September 2015, [online] available at https://sdgs.un.org/goals
[Vis20]	Harish Viswanathan, “Towards a 6G era”, Bell Labs, 2020
[VKS24]	B. Valkhof, E. Kemene, J. Stark, “Data volume is soaring. Here’s how the ICT sector can sustainably handle the surge”, World Economic Forum, May 2024, [online] available at https://www.weforum.org/stories/2024/05/data-growth-drives-ict-energy-innovation/
[VWD+23]	H. Viswanathan, S. Wesemann, J. Du et al., “Energy efficiency in next-generation mobile networks”, white paper, Nokia Bell Labs, 2023, [online] available at https://www.nokia.com/asset/212810/
[Wat25]	WatchGuard, “Compare Wi-Fi 6 Access Points”, [online] available at https://www.watchguard.com/fr/wgrd-products/access-points/compare-appliances , [Accessed 28 July 2025]
[WCZ+21]	Q. Wu, X. Chen, Z. Zhou, et al., “Deep Reinforcement Learning with Spatio-temporal Traffic Forecasting for Data-Driven Base Station Sleep Control”, [online] available at https://arxiv.org/pdf/2101.08391
[Who21]	WHO (World Health Organisation), “Decade of Healthy Ageing - Social Isolation and Loneliness Among Older People”, 2021, [online] available https://iris.who.int/bitstream/handle/10665/343206/9789240030749-eng.pdf
[Who25]	WHO (World Health Organisation), “Mental Health and Social Connection”, January 15, 2025, [online] available at https://apps.who.int/gb/ebwha/pdf_files/EB156/B156_8-en.pdf
[WI24]	World Bank and ITU, “Measuring the Emissions & Energy Footprint of the ICT Sector: Implications for Climate Action”, Washington, D.C. and Geneva, 2024, [online] available at https://documents1.worldbank.org/curated/en/099121223165540890/pdf/P17859712a98880541a4b71d57876048abb.pdf
[Wik24]	Gustav Wikström, “European view on 6G use cases”, presentation at 3GPP Stage 1 workshop on IMT2030 use cases, Rotterdam, The Netherlands, 08-10 May 2024, [online] available at https://www.3gpp.org/ftp/workshop/2024-05-08_3GPP_Stage1_IMT2030_UC_WS/Docs/SWS-240018.zip
[Win22]	WINGS, “wi.SENSE: WINGS IoT based intelligent platform for Sustainable Environments,” WINGS, 2022, [online] available at https://www.wings-ict-solutions.eu/wi-sense/ . [Accessed 24 March 2025].
[Wor23]	World Bank Group, “Green Digital Transformation: How to Sustainably Close the Digital Divide and Harness Digital Tools for Climate Action”, Climate Change

