White Paper

6G Energy Efficiency and Sustainability

Version 1.0

6G Platform Germany

Federal Ministry of Education and Research

Fraunhofer IIS

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2 Executive Summary

This white paper addresses the 6G research community as well as the 5G/6G Stakeholders.

Approved in 2020 the European Green Deal states a set of policy initiatives with the overarching aim of making the European Union (EU) climate neutral in 2050. To achieve this aim, the greenhouse gas (GHG) emission has to be halved by 2030 since GHG emissions and withdrawals must be balanced within the European Union by 2050 at the latest in order to subsequently achieve negative emissions.

In this context, the BMBF funded 6G Platform project [1] is to work on overarching issues for researching and developing the foundations for a future 6G standard, bring together future projects from the 6G initiative and contribute to a process proposal. Its mission is to address issues of high social relevance like technological sovereignty, protection of privacy, security, sustainability, ensuring comprehensive participation opportunities, social acceptance among others.

This white paper deals with the current status of the main activities towards sustainability for current mobile communication networks with extension to future development. It covers the essential aspects of helping the digitized society become climate-neutral by 2050 at the latest. Moreover, relevant scientific activities of Fraunhofer IIS will complement this general overview of the work currently done or ongoing to qualify and quantify sustainability in the mobile communication context.

Starting with motivation and challenges in Chapter 3, Chapter 4 gives an overview of industry driven initiatives and standardization activities related to sustainability of mobile communication networks. Subsequently, Chapter 5 presents metrics for sustainability already established today. Chapter 6 describes relevant energy saving techniques discussed in standardization bodies, followed by a review of referenced work from the literature and based on practical experience on sustainable 6G methods and technologies in Chapter 7. This white paper concludes by discussing the impact of new energy-saving techniques on mobile communications, as well as opening up further relevant aspects of sustainability in future 6G networks.

In this white paper we give an overview of the current state of the art of sustainability in future mobile networks.

WE CORDIALLY INVITE THE RESEARCH COMMUNITY TO WORK WITH US ON THE TOPIC OF SUSTAINABILITY IN FUTURE MOBILE NETWORKS.

3 Motivation and Challenges

3.1 Sustainability as Common Goal for Industry, Research, and Society

The word sustainability is on everyone´s lips today: a worldwide joint effort at all levels of society is needed in order to achieve it.

In view of the deterioration of the global environment and climate conditions, as well as the ever increasingly energy- and resource-intensive lifestyles of consumers in a progressively digitalized and connected society, **joint initiatives** by industry, research institutes, and **standardization bodies** are focusing their effort on sustainability matters. They work together on methods, KPIs, benchmarks and solutions for current and future generations of mobile communication.

This is the reason why the German 6G-Platform project installs an expert group for sustainability issues. This expert group, composed of the German partners of the 6G Research and Industrial Hubs, has the mission to examine the current research and standardization landscape and the activities in the 6G Hubs, to identify priority topics that deliver value to the 6G industry including verticals. Moreover, this expert group will also provide scientific input to the 6G community.

THIS WHITE PAPER IS A STARTING STATEMENT ON SUSTAINABILITY ISSUES, METHODS AND STANDARDS, FOCUSING ON THE 6G CONTEXT FOR THE 6G PLATFORM PROJECT.

3.2 Accepting Challenges

In fact, we are all aware that **the resources on our planet and therefore for our livelihood are limited.**

There is a clear finite availability of raw materials such as water, wood, metals, natural gas, coal. Due to a worldwide demand for resources e.g., for buildings, mobility, telecommunications, products, electronics, etc. we are living in a global view in an ecological deficit. For example, it takes the Earth one year and eight months to regenerate what we consume worldwide in one year [2]. The metric to measure and illustrate this is so-called "Overshoot Day", the day where a dedicated country or part of the world starts living "on credit".

Nevertheless, we notice also a **rapid growth of the digitalized society** and of the consumer behavior.

The digitalized society (Information and Communication Technologies, internet, LTE/5G, autonomous and connected mobility, smart buildings, smart home, smart cities, smart health, home working, and home schooling to list few items) produces a huge quantity of data to be generated, transferred, processed and memorized. Here is a view of the growth in IT services (Figure 1) and the mobile data volume in Germany (Figure 2), which rises continuously and steeply as shown.

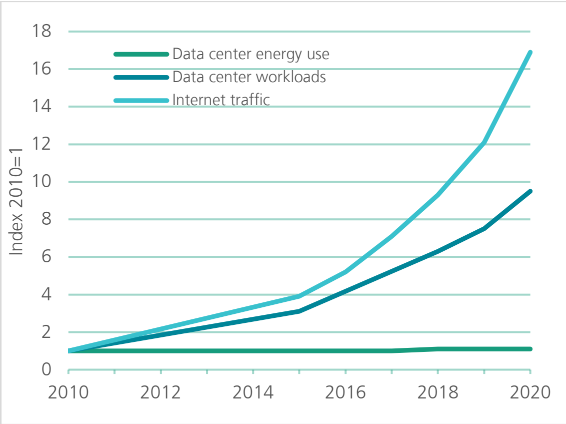


Figure 1: development of IT services between 2010- 2020 (source IEA [3])

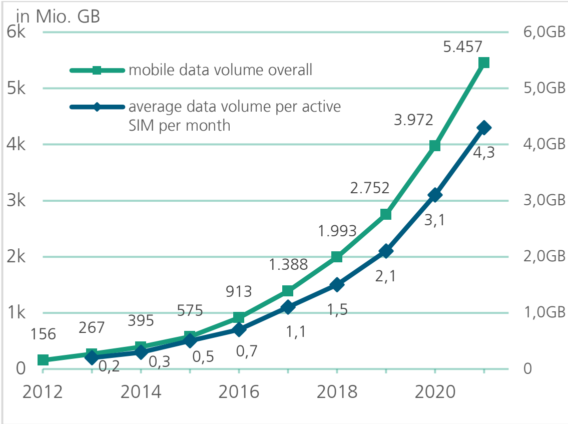


Figure 2: data volume in mobile networks in Germany (source: Bundesnetz Agentur [4])

Between 2020 and 2021, data traffic in mobile networks in Germany grew by about 30%!

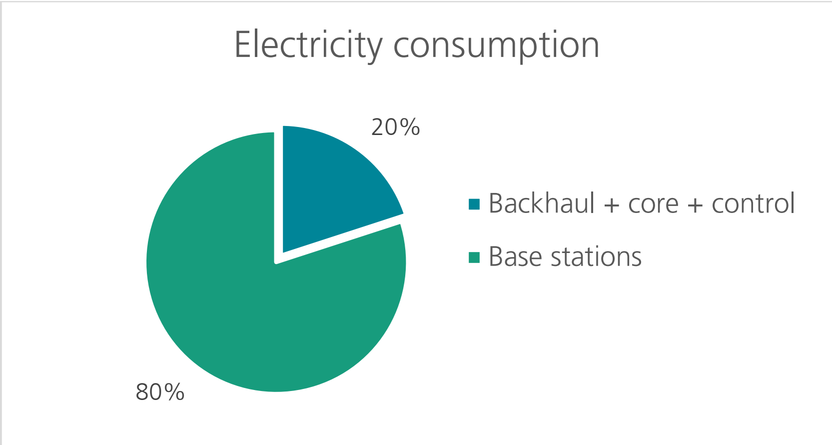


Figure 3: Energy Consumption [5]

Even if the energy consumption in data center can offset the growth of data volume, the situation on the Radio Network side is different: base stations take about 80% of the mobile network energy – see Figure 3.

From a technical point of view, it is a major challenge not to further increase or even reduce the energy consumption of the base stations despite the exploding demand for mobile data.

Through a rapid technological evolution of IT products, the consumer market pushes to change products every 2 to 5 years (e.g., smartphone, laptops) because of new features and better performances. The following figure shows the average lifespan of such products.

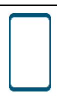
Devices							
Average lifetime in years	1,5	6	6	4	5	4	7

Figure 4: average lifespan of consumer electronics [6]

This shows that both technological and societal efforts need to be made to overcome this issue, e.g., by replacing modules, updates via download, use of more recycled materials etc.

The following subchapter introduces the sustainability case addressed in this white paper.

3.3 Sustainability with 6G or Sustainable 6G

Principally, we can associate mobile communication and sustainability in two different ways: Sustainability by using mobile communication technologies or sustainability of mobile communication technologies itself.

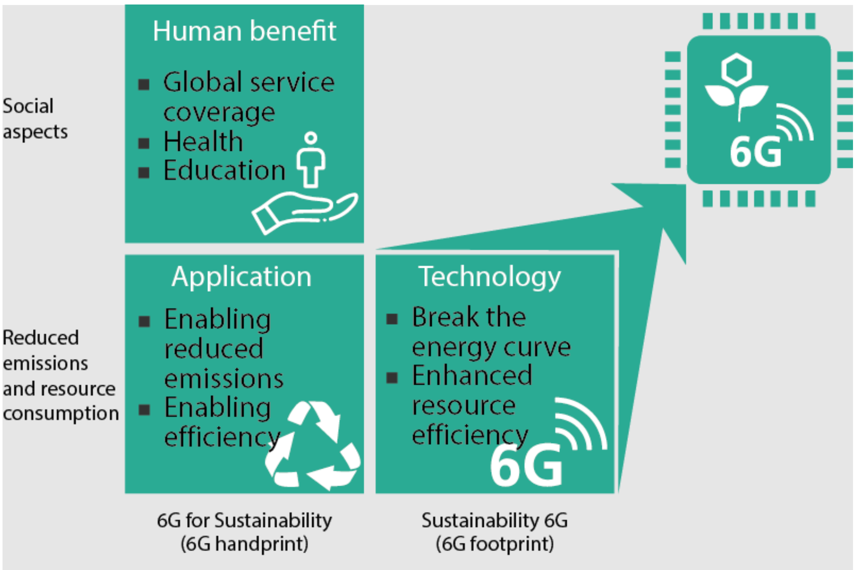


Figure 5: 6G handprint and 6G footprint

On the following, we will concentrate on the sustainable mobile communication part, focusing on issues about energy and resource efficient 6G technologies.

