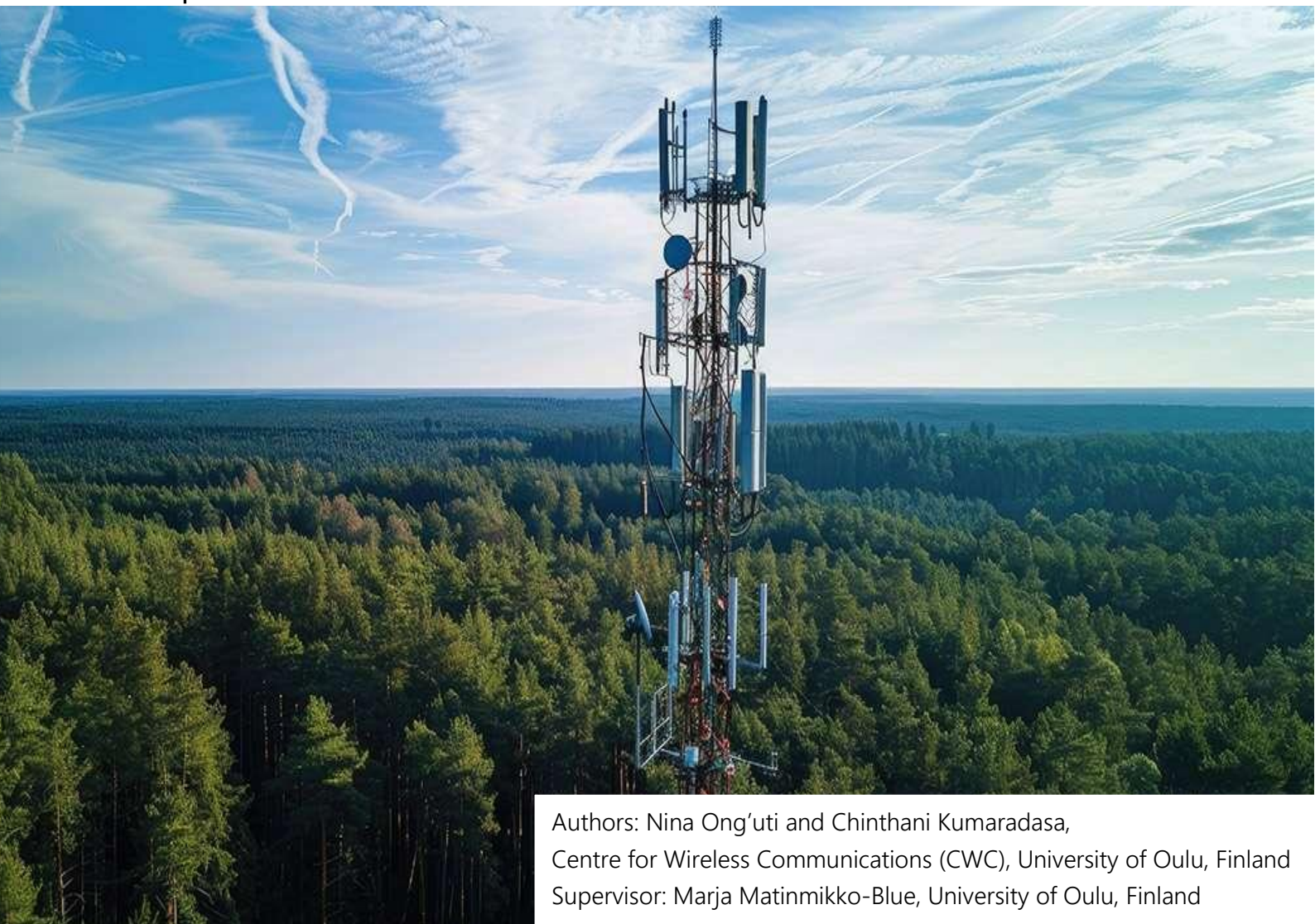


ENVIRONMENTAL SUSTAINABILITY IN MOBILE NETWORKS: Energy efficiency enhancing techniques and design principles