	and Development Series. Washington, DC, 2023, doi:10.1596/978-1-4648-2002-1. License: Creative Commons Attribution CC BY3.0 IGO, [online] available at https://openknowledge.worldbank.org/handle/10986/40653
[Wor24]	World Economic Forum, Centre for the Fourth Industrial Revolution, “Top 10 emerging technologies of 2024”, Report, June 2024, [online] available at https://www.weforum.org/publications/top-10-emerging-technologies-2024/
[Wor25]	World Economic Forum, “The Future of Jobs Report 2025”, Report, January 2025, [online] available at https://www.weforum.org/publications/the-future-of-jobs-report-2025/digest/
[WP-EU]	Worldometer, Europe Population (Live), [online] available at https://www.worldometers.info/world-population/europe-population
[WPR+18]	Mikko Wahlroos, Matti Pärssinen, Samuli Rinne, Sanna Syri, Jukka Manner, “Future views on waste heat utilisation – Case of data centres in Northern Europe”, Renewable and Sustainable Energy Reviews, Volume 82, Part 2, 2018, Pages 1749-1764, ISSN 1364-0321, [online] available at https://doi.org/10.1016/j.rser.2017.10.058
[WSS22]	Jet Wildeman, Sandor Schrijner and Jeroen Smits, “Fertility Rates and Social Media Usage in Sub-Saharan Africa”, Wiley Online Library, November 24, 2022, [online] available at https://onlinelibrary.wiley.com/doi/10.1002/psp.2635
[Wyn21]	Van Wynsberghe, A., “Sustainable AI: AI for sustainability and the sustainability of AI”, AI Ethics 1, pp. 213–218, 2021. [online] available at https://doi.org/10.1007/s43681-021-00043-6
[XHY+22]	Z. Xiang, M. Höweler, D. You, M. Reisslein, and F. H. P. Fitzek, “X-MAN: A Non-Intrusive Power Manager for Energy-Adaptive Cloud-Native Network Functions”, IEEE Trans. Netw. Serv. Manag., vol. 19, no. 2, pp. 1017–1035, Jun. 2022, doi:10.1109/TNSM.2021.3126822.
[You22]	YouTube, “Smart office Chalucet using Optical Camera Communication indoor mapping system”, 2022, [online] available at https://youtu.be/VC2M7tvA_F4
[ZAD+24]	M. Zhang, M. Abdi, V. R. Dasari, F. Restuccia, “Semantic Edge Computing and Semantic Communications in 6G Networks: A Unifying Survey and Research Challenges”, [online] available at https://arxiv.org/abs/2411.18199 , November 2024
[ZWX+22]	Z. Zhang, M. Wei, X. Xu, C. Hu and W. Xie, “Intelligent Energy Saving Technology and Strategy of 5G RAN”, 2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Bilbao, Spain, 2022, pp. 1-6, doi:10.1109/BMSB55706.2022.9828681.
[ZZG+15]	S. Zhang, S. Zhou, J. Gong, et al., “Spatial Traffic Shaping in Heterogeneous Cellular Networks with Energy Harvesting”, 2015 IEEE Global Communications Conference (GLOBECOM), San Diego, USA, December 6-10, 2015, doi: 10.1109/GLOCOM.2015.7417251
[ZZT+24]	H. Zou, Q. Zhao, Y. Tian, L. Bariah, F. Bader, T. Lestable, M. Debbah, “TelecomGPT: A Framework to Build Telecom-Specific Large Language Models”, [online] available at https://arxiv.org/abs/2407.09424

10 List of Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
5G	5th Generation mobile wireless communication system
5G-AKA	5G Authentication and Key Agreement
6G	6th Generation mobile wireless communication system
ADMS	Advanced Distribution Management Systems
AES	Advanced Encryption Standard
API	Application Programming Interface
AR	Augmented Reality
BEREC	Body of European Regulators for Electronic Communications
BS	Base Station
CAGR	Compound Annual Growth Rate
CAPEX	CAPital EXpenditure
CoC	Code of Conduct
CP-OFDM	Cyclic Prefix Orthogonal Frequency Division Multiplexing
CSI-RS	Channel State Information Reference Signal
CSO	Cell Switch Off
CU	Central Unit
DERMS	DER Management Systems
DER	Distributed Energy Resources
DP	Differential Privacy
DRL	Deep Reinforcement Learning
DSO	Distribution System Operator
DU	Data Unit
E2E	End-to-End
ECC	Elliptic Curve Cryptography
EMF	Electromagnetic Field
EMS	Energy Management System
EPD	Environmental Product Declarations
FiWi	Fiber Wireless
HA	Hardware Accelerator
FOMO	Fear of Missing Out
FSO	Free Space Optics
FTTC	Fiber-to-the-Curb
FTTR	Fiber-to-the-Room
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GEO	Geosynchronous Equatorial Orbit
GHG	Greenhouse Gas
G-PON	Gigabit Passive Optical Network
HAP	High-Altitude Platform
HIPAA	Health Insurance Portability and Accountability Act
HMD	Head-mounted Display
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission

IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMT	International Mobile Telecommunications
IoT	Internet of Things
IR	Infrared
ISO	International Organization for Standardisation
ITU	International Telecommunication Union
KPI	Key Performance Indicator
KV	Key Value
KVI	Key Value Indicator
LAN	Local Area Network
LAPS	Low Altitude Platform Service
LCA	Life Cycle Assessment
LEM	Local Energy Market
LEO	Low Earth Orbit
LLM	Large Language Model
LoRaWAN	Long Range Wide Area Network
LTE	Long Term Evolution
LV	Low Voltage
MDR	Medical Device Regulation
MIMO	Multiple Input Multiple Output
ML	Machine Learning
MNO	Mobile Network Operator
MV	Medium Voltage
NB-IoT	Narrowband Internet of Things
NE	Network Element
NIST	National Institute of Standards and Technology
NR	New Radio
NTN	Non-Terrestrial Network
OADM	Optical Add-Drop Multiplexers
OCC	Optical Camera Communication
OEO	Optical-Electronic-Optical
OLT	Optical Line Termination
ONT	Optical Network Termination
OPEX	Operational Expenditure
PAPR	Peak-to-Average Power Ratio
PET	Privacy Enhancing Technologies
PON	Passive Optical Network
PQC	Post-Quantum Cryptography
QoE	Quality of Experience
QoS	Quality of Service
QPS	Quantum Signal Processing
RAN	Radio Access Network
RES	Renewable Energy Sources
RF	Radio Frequency
RL	Reinforcement Learning

RoHS	Restriction of Hazardous Substances
ROI	Return on Investment
RSA	Rivest–Shamir–Adleman
RX	Receiver
SBA	Service Based Architecture
SbD	Sustainability-by-Design
SCADA	Supervisory Control and Data Acquisition
SDK	Software Development Kit
SGAM	Smart Grid Architecture Model
SIB1	System Information Block 1
SME	Small and Medium Enterprises
SNS	Smart Networks and Services
SotA	State-of-the-Art
SSB	Synchronisation Signal Block
TCO	Total Cost of Ownership
TLS	Transport Layer Security
TN	Terrestrial Network
TSOs	Transmission System Operators
TX	Transmitter
UAV	Unmanned Aerial Vehicle
UC	Use Case
UN SDGs	United Nations Sustainable Development Goals
URLLC	Ultra-Reliable Low-Latency Communication
VL	Visible Light
VR	Virtual Reality
WDM	Wavelength Division Multiplexing
WEEE	Waste Electrical and Electronic Equipment
WHO	World Health Organisation
WP	Work Package
XR	eXtended Reality

11 Glossary and Definitions

The definitions provided in the following list reflect the consensus within the SUSTAIN-6G consortium at the time of the respective publication. These terms may be revised in the future if needed.

Term	Definition	Notes
Eco-design	The integration of environmental aspects into the product development process, by balancing ecological and economic requirements. Eco-design considers environmental aspects at all stages of the product development process, striving for products which make the lowest possible environmental impact throughout the product life cycle.	See https://www.eea.europa.eu/help/glossary/eea-glossary/eco-design UNEP. 2001. Cleaner production: a guide to information sources.
Effect	“Effect” refers to the result or consequence on the environment, economy or society that follows from ICT existence or usage.	Effects can be short term/long term, intended/unintended, reversible/irreversible, desired/undesired, direct/indirect, etc.
Enablement	Enablement is the positive second order effect covering environmental, societal and economic pillars	ITU-T definition was widened to other environmental aspects as well, such as societal and economic aspects. It is always about positive – second order effects – covering environmental, societal and economic aspects.
Evaluation	Evaluation is the process of computing quantitative information or assembling qualitative assertions of characteristics of a certain design and is linked to KPIs or KVIIs.	
First order effect	This is the direct economic, societal or environmental effect associated with the existence of an ICT based solution, and generic processes supporting the deployment and operation of the ICT based solution. These could be positive and/or negative for a stakeholder.	Effect is recursively used. Proposal is to use outcome in the definition. Note: Examples of first order effects include, the raw materials acquisition, production, use and end-of-life treatment stages. Note: First order effects are related to the technology deployment choice
Impact	Impact refers to the effect activities have on sustainability values. Here, a direct impact means that the provisioning of a service is studied, while an indirect impact means that the usage of a service is studied. Both direct and indirect impact can be either positive or negative.	
Key Performance Indicator (KPI)	Quantitative indicators for measuring the technology components and technical enablers of a UC throughout its lifecycle.	
Key Value Indicator (KVI)	Forward-looking qualitatively or quantitatively measurable indicators for the KVs to align outcome and impact against objectives. Specifically, UC KVIIs are used to assess the impact of a UC outcome, while technology enabler KVIIs are used to assess the impact of the technology applied to a UC to deliver the outcomes, on the KVs of the UC.	