Addressing the issue of sustainable future mobile communication is one key point of the German 6G-Platform project. The working group "sustainability" focuses on gathering and networking interested partners from the 6G community and moderating the exchanges in the sustainable group.

The main goal is to reinforce the importance of sustainability to reduce the carbon footprint of future mobile networks and to generate added value regarding new green technologies and solutions.

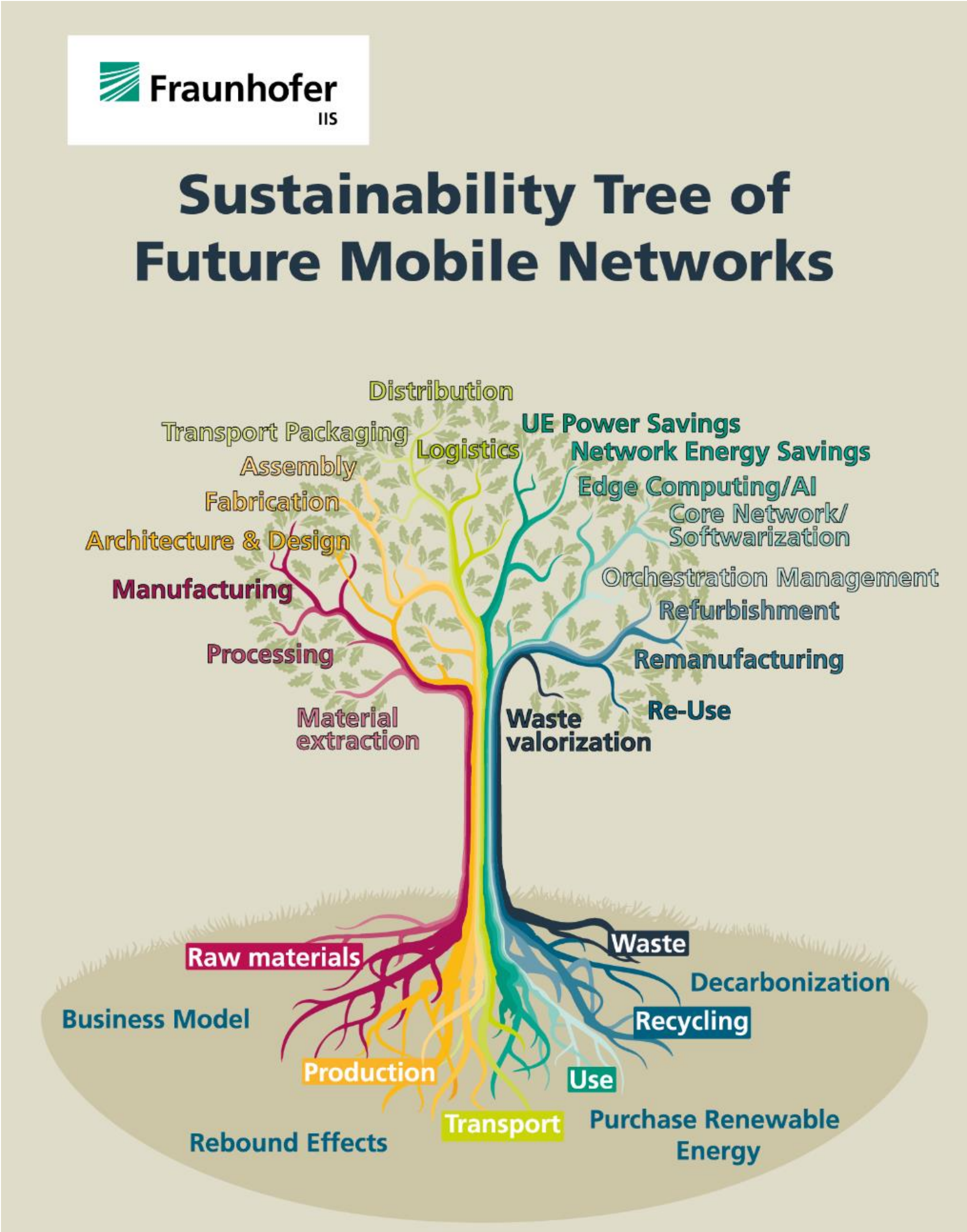


Figure 6: Sustainability Tree of Future Mobile Networks

The picture above (Figure 6) illustrates:

- with the roots and the floor the basic topics for a Life Cycle Assessment (LCA) and
- with the branches some of their associated categories.

This figure is far from showing all aspects of the LCA and sustainability of mobile communication, but it conveys the complexity of this topic to be addressed.

The next chapter gives an overview of current industry driven initiatives and standardization activities.

4 Initiatives and Standardization Activities

Today multiple standardization bodies, industrial associations as Open-Source Initiatives are involved in sustainability issues of mobile communication. Just to mention a few of them which have an aligned focus on those issues: the standard design organizations (SDOs) 3GPP, ISO, ETSI and ITU-T as the industry driven initiatives GSMA, NGMN, ATIS among others.

4.1 The Pathway to the 1.5°Climate Goal

SCIENCE BASED TARGETS

Science-Based Targets (SBT) provide a clearly defined pathway for companies and financial institutions to reduce greenhouse gas (GHG) emissions. They are calculated on a scientific basis to ensure that global warming is limited to well below 2°C and continue efforts to limit it to 1.5°C. The Science-Based Targets initiative (SBTi) has become the internationally recognized initiative proposing standards for emissions reduction for companies and providing guidance documents for different sectors.

NET ZERO

The latest standard for SBT is called the "Net-Zero Standard" - it specifies short- and long-term CO_2 reduction targets. With the Net-Zero Standard[1], companies not only set short-term CO_2 targets, but also commit to achieving a Net-Zero balance latest by 2050. Future approaches and new technologies in research will be needed to achieve these challenging sustainability goals.

4.2 Industry-driven Initiatives

The **GSMA** supports the mobile industry's commitment to address the United Nations Sustainable Development Goals (SDGs). As well as driving sustainability initiatives and convening the industry in support of the United Nations SDGs, the GSMA is itself committed to achieving sustainability within its own operations.

The GSMA addresses with internal processes such as green initiatives to Carbon Neutral on the path to **Net Zero** [7] in the various Mobile World Congresses that the GSMA organizes annually.

The **Next Generation Mobile Networks Alliance** (NGMN) is an open forum founded by world-leading mobile network operators. With the cooperation of telecommunication equipment vendors, software companies and many other leading industry players and research institutes, NGMN aims to substantially contribute to mid- to long-term innovation. The NGMN project Sustainability **- Green Future Networks** [8] focuses (among others) on reducing environmental impact, developing End-to-End service footprint calculation method, working on network energy efficiency and industry standard for sustainability green network benchmark.

The **Alliance for Telecommunications Industry Solutions** (ATIS) delivers standards and solutions to advance ICT industry transformation. ATIS is accredited by the American National Standards Institute (ANSI). The organization is the North American Organizational Partner for the 3rd Generation Partnership Project (3GPP). One initiative of ATIS launched in

[1] https://www.itu.int/rec/T-REC-L.1471

October 2020 is the **Next G Alliance** with the objective to advance North American wireless technology leadership. The **Green G Working Group** [9] addresses reducing energy consumption and environmental impacts of future generations of wireless technology.

4.3 Contribution of Standardization Bodies to Sustainability

In summary, many Standard Developing Organizations (SDOs) are working on energy efficiency, eco-design of the network equipment, using renewable energy, and compensation through investment in carbon sinks:

- 3GPP has been constantly addressing **energy efficiency aspects of UEs**, e.g. on Release-16 [10]and Release-17 [11]. In addition, further power saving aspects for UEs were defined in the Study and Work Items related to devices with reduced capabilities (RedCap) used e.g., for wearables (e.g., wearable medical devices, smart watches) or industrial wireless sensors [12].
  3GPP started in the 2Q 2022 release 18 with a study item on Network Energy Saving to address RAN energy consumption [13].

- ETSI focuses with the technical committee (TC) environmental engineering (EE) on defining the environmental aspects for telecommunication infrastructures and equipment.

- ISO defines a methodology of a Life Cycle assessment as also aspects of environmental impact of a company, a product or a service not only limited to CO_2 balances. It addresses all environmental aspects throughout the entire life cycle: from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave). The ISO Standards provide requirements and guidelines for LCA inclusive tools, performances evaluation as audits and reporting issues.

- ITU-T (study group 5) works on standards and guidelines towards assessment of mobile network energy efficiency, smart sustainable cities, management of batteries, e-waste as also on energy efficient blockchain systems and circular economy.

4.3.1 3GPP Standards and Activities

3GPP is responsible for the standardization of mobile networks, including for example 4G LTE and 5G NR. Energy efficiency of mobile networks has long been an important aspect in 3GPP. E.g., already the second LTE release (Release 9) introduced signaling among eNodeBs to exchange messages related to network energy saving [14]. This mechanism allows eNodeBs to inform neighbors when they deactive capacity-booster cells and conversely, neighbor eNodeBs can request cell activation.

However, the increase of overall network energy consumption is continuing as the increase of mobile data is immense and is not compensated by the effort to save energy. Besides the sustainability aspect, network energy consumption is a significant part of OpEx[2] in mobile networks. For both reasons, 3GPP continues actively pursuing network energy savings.

A recent effort in 3GPP was the definition of Energy Efficiency, KPIs and methods to measure them as defining uses cases and solutions for Energy Savings [13]. This effort is a

[2] Operational Expenditures: cost for raw materials, operating supplies, personal, leasing, energy etc.

part of the industry-wide activity on 5G, spanning an eco-system that also includes energy efficiency related output from the other key players GSMA, ETSI, ITU-T and NGMN.

More recently, a new study item on network energy savings was started on the Radio Access Network (RAN). According to GSMA the **RAN** consumes the lion´s share of energy used to maintain a mobile network (Figure 7). Therefore, techniques for reducing power consumption on RAN should provide the highest benefit in terms of energy saving. The study item [13] includes the definition of base station consumption model, evaluation methodologies and the identification of suitable network energy saving techniques. The outcome of the study is captured at TR 38.864. For further details refer to section 6.2.