Report 3 of 3



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Abbreviations

3GPP	3rd Generation Partnership Project
4G	Fourth Generation Mobile Network
5G	Fifth Generation Mobile Network
5GC	Fifth Generation Core Network
6G	Sixth Generation Mobile Network
AC	Alternating Current
AI/ML	Artificial Intelligence / Machine Learning
ASIC	Application-Specific Integrated Circuit
ASSP	Application-Specific Standard Product
CAPEX	Capital Expenditure
CO ₂	Carbon dioxide
DC	Direct Current
ETSI	European Telecommunications Standards Institute
EU	European Union
FPGA	Field-Programmable Gate Array
GaN	Gallium Nitride
GHG	Greenhouse Gas
GSMA	Global System for Mobile Communications Association
GPU	Graphics Processing Unit
GWCN	Gateway Core Network
ICT	Information and Communication Technology
IoT	Internet of Things
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radiocommunication Sector
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
KPI	Key Performance Indicator
MIMO	Multiple-Input Multiple-Output
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
MORAN	Multi-Operator Radio Access Network
NGA	Next G Alliance
NGMN	Next Generation Mobile Networks Alliance
NSA	Non-Standalone Architecture
OPEX	Operating Expenditure
O-RAN	Open Radio Access Network
RAN	Radio Access Network



RF	Radio Frequency
SA	Standalone Architecture
SIBs	System Information Blocks
tCO ₂ e	Tonnes of carbon dioxide equivalent
TEPs	Telecommunications Equipment Providers
UE	User Equipment
UN	United Nations
UNFCC	United Nations Framework Convention on Climate Change
UN SDGs	United Nations Sustainable Development Goals
vRAN	Virtualized Radio Access Network
WEEE	Waste Electrical and Electronic Equipment

Abstract

Title of publication

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This report examines environmental sustainability in mobile communication networks, with a focus on energy efficiency-enhancing techniques and design principles for current and future networks. This is the third report in a series of three reports prepared by University of Oulu in Green ICT VISIIRI project. A structured multi-phased methodology was adopted to analyse energy efficiency in mobile communication networks. Stakeholders relevant to building and maintaining mobile communication networks were identified. Data on energy efficiency of mobile communication networks was collected from documents from mobile network operators, standardization and regulatory bodies, telecommunication equipment providers, industry forums and the research domain. Analysis of the data resulted in the identification of a number of techniques to improve energy efficiency of mobile communication networks, and the introduction of design principles for energy efficient networks. The findings of the report show that improving energy efficiency of mobile networks requires an end-to-end and life-cycle approach that combines technological innovation, intelligent network management, architectural optimisation, and environmentally sustainable operational practices.

Keywords – energy consumption, energy efficiency, environmental sustainability, greenhouse gas emissions, mobile communications, mobile network operator, network design, stakeholder

1

Introduction



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1 Introduction

Sustainable development can be generally defined as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” based on the seminal work in (Brundtland, 1987). Sustainability on the other hand can be seen as the “principle of ensuring that our actions today do not limit the range of economic, social, and environmental options open to future generations” (Elkington, 1997).

Within the information and communication technology (ICT) sector, sustainable development and sustainability are nowadays generally addressed through three interrelated pillars: economic, social, and environmental sustainability (Hexa X II, 2022). These three sustainability pillars present distinct but closely interconnected views. As the demand for digital solutions and services expands to cloud computing and Artificial Intelligence (AI) and mobile connectivity requirements continue to grow, so does the ICT sector’s environmental impact (IEA, 2025a) (ITU/WB, 2024). Growth in data traffic, use of devices, and virtualization of services increases energy consumption, and the use of resources and materials, contributing to increased greenhouse gas (GHG) emissions. The ITU and the World Bank assessed 200 leading digital companies and reported that these companies consumed an estimated 581 TWH of electricity, which is equivalent to 2.1% of global electricity consumption. The combined operational emissions from 166 of the 200 companies were 297 million tCO_{2e}, which is approximately 0.8% of global emissions related to energy. This represents a 1.4% increase in emissions from the previous year (ITU and WBA, 2025).