Key Values (KV)	Key Value refers to principles or qualities that individuals or groups deem important, desirable, or intrinsically good that may be addressed or impacted by ICT.	
KVI target value	Estimates / targets regarding the changes envisioned as an outcome of the UC execution (positive or negative, as a limit). KVIs should have a baseline value reflecting the status quo.	
Platform	A platform is a coherent ecosystem comprising hardware, software, and tools for validation, evaluation, and verification that enables end-to-end (E2E) integration, experimentation, and monitoring of 6G technologies. Platforms may include multiple testbeds and support PoC implementation. They can be purely software-based, hardware-based, or hybrid, and are designed to support the integration of different technologies.	
Requirements	Functionalities or performance parameters defined as KPIs for the realisation of a component / system or network for one of different UCs.	
Scenario	A broader description of a context within which a system, product, technology, service is used: environment, background, circumstances of use, users, and vision of a future desired state. Scenarios can encompass multiple use cases or interactions and provide context for understanding the users' needs, behaviours, motivations. Examples: agriculture e-health / telemedicine, energy / smart grid.	
Scope 1 emissions	Direct emissions from owned or controlled sources	Reference: [BCB+11]
Scope 2 emissions	Indirect emissions from the generation of purchased energy consumed by the reporting company	Reference: [BCB+11]
Scope 3 emissions	All other indirect emissions that occur in a company's value chain	Reference: [BCB+11]
Second order effect	This is the effect induced by the use and application of ICT based solution which includes economic, societal or environmental changes. These could be positive and/or negative for a stakeholder.	Effect is recursively used. Proposal is to use outcome in the definition. Note: Examples of second order effects include reduced GHG emissions from reduced travel due to the use of ICTs, more efficient agriculture (e.g., less fertiliser/water consumption) thanks to ICT solutions, increase of video streaming usage due to its ease of use, social media Note: Second order effects target the intended purpose of use of ICT technology in the vertical sector. Second order effects also consider broader effects that the technology might trigger in society that we do not have full control over.
Sustainability	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs	United Nations (SDGs)
Sustainability pillars	Environmental sustainability: refers to responsibility to conserve natural resources and protect global ecosystems	

	to support health and wellbeing. Societal sustainability : refers to inclusive, empowered, and resilient societies where citizens have equal opportunities, access to affordable energy, water, food, housing, education, healthcare, and job opportunities, where they have a voice, and governments respond. Economic sustainability : refers to practices that support long-term economic growth without negatively impacting societal, environmental, and cultural aspects.	
Sustainability aspects	Sustainable 6G : refers to the ambition to minimise the direct negative sustainability value outcomes, i.e. the first order effects. 6G for Sustainability : refers to the indirectly induced contribution (benefits and challenges) of 6G to the various aspects of sustainability in vertical sectors, with the ambition to maximise positive sustainability value outcomes.	
Sustainability dimensions	Six combinations of sustainability pillars and sustainability aspects	
Technical enabler	The technology components / systems or networks needed to deliver the key values for a UC.	
Testbed	A testbed is a physical or virtual environment designed for experimentation, validation, and evaluation of network technologies. These environments include various infrastructure elements such as radio access networks, core networks, edge/cloud resources, user equipment devices and other relevant elements.	
Use Case (UC)	Specific description of an interaction between a system and its users, or multiple systems / users within a scenario. Outlines the usage of a system, product, service, technology to achieve a specific outcome, with details on deployment and user actions. Focus on functionalities and interactions, detailing the sequence of events from the user's perspective, and requirements measurable by key performance indicators.	
Validation	The process to check whether a certain design is appropriate for the purpose and meets the requirements and constraints. The outcome of validation is the assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. Validation is linked to requirements specification. It answers the question “Are we building the right system?”	
No split to outcome and goal	High-level human values as goals, like United Nation Sustainability Development Goals (UN SDGs) or subsets.	
No split to outcome and goal	The positive and negative impacts of the technology to the values as goals. Possibly positive and negative from the use of the technology and negative from its deployment. That is, values directly and indirectly impacted by the deployment and use of the technology.	