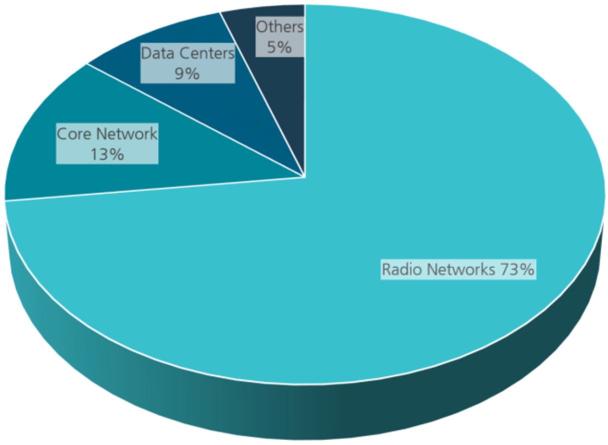


Figure 7: Network Operator - Energy consumption breakdown, GSMA 2021

As for RAN or UE the Energy Efficiency is often defined as a performance metric divided by their Energy Consumption. The definition of the performance depends on the type of network entity it applies to. The 3GPP SA5 Group[3] extended its scope to the whole 5G system defining Energy Efficiency KPIs for the 5G core network and network slides in the TS28 series.

Technical Specification/Report	Standards related to sustainability: title
TS 28.310	Management and orchestration; Energy efficiency of 5G
TS 28.541	5G Network Resource Model (NRM)
TS 28.552	Management and orchestration; 5G performance measurements
TS 28.554	Management and orchestration; 5G end to end Key Performance Indicators (KPI)
TS 28.622	Telecommunication management; Generic Network Resource Model (NRM) Integration Reference Point (IRP); Information Service (IS)
TS 28.813	Study of new aspects of Energy Efficiency for 5G
TR 38.864	Study on network energy savings for NR
TR 38.840	Study on User Equipment (UE) power saving in NR

[3] 3GPP Technical Specification Group Service and System Aspects (TSG SA) Working Group 5 specifies Management, Orchestration and Charging requirements, solutions and protocol specific definitions

Table 1: 3GPP standards related to sustainability

4.3.2 International Organization for Standardization ISO

The ISO Standards cover a large range of activities: quality management (ISO 9000 family), environmental management (ISO 14000 family [15]), health and safety (ISO 45001), energy management (ISO 50001), food safety (ISO 22000), IT security (ISO/IEC 27001).

The ISO technical committee related to environmental management (ISO/TC 207) addresses environmental and climate impacts, including related social and economic aspects, in support of sustainable development.

The subcommittees SC5 (Life Cycle Assessment) and SC7 (Greenhouse gas management and related activities) drive the work on the relevant ISO 14000 family standards listed below.

Life Cycle Assessment is a standardized methodology to quantify the environmental impact related to processes, products and services. Its application is regulated by ISO standards 14040 and 14044.

The ISO 14060 family of standards provides clarity and consistency for quantifying, monitoring, reporting and validating or verifying GHG emissions and removals to support sustainable development.

ISO 14000 family	Standards of Environmental Management
ISO 14001	defines a framework for setting up an Environmental Management System
ISO 14010	Audit guidelines
ISO 14011	Audit methodology
ISO 14012	Qualification of auditors
ISO 14013-14015	Audit processes
ISO 14020-14025	Aims to standardize environmental labels and declarations.
ISO 14031-14032	Environmental performance evaluation
ISO 14040 / 14044	Life Cycle Assessment – General principles and practices
ISO 14050	Terms and Definitions
ISO 14064	set of tools for programs to quantify, monitor, report and verify greenhouse gas emissions
ISO 14067	Carbon Footprint of Product
ISO 19011	Guide for management systems auditing

*Table 2: Overview of the ISO 14000 family standards [15]**Fehler! Verweisquelle konnte nicht gefunden werden.***

4.3.3 European Telecommunications Standards Institute ETSI

One engineering aspect related to sustainability relies on eco-environmental matters like energy efficiency, environmental impact analysis, and alternative energy sources.

This includes:

- the Life Cycle Assessment (LCA) of ICT goods, networks and services

- methods to assess the energy efficiency of wireless access networks and equipment, core networks and wireline access equipment including Efficiency metrics/KPI definition for equipment and network
- network standby mode for household and office equipment
- Circular economy standard for ICT solutions

In the following table, some relevant ETSI standards are listed:

TC	TC Environmental Engineering
ETSI ES 203 228	Assessment of mobile network energy efficiency (jointly with ITU-T Study Group 5 and 3GPP SA5 and RAN3) – *technically-equivalent to ITU-T L-1331*
ETSI ES 203 199	Methodology for environmental Life Cycle Assessment (LCA) of Information and Communication Technology (ICT) goods, networks and services – *technically-equivalent to ITU-T L.1410*
ETSI ES 202 706	Measurement method for power consumption and energy efficiency of wireless access network equipment
ETSI ES 201 554	Measurement method for Energy efficiency of Core network equipment
ETSI EN 303 470	Measurement Process for Energy Efficiency KPI for Servers
ETSI EN 303 471	Energy Efficiency measurement methodology and metrics for Network Function Virtualization (NFV)
ETSI EN 303 472	Energy Efficiency measurement methodology and metrics for RAN equipment
ETSI TS 128 552	5G; Management and orchestration; 5G performance measurements (3GPP TS 28.552)
ETSI TS 128 554	5G; Management and orchestration; 5G end to end Key Performance Indicators (KPI) (3GPP TS 28.554)

Table 3: ETSI relevant standards to sustainability

4.3.4 International Telecommunication Union - ITU

The Telecommunication Standardization Sector of ITU (**ITU-T**) develops international standards known as ITU-T Recommendations which act as defining elements in the global infrastructure of information and communication technologies (ICTs).

The **Study Group SG5** works on the environment and circular economy topics. SG5 is responsible for studies on methodologies for evaluating ICT effects on climate change and publishing guidelines for using ICTs in an eco-friendly way. Moreover, studies on design methodologies to reduce ICTs and e-waste's adverse environmental effects are also part of its mandate.

ETSI-TC EE and **ITU-T SG5** are working together to develop technically aligned standards on energy efficiency, power feeding solution, circular economy and network efficiency KPI and eco-design requirement for ICT, with the aim to build an international eco-environmental standardization.

In the following table, some relevant recommendations on sustainability of mobile communication networks are listed.

Recommendations	Topic energy feeding and efficiency [16]
ITU-T L.1210	Sustainable power-feeding solutions for 5G networks
ITU-T L.1220 – L.1222	Innovative energy storage technology for stationary use
ITU-T L.1310	Energy efficiency metrics and measurement methods for telecommunication equipment
ITU-T L.1331	Assessment of mobile network energy efficiency
ITU-T L.1350	Energy efficiency metrics of a base station site
ITU-T L.1351	Energy efficiency measurement methodology for a base station site
ITU-T L.1380	Smart energy solution for telecom sites
ITU-T L.1381	Smart energy solution for data centers
ITU-T L.1382	Smart energy solution for telecommunication rooms
ITU-T L.1383	Smart energy solutions for cities and home applications
	Green ICT [17]
ITU-T L.1035	Sustainable management of batteries
ITU-T L.1050	Methodology to identify key equipment for environmental impact and e- waste generation assessment of network architectures
ITU-T L.1317	Guidelines on energy efficient blockchain systems
ITU-T L.1470 – L.1471	Actions to lead the ICT sector by setting Net Zero targets and strategies
ITU-T L Suppl. 36	ITU-T L.1310 – Study on methods and metrics to evaluate energy efficiency for future 5G systems
ITU-T L Suppl. 41	Requirements on energy efficiency measurement models and the role of artificial intelligence and big data
ITU-T L Suppl. 43	Smart energy saving of 5G base stations: Traffic forecasting and strategy optimization of 5G wireless network energy consumption based on artificial intelligence and other emerging technologies
ITU-T L.1023	Assessment method for circular scoring of ICT goods
ITU-T L.1024	The potential impact of selling services instead of equipment on waste creation and the environment – Effects on global information and communication technology

Table 4: ITU-T recommendations on sustainability issues

5 Key Aspects of Sustainability in Future Mobile Communication Networks

Figure 8 shows the evolution of the mobile communication standards from 2010 to about 2030. It outlines the progress of the digitalization of our society in a 20 years' time frame, answering the needs of each decade. The following figure shows the development of the KPIs of each generation of mobile communication.

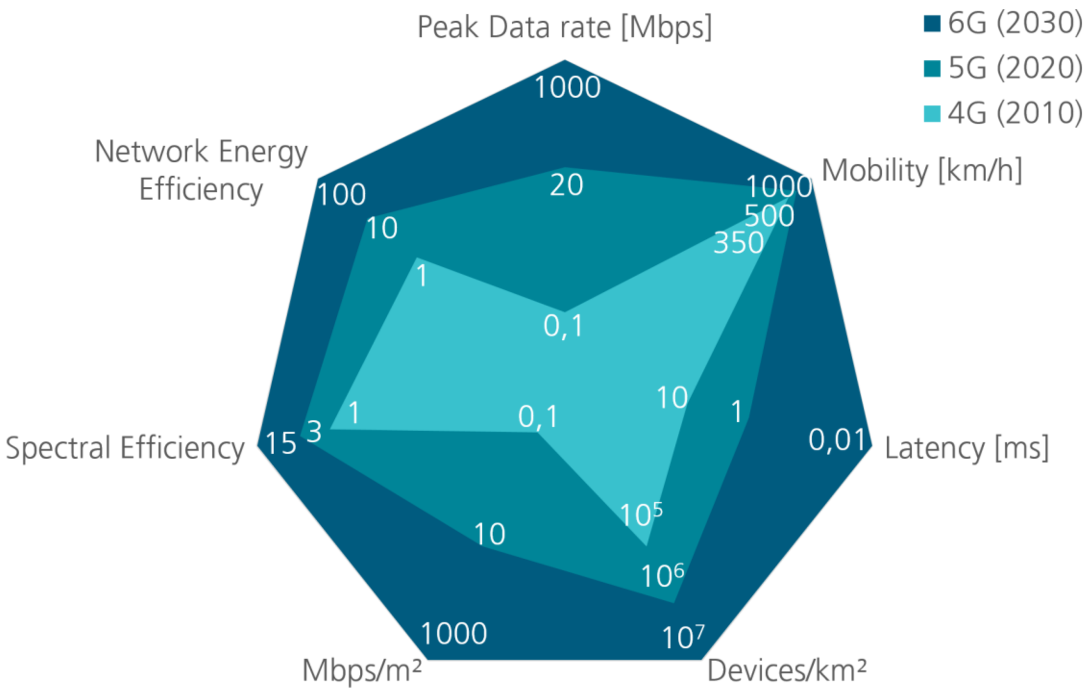


Figure 8: The evolution of the mobile communication standards from 4G to 6G (source: The shift to 6G communications [18])

In order to achieve the ambitious performance goals 6G might introduce new technologies as important enabling technologies [19] e.g.:

- Terahertz radio technologies for ultra-high data rates
- Flexible networks for situationally adapted network availability
- Fully integrated accurate localization and sensing of the environment
- Optimized network architecture for best service quality and reliability
- AI for the orchestration of the high flexibility feature of the 6G network (robust, self-organizing, self-healing, and self-optimizing wireless network)

The identified KPIs of 6G are related to the technical performances. Only the KPI "Network Energy Efficiency" addresses directly sustainability matter.