The sustainability related regulatory frameworks and standards impacting the ICT sector include the Paris Agreement (UNFCCC, 2026) the United Nations Sustainability Development Goals (UN SDGs) (UN, 2026) and the European Green Deal (European Commission, 2026a) among others. They define the high-level targets for the ICT sector to manage its environmental sustainability impact. The Paris Agreement (UNFCCC, 2026) is an international treaty on climate change that was adopted by 195 countries in Paris France in 2015 to ensure that global average temperatures remain well below 2°C above pre-industrial levels and to limit temperature increase to 1.5°C above pre-industrial levels. The UN SDGs (UN, 2026) are the internationally agreed agenda with 17 goals that call for action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030, among other targets. The European Green Deal (European Commission, 2026a) is a legally binding strategy that aims to cut greenhouse gas emissions by at least 50% by 2030 and achieve climate neutrality by 2050 by transforming Europe’s economy, energy systems, transport, and industries.

Mobile communication network infrastructure within the ICT sector is the backbone for modern societies. Mobile communication networks have a dual role in environmental sustainability discussions.

On one hand, they create environmental sustainability burden by producing e.g., greenhouse gas emissions through energy consumption, manufacturing, logistics and operations, resulting in so-called environmental footprints. On the other hand, they function as enablers for environmental sustainability improvements including decarbonization across different sectors by providing digital solutions that optimize the use of resources, reduce travel, and improve operational efficiency among others, resulting in so-called environmental handprint. For example, the use of mobile communication solutions can enable intelligent transport solutions, remote working, and precision agriculture and contribute to enabling emissions reductions in other sectors. This dual role presents both a challenge and an opportunity for the mobile communication sector to contribute to sustainable development (GSMA, 2023) (NGA, 2022a)

Increase in energy consumption in the ICT sector has a direct effect on carbon emissions. According to 3GPP, the mobile telecommunications sector produces 0.2 to 0.3% of global emissions (3GPP, 2025). The European Commission estimates that digital technologies accounted for 8-10% of energy consumption in the EU and 2-4% of greenhouse gas emissions (ECO, 2022). The rapid growth of data traffic has increased the environmental footprint of mobile networks, especially in terms of energy consumption and GHG. As networks evolve from 4G to 5G and later to 6G, it is expected that infrastructure use will become more dense, new frequency bands will be deployed and computational requirements will increase, leading to an expected increase in energy consumption. Commitments to environmental sustainability, also add to the need to reduce energy consumption, which directly affects GHG emissions. Regulatory requirements demand accountability and transparency. With energy costs of operators being approximately 23% of operation costs (ITU/WB, 2024), operators are increasingly expecting vendors to prioritize energy efficiency in their products, and this requirement spreads in the supply chain. This makes energy efficiency a critical concern for mobile networks. The ITU-T defines general energy efficiency as the relation between useful output and energy/power consumption (ITU-T L.1330, 2015). It is a central environmental sustainability issue in mobile communications since mobile communication networks consume electricity for radio access networks, backhaul, core network, power systems, cooling systems, and supporting infrastructure. It is widely adopted as a key performance indicator (KPI) for quantitative assessment of energy consumption in mobile networks.

This study is conducted in the VIISIRI project, a national Green ICT initiative in Finland that aims to accelerate the green transition of the ICT sector by fostering environmentally sustainable practices, reducing environmental impact, and promoting energy-efficient solutions for ICTs including mobile communication networks. This report is the third in a series of three reports on Environmental Sustainability in Mobile Networks prepared by University of Oulu in the Green ICT VISIIRI project. The companion reports in this series are: Environmental Sustainability in Mobile Networks: A study of mobile communication stakeholders' activities and indicators (first report), and Environmental Sustainability in Mobile Networks: Analysis of regulations and standards (second report). The reports can be read independently of one another. This report consolidates current global environmental sustainability

activities from the key stakeholders of the mobile communication sector within the ICT sector including leading mobile network operators (MNOs), telecommunication equipment providers (TEPs), and industry forums. Combining the activities and indicators promoting environmental sustainability by the mobile communication sector's stakeholders in a comprehensive format aims to help ICT companies and all interested parties to integrate environmental sustainability practices into their operations.

The remainder of this report is structured as follows. Chapter 2 describes the methodology used in the study. Chapter 3 provides an overview of the architecture of the mobile communication network and how energy is consumed in the different parts of the network. Chapter 4 identifies techniques that improve energy efficiency. Chapter 5 discusses design principles to improve the energy efficiency of future mobile communication networks. Finally, Chapter 6 provides conclusions.