Regarding the gain factor between 5G and 6G of the KPI "Energy Efficiency" we can find in the scientific literature different values in comparison tables or spider diagrams: from factor 2 [20] through factor 10 [21], factor 100 [22] all the way up to a factor of 300 [23]. This means, that this feature is today not mature enough to be quantified properly. E.g., network load, scenario have an influence on the result. This is the starting point of the following discussion.

In view of the novelty of the future mobile network - e.g., cell-free, dynamic cluster, channel charting function - this KPI is currently being discussed in various bodies and committees with the issue to identify appropriate metrics for this purpose as also define measurement methods and setups to quantify the KPI.

This chapter gives first an overview about environmental KPIs that affect the business aspects of mobile communication and then an overview about the current status of the discussion on the (Network-) Energy Efficiency.

5.1 Environmental KPIs – Carbon footprint

The basic idea of the carbon footprint is to create a basis with which influences on the climate can be compared quantitatively. The carbon footprint maps the greenhouse gas emissions of an individual, an organization, a production site or a product. The unit CO_{2e} (also written as carbon dioxide equivalent, CO_2 equivalent or CO_{2eq}) is a metric measure that is used to compare emissions from various greenhouse gases – CO_2, NH_4, N_2O, etc. - based on their own global warming potential by converting amounts of other gases to the equivalent amount of CO_2.

Moreover, in order to set up a comprehensive sustainability strategy, concrete information about the impact of one's own processes and products is needed. This information is provided by life cycle analyses, life cycle assessments and analyses of resources and eco-efficiency. An ISO standard compliant LCA typically comprises four phases: the definition of objectives and the scope of the study, the preparation of a life cycle inventory (an inventory of inputs and outputs), the impact assessment and finally the evaluation.

To visualize the entire perspective, this subchapter gives a short overview about the complexity of an overall view of sustainability for company, products and services.

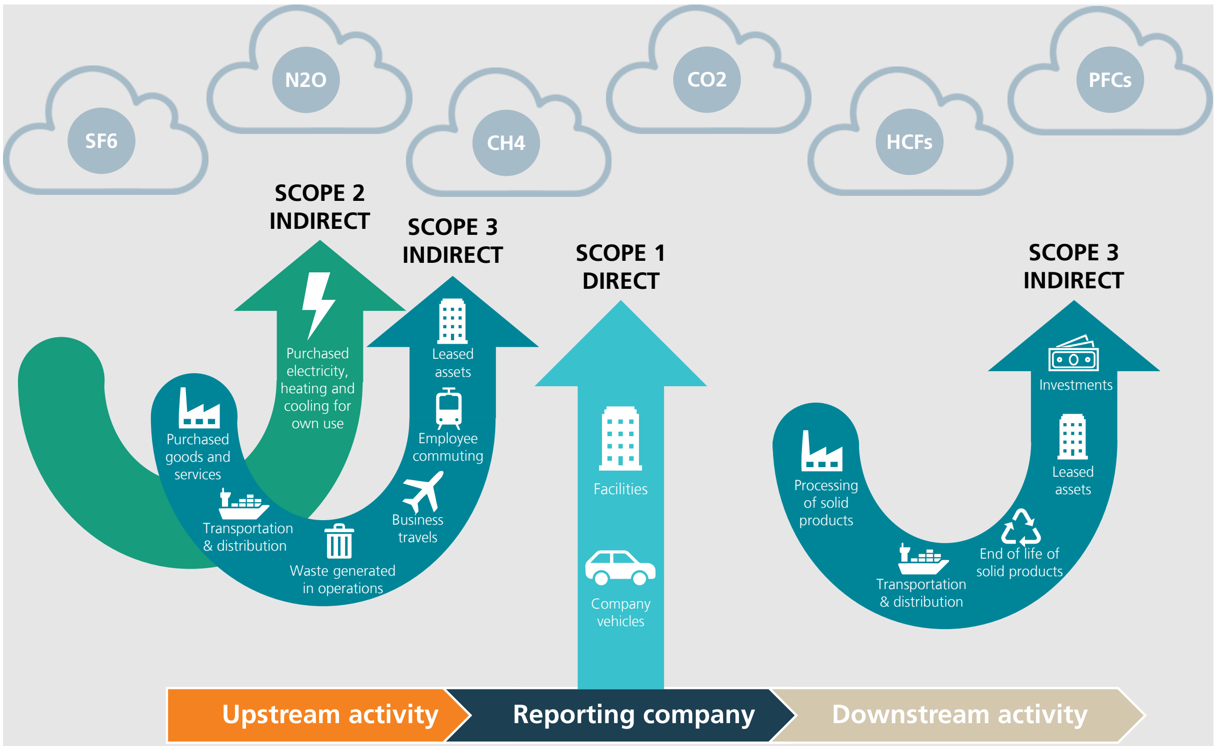


Figure 9: direct (Scope 1) and indirect emissions (Scope 2 & 3) [7]

The picture above shows that, in the mobile network ecosystem, GHG emissions are produced at all stages of the life cycle. In short, Scope 1 emissions are direct emissions from company-owned and controlled resources. Scope 2 emissions are indirect emissions from the generation of purchased energy, from a utility provider. Scope 3 emissions are all indirect emissions – not included in scope 2 – that occur in the value chain of the reporting company, including both upstream (suppliers of the company) and downstream (the company's customers) emissions.

To meet the targets of the EU Green Deal, telecom operators, as other industries, need to set targets on their emission reduction. Each company and stakeholder have to define their own strategies for that purpose, depending on their size and business activities (e.g., network operator, equipment-, energy-, service- supplier). The next step is to choose which KPIs and metrics are relevant to address their GHG emissions, and their saving goals.

The carbon footprint can be compiled company wide as a "Corporate Carbon Footprint" (CCF). Or product specific as a "Product Carbon Footprint" (PCF) for the entire life cycle – taking into account all 3 scopes - or specific life cycle stages of a product or service. The ISO standards respectively ISO 14064 and ISO 14067 define a systematic approach to this.

The carbon footprint can be also used as a metric to evaluate power and energy consumption as energy savings. Depending on the source of the energy in consideration (from a power plant, fuel, oil, mix with renewable energy sources etc.) conversion factors are available to convert the energy value (kWh or Liter or m^3) into CO_{2e} unit.

GHG emissions and energy use are as sustainability related KPIs widely used.

Regarding the more scientific related and technology-oriented scope of this white paper the following chapters will concentrate on new technologies and issues related to energy efficiency of a mobile communication network in operation.

5.2 Energy/Power Efficiency - KPI and the related Metrics

In the following table key power- and energy-related definitions are listed:

Metric	Unit	comments
Power Consumption	W or J/s	Amount of energy that is transferred or converted per time unit
Energy Consumption	kWh or J	Amount of power used over a time period – 1 kWh corresponds to $3.6x10^6$J
Energy Efficiency	% or label or kWh/unit	Ratio of output of performance, service, goods or energy, to the input of energy.
Power Efficiency	%	Output power / Input power
Energy Performance	Mbits/kWh	Ratio between the produced task or work and the consumed power for producing this task or work over a time period

Table 5: relevant basic metrics

5.2.1 Metrics related to the RAN Side

From the RAN side the Energy Efficiency KPI is also represented with different metrics related to the focus of the subcomponents of the network.

The overall Energy Efficiency consists of 3 factors (Figure 10): power efficiency of the site infrastructure, power efficiency of the base station equipment, and energy performance of the air interface.

P_{AC} is the AC Input from the grid, P_{BS} the DC input power to the main equipment (base station), P_{output} is the cabinet-top power output of the base station antenna and S_{pi} the service provided by the base station (e.g., delivered bits, coverage, or number of subscribers served by the base station).

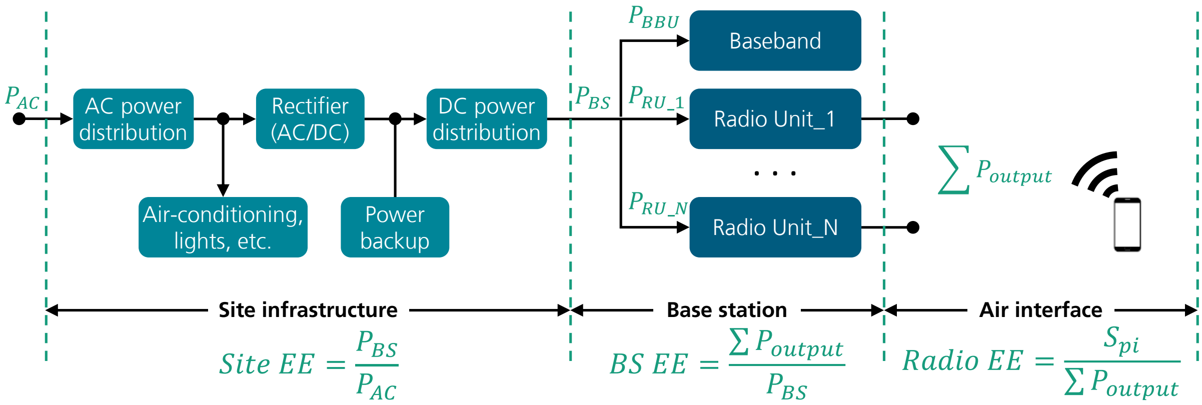


Figure 10: overview of the RAN side [8]

The overall Energy Performance is represented by:

$$EP = \frac{P_{BS}}{P_{AC}} \times \frac{\sum P_{output}}{P_{BS}} \times \frac{S_{pi}}{\sum P_{output}} = \frac{S_{pi}}{P_{AC}}$$

This ratio integrated over a time period is expressed then in Mbits/kWh or Mbits/J.

5.2.2 Metrics related to Mobile Network Energy Efficiency

Furthermore, Energy Efficiency KPI is also represented with different metrics focusing on different performance values. Most of them are defined in ITU-T L.1330. In this subchapter a list of relevant metrics is shortly explained.

The Energy Consumption of the mobile network (EC_{MN}) is the sum of the energy consumption of each piece of equipment included in the MN (definition in ITU-T L.1331 or ETSI ES 203 228).

The **mobile network data Energy Efficiency** ($EE_{MN,DV}$) is the ratio between the data volume (DV_{MN}) and the energy consumption (EC_{MN}) when assessed during the same time period:

$$EE_{MN,DV} = \frac{DV_{MN}}{EC_{MN}} \quad \left[\frac{bit}{J}\right]$$

The **mobile network coverage Energy Efficiency** ($EE_{MN,CoA}$) complement $EE_{MN,DV}$ for MNs handling low data volumes, in particular in rural or deep rural areas. It is the ratio between the area covered by the MN and the energy consumption when assessed during one year:

$$EE_{MN,CoA} = \frac{coverage\ area}{EC_{MN}} \quad \left[\frac{m^2}{J}\right]$$

The **Power Usage Effectiveness** (PUE) is also a metric to determine Energy Efficiency of a Data Center. PUE was published in 2016 as a global standard under ISO/IEC 30134-2:2016. It describes how efficiently a computer data center uses energy.

$$PUE = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy} \quad [\%]$$

Further KPIs are associated to the **decarbonization of the network**, which are also relevant for mobile communication networks' operators [7]:

The **Renewable Electricity Ratio** represents the percentage out of the total energy consumed by fixed and mobile networks coming from renewable sources:

$$Renewable\ Electricity\ Ratio = \frac{Renewable\ electricity\ consumption}{Total\ electricity\ consumption}\ [\%]$$

The **Energy Consumption per customer** gives a quantitative value of the network energy efficiency per client:

$$Energy\ consumption\ per\ customer = \frac{Total\ Energy\ consumption\ in\ kWh}{Total\ customers\ (both\ fixed\ and\ mobile)}$$

The network Energy consumption per data volume or **Energy Intensity** gives a quantitative value about the network energy efficiency per data unit (TByte):

$$Energy\ Intensity = \frac{Energy\ consumption\ in\ kWh}{IP\ data\ volume\ transmitted\ in\ Tera\ Byte}$$

A new KPI in discussion is the **Network Carbon Intensity** (NCIe). The standardization body ITU-T SG5 started activities to define indicators for the GHG emission of network to give operators a tool to evaluate, monitor network GHG emission and establish a plan to improve their environmental footprint. ITU-T SG5 is currently working on two work items to calculate the network carbon intensity: ITU T L. NCIe and ITU T L. GHG intensities.

$$Network\ Carbon\ Intensity\ (NCIe)\left(\frac{kgCO2e}{TB}\right) NCIe = \frac{Total\ Carbon\ Emission}{Total\ Data\ Volume} = \frac{ECtotal}{Total\ Data\ volume} * CF$$

CF is the carbon conversion factor (kg CO_{2e}/kWh). For example, the CF in Germany for the electricity consumption was according to UBA (Umwelt Bundesamt) 2020 about 0,455 kg CO_{2e}/kWh.

6 Energy Saving Techniques and Performance Evaluation Metrics in 3GPP

This chapter introduces Energy Saving Techniques elaborated in 3GPP-Standardization, from the User Equipment (UE) and the network site, and methods for performance evaluation.

6.1 UE Power Saving Techniques

The sustainability of mobile services depends both on infrastructure and UE energy consumption. Furthermore, battery lifetime is a significant dimension of Quality-of-Experience (QoE). From the very beginning (release 15), 5G NR includes features for UE power saving such as Discontinuous Reception (DRX) and the new Radio Resource Control (RRC) Inactive state. In LTE, only two main UE operational states for user equipment were defined: RRC connected and RRC Idle. The uprise of always-on apps and dynamic webpages has led 4G to an inefficient operation from power and signaling perspective where the UE is constantly changing between these 2 states only to transmit small amounts of data. For this reason, NR introduced a new state called RRC Inactive (See Figure 11). The transition from RRC Inactive to RRC Connected involves less signaling and the connection can be resumed more quickly leading to less UE power consumption.

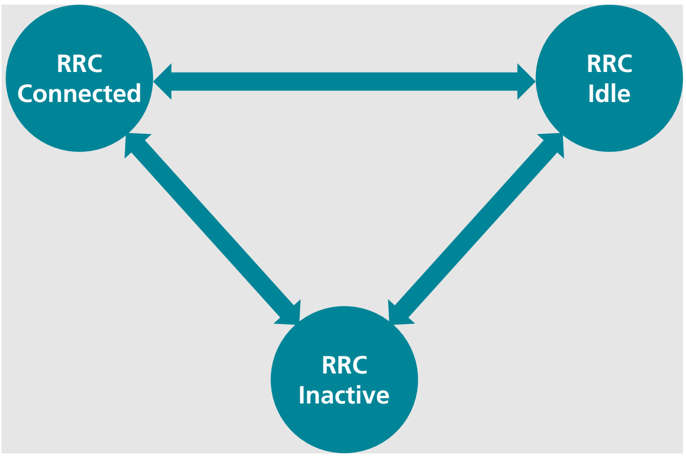


Figure 11: Radio Resource Control (RRC) states in New Radio (NR) technology.

In spite of better efficiency per bit and enhanced design in NR the power consumption at UE is always a growing concern. Due to the increased bandwidth, more antennas and higher data rates, a 5G NR User Equipment (UE) may actually consume more power than a typical LTE UE. In early deployments also the UE needs to maintain both a LTE and a NR connection. For all this reasons, 3GPP has continued to improve UE power consumption also on release 16 and 17.

6.1.1 Power Saving UE Enhancement in Release 16

DRX is a mechanism in which a UE switches off its RX chains in order to save energy for time intervals configured by the network. This feature achieves the highest gain in terms of power consumption when the traffic pattern is deterministic traffic. In contrast, it is not efficient for a scenario with sporadic traffic. The introduction of a Wake-up Signal (WUS) allow more dynamic power savings by letting the UE to quickly determine if it should monitor the DRX on-period or if it can go back to sleep.

The usage of Multiple Input Multiple Output (MIMO) can increase date rates according to the number of used antennas. However, the power consumption also increases with more active transceiver chains needed to feed more antennas. Because of that, Release 16 introduces adaptation of the number of antennas in the downlink so that the UE could reduce the number of in-use layers, resulting in reduced power consumption at the UE. Similarly, the number of antennas in uplink can be selected precisely, reducing transmission power at UE side and saving energy at the UEs.

UEs need to frequently perform measurements which are used as input for Radio Resource Management (RRM) procedures. In Release 16, the frequency of these RRM measurements may be reduced in order to reduce the power consumption. As the measurement requirements are relaxed, this technique is known as RRM relaxation. In general, several criteria can be considered to relax RRM measurements, e.g., mobility of UE, quality of UE signal towards a serving cell, and beam status of a serving cell, to name a few. Remarkably, the proximity of UE to the serving cell and users with lower mobility mainly influences the RRM relaxation interval.

6.1.2 Power Saving UE Enhancement in Release 17

Release 17 introduced further criteria for RRM relaxation and made it also applicable for RRC connected mode. Also, measurements related to link and beam failures can be relaxed in release 17.

While Release 16 WUS apply to RRC connected mode, in Release 17 a similar concept is introduced for RRC Idle: Paging Early Indication (PEI). The UE needs to monitor Paging Occasions (POs) in order to have enough responsiveness to incoming messages from the network, such as an incoming call. However, significant UE energy is consumed due to waking up and monitoring PO messages. The PEI allows the UE to determine more quickly if there paging messages are present or not and in case there is nothing to be decoded the UE can stay less time awaken and sleep again more quickly.

Other Release 17 power saving enhancements include small data transmission in RRC Inactive, extended paging/DRX cycles, reference signals for quicker synchronization in Idle/Inactive and dynamic aperiodic skipping of control channel monitoring in RRC Connected.

6.2 Network Energy Saving

In Release-18, a study item on Network Energy Saving [13] was addressed to identify and evaluate potential techniques, which are summarized in a technical report TR 38.864. Following the study item, still in Release-18, a work-item phase is planned starting Q1 2023 where some of the solutions for Network Energy Saving shall be standardized. Furthermore, such a study item may lay the foundation for enhancements in further 5G NR releases and eventually also in 6G.

The study item started by defining a base station energy consumption modeling, an evaluation methodology and the KPIs to be evaluated. Also, several techniques that can potentially improve the energy footprint of 5G NR networks were identified and evaluated.

As in the UE power consumption model [24], several transmission states, reception states and sleep modes may be considered. The different sleep modes correspond to the ability to switch off different parts of the hardware [25], [26]. Furthermore, the transition between different sleep states involves a transition time and transition energy between the states. For instance, as per the current agreement in the drafting of TR 38.864, the different sleep modes and active states of a BS are deep sleep, light sleep, micro sleep, active downlink transmission and active uplink reception. The micro sleep simply means no transmission or reception and has zero transition time to enter the active modes. The deep sleep and light sleep modes correspond to shutting down of several hardware components and therefore have respective transition times to the micro sleep or active modes. Further, the active transmission and reception are modeled with appropriate scaling to account for the share of active antenna units, bandwidth, transmission power and power amplifier efficiency.