2

Methodology



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2 Methodology

This study investigates energy efficiency in mobile communication networks through techniques that improve the energy efficiency of the networks with the goal of reducing energy consumption. The study analyses how different parts of the network contribute to energy consumption and introduces and discusses the techniques that can improve energy efficiency within mobile communication networks. The steps taken in the methodology are shown in figure 2.1 including stakeholder identification, data source selection, data extraction and sorting, data analysis and categorization and finally reporting, which are described in more detail in the following.

In phase one, relevant stakeholders were identified for the study. These include mobile network operators (MNOs), telecommunication equipment providers (TEPs), regulatory and standards bodies, industry forums, and researchers. TEPs include vendors who design and supply network infrastructure and equipment, such as base stations, core network systems and devices. They influence energy consumption through equipment design including hardware and software. Industry forums bring together operators, vendors and other stakeholders to define share information and best practices, promote common interests and develop guidelines for the industry. They help shape sustainability frameworks, including energy efficiency metrics and targets. Regulatory bodies define the rules and conditions for companies to operate in the mobile communication sector to ensure fair competition and guarantee access to reliable services, among others. Standards bodies create the industry consensus in standards that networks and devices should adhere to for communication to occur seamlessly in the multi-stakeholder environment. Finally, researchers from different organizations carry out research on mobile communication networks. They publish their latest findings on future technologies including hardware and software solutions, all of which contribute to the development of modern mobile communication networks.

In phase two, the sources of data were identified including various types of publications and reports. These included publications on sustainability and energy efficiency and white papers on technology from MNOs and TEPs. From industry forums, we identified several reports on energy management, energy efficiency, future technologies like 6G and state of the mobile industry. Technical documents and white papers from equipment vendors were included to provide insight into hardware design and radio technologies. From the regulatory and standardization bodies, we identified reports and recommendations on energy saving technologies and network architecture including documents from Third Generation Partnership Project (3GPP), the International Telecommunication Union-Telecommunication Standardization sector (ITU-T), International Telecommunication Union-Radiocommunication Sector (ITU-R) and the European Commission. Peer-reviewed journal and conference articles were used to reflect the state of the art from the research domain.

In phase three, we extracted data from the collected documents including e.g. description of network architecture, factors that contribute to energy consumption, energy efficiency techniques, constraints and trade-offs associated with these energy efficiency techniques. Additionally, we were going through the data sources and extracting information on network design, with the aim of identifying emerging principles that dictate how networks can be designed, deployed and operated with higher energy efficiency.

In phase four, about 30 techniques to improve energy efficiency and reduce energy consumption were initially collected and later merged. Analysis of the data collected resulted in consolidating information to four energy-saving domain technologies, a list of complementing energy-saving techniques and energy-efficiency design principles. Finally, in phase five, the information was integrated and presented in this report.