Regarding network energy saving techniques the focus is on improving the savings on idle, low or moderate load so as to benefit from entering the sleep modes and scaling down the resources in the active modes. The techniques addressed by the study item are categorized as the ones targeting optimization over time, frequency, spatial, and transmit power resources. In general, the energy efficiency of 5G NR on high loads and thereby on full-scale active modes is already much higher compared to LTE, because of the enhanced spectral efficiency. However, a very large capacity is not needed throughout the day nor in every cell at the same moment. Therefore, there are a lot of potential savings, for example at night when the traffic may be significantly lower than during the day. In this regard, the most promising techniques in the scope of 5G standardization would be the reduction of always-on common signaling from the base stations so that to optimize the possibility of effectively entering sleep modes.

6.3 Performance Evaluation Metrics

In 3GPP Performance metrics are critical metrics that evaluate network or user performance from a system- or link-level view. 3GPP strives to specify evaluation methodology and key performance indicators (KPIs) by which different approaches proposed by the companies are compared, and a decision is made based on the approach achieving the best performance.

(UE) were extensively studied in Release 16 [24], and several performance metrics were specified to compute the overall gain from a system or link-level perspective. More specifically, the following performance metrics are defined in Release 16.0:

- UE power saving gain,
    - wherein the power-saving gain of a UE is computed considering the power consumption model for a specific scenario
- Latency, scheduling delay and user throughput,
    - wherein system performance considering UE power-saving techniques is evaluated,
- Other performance metrics, e.g. false alarm rate and miss detection rate,
    - These metrics indicate errors that occur when a procedure or signal is triggered. For example, in the case of miss detection, if a paging procedure is triggered, the receiver could not detect the signal due to channel impairment or decoding errors. As another example, consider a case where a paging message is broadcasted for all UEs within a defined paging area, and the message belongs to only specific UEs. However, the unpaged UEs are also mandated to decode the signal as a part of a conventional procedure. This is considered a false alarm at the UE, resulting in further power consumption.

Moreover, considering other KPIs when introducing a new signal was not precluded. For instance, when an early paging indicator feature is configured, the newly introduced signal is compared with the legacy paging signal concerning the overhead and complexity.

Release 18 was decided to investigate the avenues assisting the RAN with energy consumption reduction while considering much better traffic capacity. For this purpose, initially, 3GPP has commenced a study to enhance the current power consumption model specified for the UE to be applied to the network. In addition, the necessity of updates on qualitative and quantitative KPIs was discussed. The target was defined to design a network with the ability to deliver the traffic efficiently to the UE and be sufficiently flexible to stop transmission when there is no traffic to transmit, considering network availability. Having this in mind, at least the following KPIs were agreed to be specified in addition to the energy-saving gain for base station consumption evaluation:

- User-perceived throughput (UPT), access delay, and latency

Besides, it is under discussion to decide whether quantitative KPIs like bits per Joule shall be used or not. These KPIs are related to the energy efficiency of the Radio Access Network

(RAN), and it was suggested that the following definition in [27] is used as a base and be further studied in the 3GPP:

$$EE_{global} = \sum_{scenario\ K} b_k EE_{scenario\ K},$$

where b_k is the weight of every deployment scenario. The network energy efficiency for each scenario yields:

$$EE_{scenario} = \sum_{load\ level\ 1} a_1 \frac{V_1}{EC_1},$$

where $\mathbf{V_1}$ is the traffic per second served by a base station (in bits/s), $\mathbf{EC_1}$ is the power consumed by a base station to serve V1 (in Watt = Joule/s), and $\mathbf{a_1}$ is the weight for each traffic load level.

7 Assignment of Sustainability Aspects to different Subsystems of a 6G Mobile Network

This chapter deals with studies and projects addressing relevant results of research work toward sustainability issues of mobile network components that could be relevant for future 6G activities.

7.1 Waveform Design for Network Energy Efficiency

A recent article on power consumption modeling for 5G base stations [28], noted the lack of accurate and tractable approaches and proposed a model to better capture the benefits of energy saving techniques for future research standardization. For training the proposed model, [28] used data collected via hourly measurements over 12 days performed on real deployment of base stations and observed that the base stations implement deep dormancy, carrier shutdown, channel/symbol shutdown, each switching off distinct components of the active antenna unit, depending on the how low traffic load becomes. Regarding power consumed in active transmission, however, scaling of frequency resources down alone is observed to have no significant power saving gains. While the techniques considered presently by 3GPP for the study item on network energy saving (see Section 6.2) do not yet consider fundamental alterations to the waveform design, future releases towards 6G should revisit it for the prospect of reducing energy consumption active transmission and reception.

The initial study phase of the 5G NR standardization (for Release 15) conducted a detailed study on suitable waveforms and selected the cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) for downlink and uplink transmissions, while providing an optional the discrete Fourier transform-spread-OFDM (DFT-s-OFDM) only for the uplink [29]. Although several multi-carrier and single-carrier waveform variants were considered as candidates in the early 5G evaluations [30], the assessments were based on a limited set of use cases that did not include the ones adopted subsequently (since Release 16) like non-terrestrial networks (NTN) including satellite communication. Moreover, the operating frequencies of interest as per Release 15 have been the FR1 and FR2 ranges going up to 52.6 GHz. Therefore, the NR physical layer design including the waveform is arguably optimized for operation under 52.6 GHz and for maximizing the synergies between an early set of use cases [31].

The 5G NR physical layer employing OFDM-based transmission has many advantages, including the flexibility in configuring the waveform for multiplexing in frequency and time, while being robust to highly frequency and time selective fading channels [29]. Moreover, it is intended to be flexible and scalable with the possibility to incorporate additional features needed to deal with a wide range of scenarios and use cases desirable for 5G and beyond. 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 (PA) backoff to reduce nonlinear distortions, thereby meeting the out-of-band emission (OOBE) and the modulation quality requirements [32]. The power backoffs become a disadvantage because it reduces the energy efficiency of the transmitter and limits the transmit power in turn affecting throughput and coverage. The increase in PA backoff also affects the other device requirements, e.g. the dynamic range of the ADC and DAC [31]. While the PAPR disadvantage of CP-OFDM would be tolerable for several use cases and low frequencies below 52.6 GHz in general, this would not be the case for use cases with power-limited links such as the satellite downlink [33], [34], and for high frequency operations, in general [31], [35].

Compared to lower frequency bands, operation beyond 52.6 GHz, in general, is faced with more challenges, including larger propagation loss and lower power amplifier efficiency, which further aggravates the PAPR related issues. The 3GPP technical report [31] on the study on requirements for NR beyond 52.6 GHz (Release 16) suggested to investigate waveform design as one of the important requirements for NR system operating in frequencies between 52.6 GHz and 114.25 GHz, emphasizing on the following aspects to be considered for the evaluation:

- Power efficiency of PA
- Dynamic range of ADC and DAC
- Modulated signal accuracy and out-of-band emission
- Complexity and performance of waveform
- Spectrum flexibility of waveform
- Robustness to frequency offset and phase noise
- Feature re-usability and design commonality with existing NR specification

However, for Release 17 work item considering 52.6-71GHz, no waveform change is introduced other than subcarrier spacing, mainly because of limited EIRP for operation in the band and considering faster time to market, as per [36]. Further, [36] noted the stronger need for studying a single carrier waveform for the 71-114.25 GHz band and for use cases such as NTN, and listed three possible approaches:

- Simple approach: introducing DFT-s-OFDM waveform for DL, similar to the DFT-s-OFDM waveform already available in UL
- Complex approach: introducing (filtered) single-carrier waveform for both DL and UL
- Other: novel waveform design for both DL and UL

7.2 Radio Unit, MIMO and Reconfigurable Intelligent Surface

This chapter deals with studies and projects addressing relevant findings of research work toward sustainability issues of mobile network components focusing on RAN technologies that could be relevant for future 6G activities.

As already mentioned in 4.3.1 the transmission chain is responsible for about 75% of the network energy consumption. Figure 12 shows the split of the power consumption of a base station – of course those values can differ lightly depending on the operator and equipment.

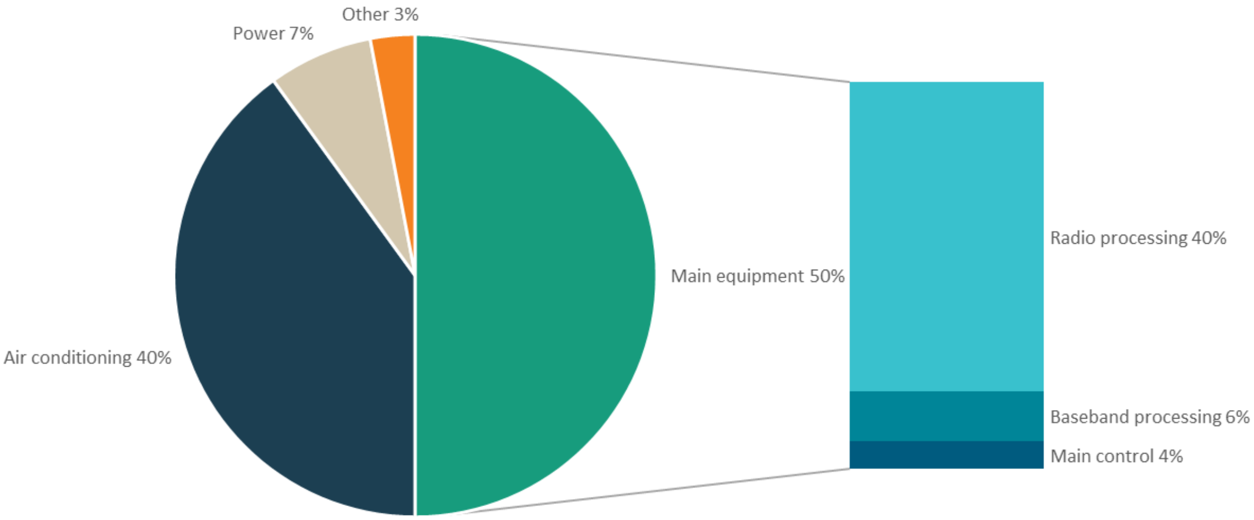


Figure 12: breakdown of the power consumption in a base station – source [8]

Regarding the main equipment, the radio unit or antenna unit is the main energy demanding component. In the antenna unit the power amplifiers are the energy hungry part of the hardware chain. 5G introduced massive MIMO based antenna unit, for 6G ultra-massive-MIMO-antennas are planned to respond to the higher transmission capacity and new frequency bands requirements. This means that the energy demand of a base station will exponentially grow with the number of antenna elements. For this purpose, few analyses on architecture considering deployment density, on the RF-chain (MIMO-antenna) and on the PHY-Processing platform are studied in the BMBF-Edge Limit projects[4] .