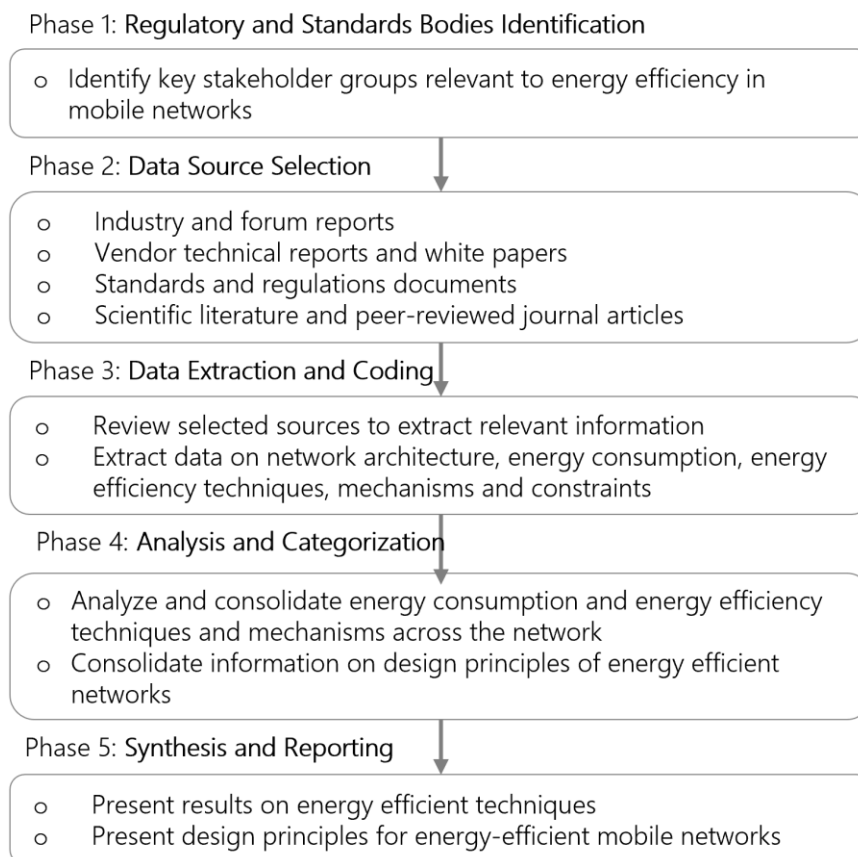


Figure 2.1: Methodology for identifying energy efficiency enhancing techniques and design principles

3

Mobile network architecture and energy consumption



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3 Mobile network architecture and energy consumption

Mobile communication networks have become increasingly complex with each new generation (e.g., 2G, 3G, 4G, 5G and upcoming 6G) as they introduced new features and capabilities and are required to support higher data rates, a growing number of connected devices and with lower latency compared to previous systems (Narjes Lassoued et al, 2026) (ITU-R, 2022) (Salma Tika et al, 2025). The evolution of mobile communication networks has resulted in increased energy consumption across the networks, despite a newer generation typically being more energy efficient compared to the older generation.

3.1 5G network architecture

The 5G network architecture is an end-to-end system comprising the User Equipment (UE), the Radio Access Network (RAN), the 5G core (5GC) and cloud and data centre infrastructure (ITU-R, 2022) (3GPP, 2022) as shown in Figure 3.1. Collectively, these domains support communication and contribute differently to the overall energy consumption of the network.

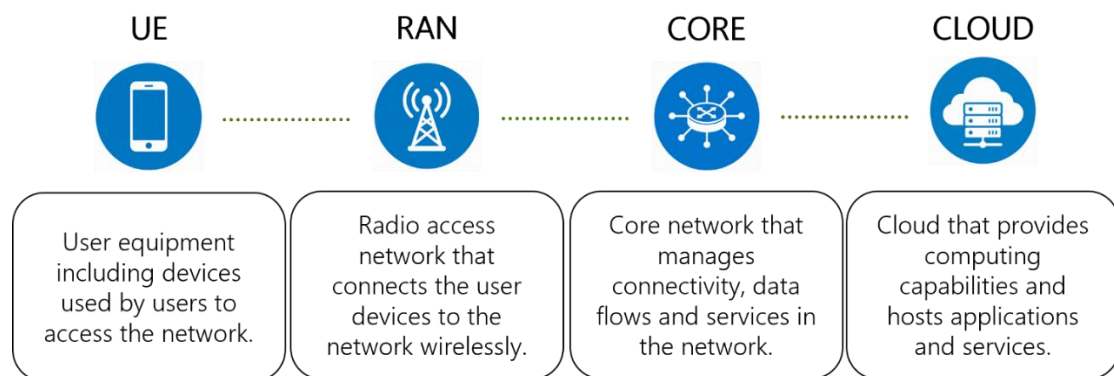


Figure 3.1 Mobile network architecture

The UE is any device that the user is using to connect to the 5G network. UE can be smartphones, IoT devices, wearables, autonomous vehicles and connected systems that access the system through RAN. These devices generate and consume data and interact directly with the network. Energy consumption in the UE is impacted by growth in connected devices and data traffic as the increase in data traffic leads to more frequent transmission and signalling activity which increases energy consumption at the device and network levels (Xiao Yao et al, 2025) (ITU-R, 2022).