The vision of 6G introduces new topics that have further impacts on the energy demand of the radio part, as for example THz frequency ranges (associated also with higher bandwidths), ultra-massive-MIMO-Antennas as the deployment of cell-free-networks.

6G might range from conventional (sparse and macro) deployments (with old frequency ranges, which remain to be there) to brand new ultra-dense deployments with simple RUs for distributed massive-MIMO.

The method for energy saving benchmarking proposed is to hypothetically design some 6G model networks to analyze in different conditions, to get the extremes and find out compromise depending on the scenarios.

A further point of interest are the Reconfigurable Intelligent Surfaces (RIS). Those new elements enable MNOs to control the radio waves (scattering, reflection, and refraction characteristics) to eliminate the negative effects of natural wireless propagation. RIS could transform the random (given by the environment) channel into a programmable channel. Further investigations are required to evaluate their potential in use with respect to network energy savings.

[4] https://www.iis.fraunhofer.de/content/dam/iis/en/doc/pr/2021/20210827_lv_edge_limit.pdf

Regarding the antenna unit different antenna types will remain to be available: massive-MIMO, ultra-massive-MIMO, sectorized arrays, fixed antennas. Their influence on network energy consumption still needs to be examined more closely.

Also, on component level further analysis towards energy consumption are required:

- Processor Platform (e.g., RFSoC),
- component architecture (e.g., number of Transceiver units per SoC),
- RF-components including semiconductor material like PA, phase shifter, combiner/splitter including fully integrated beamforming IC-fashion)

Overall, the combination of energy-efficient components and optimized organization should reduce energy losses in the remote radio head (RRH) implemented in the Green ICT-EdgeLimit[4] project by at least 50%.

7.3 Orchestration architecture of the network

7.3.1 Distribution of containers

There are already some energy saving approaches on architecture level that can be realized in the orchestration of the core network. First it should be noted that the research field for increasing energy efficiency in virtualization and orchestration is still young. For 5G and 6G, the first research results were adopted for the efficient operation of data centers in cloud computing. The first step was to introduce containers, e.g., based on Docker, instead of running virtual machines (VM). Containers use the operating system and architecture of the host. They contain only the necessary applications and files, which are required for the functionality. A virtual machine works as a virtualized hardware machine that contains its own operating system and can execute several resource-intensive functions in parallel. This is the reason why containers require significantly lower resources compared to VMs and can therefore be operated in a more energy-efficient manner. Further research has shown that energy efficiency can be increased with the proper use of runtime environments with containers. The use of caches significantly reduces the measured energy consumption for Docker. Deleting and rebuilding containers directs to another remarkable saving compared to stopping and starting. As part of the TRAICT 2021 project[5], Fraunhofer IIS analyzed the energy efficiency of different container runtime environments. It was found that the various solutions differ significantly from each other. This applies to performance and energy consumption.

7.3.2 Edge-/RAN- Cloud

In the area of orchestration, a new strategy for distributing containers across different servers opens an opportunity to increase energy efficiency. Today, the focus of orchestration is on the accessibility of a server, considering the metrics of processor load and memory availability. This is based on solving the "bin packing" problem. This algorithm finds the smallest number of servers in which all current containers can be orchestrated. This allows optimization in terms of energy efficiency. Unused servers should be switched off. Due to the high-power consumption in idle mode, servers in part-load also generally do not operate in an energy-efficient manner. The strategy is to run computing resources at full load as much as possible. To achieve this, containers on servers in part-load should be

[5] TRAICT: Trusted and Resource Aware ICT - https://www.iis.fraunhofer.de/en/magazin/2021/fmd-mikroelektronik-interview-heuberger.html

moved to other servers and then the emptied server should be switched off. At Fraunhofer IIS, a new scheduler for orchestration using new metrics is being examined as part of the GreenICT-EdgeLimit project[4]. Energy measurement for recording the energy consumption of individual containers is to be integrated as a new parameter for the orchestration process.

Following studies and projects address relevant results of research work toward sustainability issues of mobile network components focusing on Edge-/RAN- Cloud technologies that could be relevant for future 6G activities.

With 5G, the increased use of the radio access network for applications in the neighborhood of the Radio Unit (RU) started. The use of the 5G FR2 frequency bands in the millimeter wave range - from 24.25 GHz to 52.6 GHz - allows to shrink the size of the radio cells significantly. Radio Units can be mounted directly on lanterns in outdoor areas. This enables the implementation of new use cases. These often require sensors and cameras mounted in the same positions. To avoid the installation of additional computing resources, it is recommended to integrate the sensor data processing or a possible sensor fusion directly in the neighborhood Radio Units. This approach increases energy efficiency and sustainability.

The described trend leads to the fact that new types of Radio Units require more computing power. The Open RAN standard defines the so-called RAN Cloud for the resource management required for this. In the GreenICT-EdgeLimit project[4], it is assumed that computing resources of the radio units are members of this RAN Cloud. This offers the opportunity that in the future additional free computing resources will be available in the Radio Units for further applications in addition to the processing of the physical layer. The project will investigate how these computing resources can be used for energy-efficient redistribution of edge services during partial load operation of the network.

The strategy for saving energy in part-load operation is to actively shift computing resources from selected system components to free or partially used resources. The purpose of this is to enable optimal utilization. Subsequently, idle systems are switched off in a controlled manner as long as they are not required. Various possible solutions are to be analyzed as part of the project. As soon as positive project results are available regarding the potential energy savings, these can be introduced into the standardization process.

In part-load operation of a radio access network, it is theoretically possible to shift functions between the Distributed Unit of the radio access network and various Radio Units operating at part load. The so-called Functional Split determines which parts of the physical layer are processed in a Radio Unit and which parts are processed in the Distributed Unit. As a rule, a dynamic change of the functionalities leads to a change of the Functional Split. Therefore, it must be analyzed whether these active changes of the system architecture lead to significant energy savings. These would justify the expense required for this purpose. Another difficulty compared with changes to applications in the edge or RAN Cloud is that the increased requirements for system stability and availability of communication relationships must be met.

7.4 Green Design of AI/ML for AI-assisted Future Networks

The future 6G network is envisioned to be a complex ecosystem of densely deployed software and hardware components [19]. AI is expected to be a key enabling technology for a great increase in flexibility and resource efficient usage of the network. But the application of AI itself goes not without resource consumption. A green design of AI functionality will not only bring AI benefits to the network, but will also ensure that AI implementations will not outweigh their resource saving benefits. Thus, it should be an integral part of all AI designs for the future 6G network.

Beamforming shall serve as an example for the need of green design of AI. Efficient beam management will be needed for massive MIMO to select the most suitable beam for each UE – a challenging task especially for moving UEs. Since an exhaustive search over all available beams is impossible, recent standardization approaches (e.g. see [37]) address this by requiring the UE to measure a small set of beams and then an AI model, usually a Deep Neural Network (DNN), predicts the next best beams when switching is required. Since, these DNN models can be quite large, might use resource intensive recurrent components (e.g. LSTMs), and are required to be queried at high frequencies, typically every 40 ms to 200ms for moving UEs [37], the computational and thus energy costs of the inference process can be challenging, especially if these DNNs reside on the UE side.

In order to make the execution of DNNs energy-efficient and resource-saving, various methods for DNN compression and compact representation have become widely accepted: they can be roughly divided into three categories, neural network pruning [38], weight quantization [39], and subspace methods [40], and are often summarized under the term of deep compression [41]. The goal of these methods is to reduce the memory and computational requirements of DNNs without significantly affecting the predictive quality of the trained networks. As a result, DNNs can be deployed on a smaller resource footprint and meet tighter latency constraints, leading to increased throughput and energy savings.

The process of training, compressing, and deploying a DNN on a target system can be automated in a configurable end-to-end pipeline [42]: Moreover, the design space between conflicting objectives such as memory consumption, computational complexity, and predictive accuracy can be explored using multi-objective optimization. The resulting set of pareto-optimal designs can either be used to select an appropriate design offline, or it can support dynamic adaptation of the quality of service (QoS) at runtime to lower energy consumption whenever possible.

In addition, the efficiency of finding suitable models (i.e. shorten the training process) can be improved by combining it with transfer-learning. Transfer learning (TL) uses a pre-trained model to enable resource efficient fine-tuning with domain-specific data in fewer training epochs. In [43] we present the effectiveness of synthetic pre-training for localization using Channel State Information (CSI) for model based fingerprinting to solve none-line-of sight scenarios with few training samples.

Research is expected to combine transfer learning with deep compression to achieve a green integration of AI in future networks.

8 Discussion

The challenges for the future generation of mobile communication could be met through scientific discussions, the development of new technologies and the standardization of products considering the listed major aspects:

- Digitalization of the society is rapidly growing and demand for data services is rising exponentially
- The nature of data transmission is changing rapidly as more traffic flows through mobile devices and networks, so the energy efficiency of data transmission networks has also to be improved rapidly
- Emerging digital technologies as AI/ML, blockchain or VR/digital Twins are likely to boost demand for data center and network services even higher
- The complexity of base station increases with energy-hungry antenna arrays (MU MIMO) to handle the growing traffic
- The complexity of the future communication network (Intelligence, Cloudification, Softwarization, Virtualization, Slicing) will need a complex orchestration and management core that proactively configure the network to the momentary traffic demand
- Network Energy Efficiency issues are in their infancy and currently in discussion in standardization bodies. This will take time until those issues are implemented and in operation

To limit the increase in energy demand of future mobile networks without limiting their specific performance, very strong efficiency improvements are required.