The RAN connects the UE to the core network and is responsible for radio transmissions. It consists of base stations including radio frequency (RF) units and baseband processing units, as well as supporting infrastructure such as power supply system and cooling equipment. The RAN is widely recognized as the largest contributor to energy consumption in mobile communication networks. According to GSMA, approximately 87% of operator energy consumption is attributed to the RAN (GSMA, 2021) while Next Generation Mobile Networks Alliance (NGMN) reports a value of around 73% (NGMN, 2021a). Vendors indicate that the RAN accounts for the majority of network energy use (Ericsson, 2022) (Nokia, 2023). In the base stations, energy consumption is dominated by RF transmission components, particularly power amplifiers, which account for a significant share of total power consumption (Huawei, 2021) (NGMN, 2021a).

The 5G Core (5GC) is responsible for network control and management functions, including authentication, mobility management, session management, and policy control (3GPP, 2022). It connects the RAN to external networks and supports end-to-end service delivery. The architecture of the 5GC is a service-based architecture (SBA), in which network functions operate as software components that provide services to other authorised network functions through standardised interfaces (3GPP, 2022). This enables modularity, scalability, and flexible deployment of network functions. The 5G core is inherently cloud-oriented through its service-based architecture (3GPP, 2022). This means network functions are deployed on cloud infrastructure implying that there is a greater dependence on computing resources. Research shows that modern network architectures are increasingly relying on compute-intensive processing where energy consumption is influenced by computing workload and data processing requirements (Rajkumar Buyya et al, 2025). Figure 3.2 shows the distribution of energy use in the 5G network into RAN, operations, core and data centre according to (GSMA Intelligence, 2026).

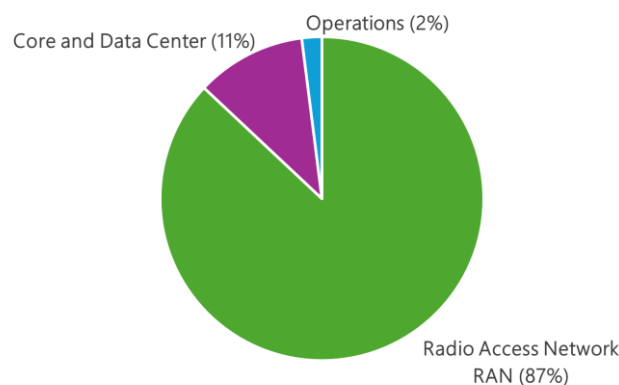


Figure 3.2 Mobile operator energy use of 5G networks (Source: Data from (GSMA Intelligence, 2026))

3.2 Energy consumption

Mobile communication networks have increased energy consumption due to architectural, operational and technological factors that span the entire network. It is estimated that 5G consumes three times more energy compared to 4G network (Tingwei Chen et al, 2025) while 5G technology is said to be four times more energy efficient than 4G (A. De Domenico et al, 2026). As mobile communication networks evolve, they are expected to become more complex, which impacts energy consumption. At the UE, the rapid growth of smartphones, IoT and other connected devices has increased energy consumption (NGA, 2022a).

Energy consumption in the RAN is driven by several factors. The adoption of advanced technologies leads to an increase in the number of active network elements which leads to increased energy consumption (Huawei, 2021) (NGMN, 2023a). The deployment of large numbers of base stations, particularly small cells, leads to higher cumulative energy demand even if individual cells consumed less power (NGMN, 2021a). The use of higher frequency bands further contributes to increased energy consumption due to higher propagation losses, which require increased transmit power and more complex radio hardware (5G Americas, 2023; Huawei, 2021).

RAN functions are increasingly being implemented as software running on general-purpose platforms which improve resource utilization but increase computational demand due to software processing. The introduction of interoperable interfaces between components further increases coordination and signalling requirements resulting in increased energy consumption (O-RAN, 2021). The core network contributes a smaller share of energy consumption of the mobile communication network. Together with the cloud, they account for approximately 12% of overall network energy consumption (GSMA, 2021). Moving network functions to software-based applications results in processing being moved from dedicated telecom hardware to general-purpose computing platforms in data centres. This increases energy consumption due to higher computational, storage, and orchestration requirements (NGA, 2022a). Recent studies confirm that energy consumption in modern network architecture is increasingly influenced by computational workload rather than fixed hardware alone (Francisco Crespo et al, 2025) (J. Lorincz et al., 2026).