In a highly complex system such as 6G, it is essential to look at improving the energy efficiency of devices and networks from a holistic perspective. For this purpose, both the positive and the negative effects of energy-saving functions of a component should be evaluated for the complete mobile communication chain.

Table 6 shows a first high level approach on impacts of energy saving technologies mentioned or described in this white paper.

New energy saving technics	**Positive impact**	**Negative impact**	**Use cases**	**Comments**
UE Energy savings technics	Reduced Energy Consumption Longer autonomy Smaller battery or Avoid battery and allow the use of energy harvesting	Increased complexity on the network	Wearables Smart Metering Smartphones	Shorter time-to-market (already standardized) At the moment there are no green battery technology for UEs.

BS Sleep modes	Reduce energy consumption of RAN network components in low load	Potential impact on UE performance and UE power consumption Network throughput, latency and reliability	Network energy savings	Longer time-to-market (yet to be standardized)
New Spectrum mmWaves	Higher Bandwidth availability	Low penetration power	Campus Network/ I4.0 / AR-VR / Robots	Frequency bandwidth efficiency – needs investigation on energy saving matters at signal link level
MU MIMO	High transmission capacity	High energy consumption due to each power amplifier chain behind each antenna element	Variable use cases	Possibility to turn off antenna path depending on current traffic demand Energy assessment with classical antenna units by high traffic
RIS	Low hardware complexity Power Efficient Eliminate negative effects of natural wireless propagation	New component at prototype level Algorithmic for control still under investigation Other drawbacks to be investigated	New dimension of the flexibility of the network configuration	Impacts on network energy savings to be explored
AI/ML (management of the network)	High flexibility of the network configuration Local shutdown of network components corresponding to the current traffic	Higher complexity of the network architecture AI processing consumes additional energy	Variable use cases	Assessment own CO_{2e} footprint compared to the reduction of CO_{2e} footprint in use of the application
Edge-/RAN-Cloud	Optimal utilization of computing resources idle systems can be switch off	Higher complexity of the network controlling management	Variable use cases	Analyses required on the resulting energy saving effects
6G waveform Design for Energy Efficiency	Optimizing the PA efficiency, which is the major energy consuming component in transmission	Needs investigation on use-cases, requirements of the components Impact is limited to non-sleep mode of the network, i.e. active transmission.	UL/DL Frequency above 52.6 GHz, power-limited links, e.g. Satellite Communication (NTN)	Very early stage of scientific design

Green Design of AI	Applying green AI design methods may enable the application of many AI functions without overhead and reduced hardware resource allocation	Methods may lead to reduced accuracy of intended functionality	Customer: Wearables Smartphones Location Awareness Provider: Flexible allocation of network resources, Provision of more AI capability on existing hardware	New research direction with overlap to federated learning and continual learning

Table 6: analysis of potential impacts of energy saving technologies to the network

A broad portfolio on emerging technologies for mobile communication is today in focus of standardization bodies like 3GPP.

The real impact of those technologies on energy savings or more generally in sustainable future mobile networks is promising but research works still have to be investigated in order to qualify and quantify solutions properly.

Investigations in simulation framework and tools with reliable energy consumption models of the communication link in several network- as traffic- configuration cases including orchestration, virtualization and AI aspects appear to be an essential complementary task.

Starting in 3GPP with Rel-16 for UE power saving and continuing with Rel-18 for Network Energy Saving diverse energy saving technologies are discussed. The timeline of current and future 3GPP RAN releases is illustrated in Figure 13.

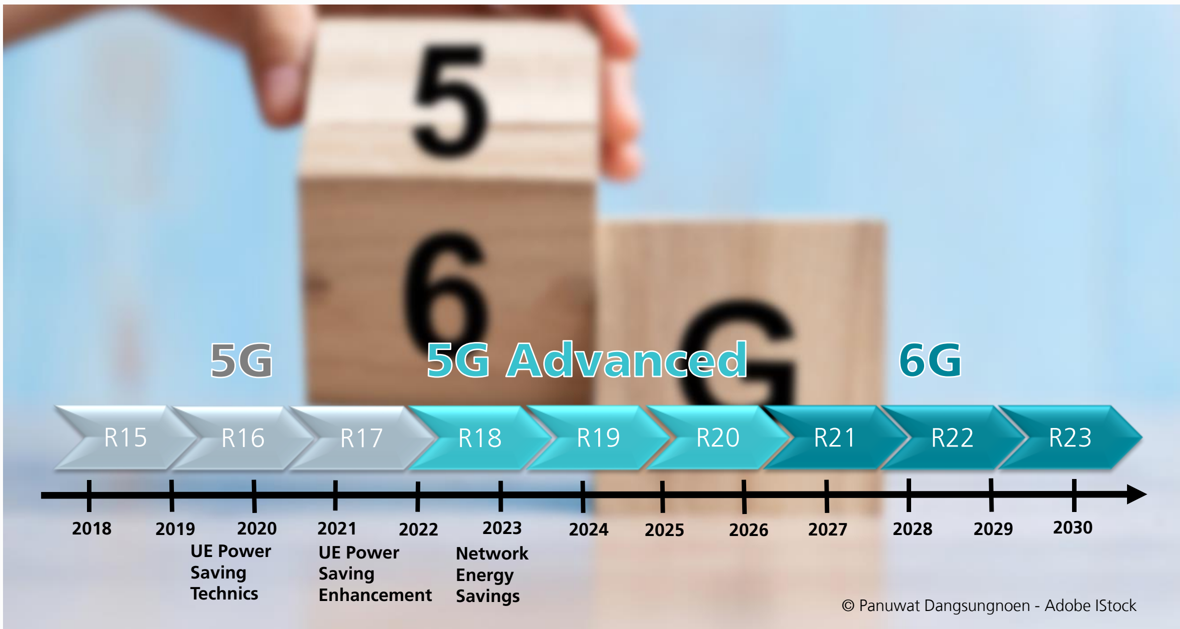


Figure 13: A tentative timeline of standards development for B5G and 6G

The 5G Mobile Communication standard currently only has defined one KPI related to sustainability focusing on energy efficiency. The progress of scientific works on each proposed energy savings technologies, with measurement results and benchmarking assessment is a starting point to drive the progress of sustainability measures (e.g., new KPIs, new components as RSI, Orchestration algorithms and AI for a green flexible network) for future mobile communication network.

For the progress of sustainability matters following questions would arise:

- Do we have the right tools and metrics to evaluate the impacts of new energy saving mechanisms in the overall communication chain and for all operative use cases? What research topics are still open to be addressed?

- How to evaluate which energy saving technologies have a relevant leverage effect in operation?

- How to introduce in the evaluation process that some enhancements are easily to implement (as a change of Hardware or Software is possible locally - upgrade or change of a unit) but other more complex upgrades involving changes in the architecture of the mobile communication means new Hardware/Software/Firmware in the UEs as base stations and Core Server. How manageable is it in terms of timing, costs, lifespan of components, downgrade-ability, etc.?

- Are incremental technological improvements toward energy savings enough to achieve the goal of CO_{2e} emission neutrality of 6G in 2050 latest? What can be achieved with a paradigm change towards Post-Shannon Communication and/or Quantum Communication?

9 Conclusion

Even if energy suppliers can provide an always growing part of renewable energy to the network operators, the next one or two decades fossil-based energy will still play an important role in our society.

Forcing the production and the use of clean energy is for sure one of the most important measures to investigate. But this means also to invest in the development of further renewable energy technologies, to diversify the sources of energy, e.g. considering development of energy storage technologies. At the end renewable energy should be also affordable for industrial processes.

The strong effort on energy efficiency improvements of the mobile communication network from the overall architecture through the data transmission, subsystems and components, combined with the effort on growing renewable energy sources, might be an initial promising combination.

In addition, there is a need to push current as future standards with industries, shareholders and customers/users in order to transfer in a fast manner the results on energy efficiency improvements into the next generation of products.

Further aspects e.g., material consumption, recyclability, longevity of the product, second life of products, software upgradeability, and decomposability into basic materials for reuse will need to get a high priority. This effect is today amplified by the current supply chain shortfalls. This implies consequently to invest among others in:

- Renewable materials for electronics, semi-conductors/ICs and batteries
- Use of recycling materials in general
- Decarbonization efforts
- New business models based on the CO_{2e} footprint of a service or of an equipment

In conclusion digitalization, green technologies as business innovations are still in their infancy but are the crucial enablers to shape a more sustainable future.

This will not substitute the fact that everybody is still responsible for his consumer behavior of internet, mobile data and mobile devices. For this purpose, incentivizing campaigns are obviously necessary measures.

The Fraunhofer IIS team is pleased to invite 5G stakeholders like MNOs, suppliers as researchers to contact us for exchange and discussion about all energy saving matters.

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11 Abbreviations

Abbreviation	Explanation
PO	Paging Occasion
AC	Alternating Current
ADC	Analog to Digital Converter
AI	Artificial Intelligence
BWP	Bandwidth Part
CCF	Corporate Carbon Footprint
CSI	Channel State Information
DAC	Digital to Analog Converter
DC	Direct Current
DCI	Downlink Control Information
DL	Downlink
DNN	Deep Neural Network
EC	Energy Consumption (maybe?)
eNodeB	Evolved Node B
GHG	Greenhouse Gas
ICT	Information and Communications Technology
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LTE	Long Term Evolution
MIMO	Multiple Input and Multiple Output
ML	Machine Learning
MNO	Mobile Network Operator
NR	New Radio
NTN	Non-Terrestrial
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PCF	Product Carbon Footprint
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Data Shared Channel
PEI	Paging Early Indicator
QoS	Quality of Service
RAN	Radio Access Networks
RIS	Reconfigurable Intelligent Surface
RRC	Radio Resource Control
SoC	System on Chip
TL	Transfer Learning
UE	User Equipment
UL	Uplink
UPT	User Perceived Throughput
VM	Virtual Machines

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