The integration of artificial intelligence (AI) and machine learning (ML) into network operations further increases computational requirements. AI/ML techniques are used across network domains to optimize performance and manage resources (Eilaf MA Babai et al, 2025) (Jibum Hong et al, 2025) (ITU-R, 2022), (NGA, 2022a). However, training and running AI models require significant computational resources, which increases energy consumption, particularly in cloud environments (IEA, 2025a) (NGA, 2023c). Another key challenge across all domains of the network is the mismatch between network capacity and actual traffic demand. Networks are typically designed to handle peak traffic conditions but operate under lower utilization for most of the time. As a result, network elements remain active

even when underutilized, leading to energy inefficiencies (NGMN, 2021a). Addressing this challenge requires dynamic resource management and adaptive energy-saving techniques (ITU-T, 2022); (5G Americas, 2023), (NGA, 2022a). All these contribute to increasing energy consumption in the networks. The energy consumption of mobile network operators is shown in Figure 3.3.

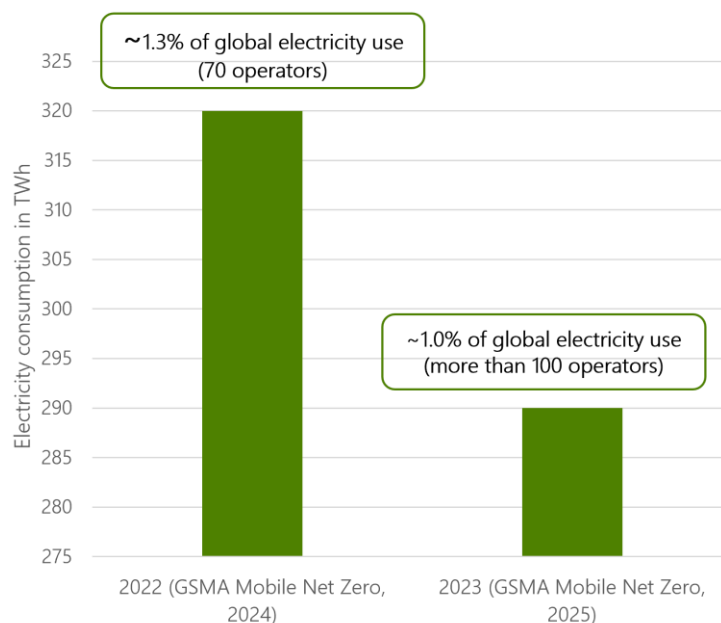


Figure 3.3: Global electricity consumption of mobile network operators (Sources of data: (GSMA, 2025b) (GSMA, 2024))

4

Techniques to improve energy efficiency



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4 Techniques to improve energy efficiency

Improving the energy efficiency of 5G mobile communication networks requires a combination of techniques that operate across different parts of the network. This chapter provides an overview of techniques to improve energy efficiency in mobile communication networks.

4.1 Categorization of energy saving technologies

To address energy consumption in mobile networks, standardization bodies like 3GPP and ITU have identified categories for energy-saving technologies, which can help improve energy efficiency of mobile communication networks (3GPP, 2025) (ITU-T, 2022). 3GPP in its release number 18 categorizes four energy saving domains as follows (3GPP, 2025):

- Time domain
- Frequency domain
- Spatial domain
- Power domain

These domains are described in more detail.

Time domain

Time-domain energy saving category refers to techniques where certain network components are temporarily switched off during time intervals when there is no valid information being transmitted. A network divides time in the network into small time units: the frame, which is divided into subframes, which is divided into slots which are divided into symbols, the smallest time unit. These units are used to transmit data (ITU-T, 2022) (Xiao Yao et al, 2025) (Taehyoung Kim et al, 2020). The network then identifies timeslots or subframes or symbols where there is no valid information to send and temporarily deactivates the power amplifier.

Several methods exist under this technique to save energy. One method is the advanced sleep mode which reduces transmissions in the control and user planes like the synchronization signal blocks (SSB) and the system information blocks (SIBs) to extend the sleep time, saving energy (Toufiqul Islam et al, 2023). Another technique is the discontinuous transmission/reception which allows the transmitter and the receiver to go into inactive states during periods where the symbols, timeslots or subframes

have no valid information. The network reduces power consumption in this state. Wake-up signals are used to activate transmissions only when needed and not have them continuously transmitted, which reduces transmit power. In 4G long term evolution (LTE), the cell reference signals are transmitted every 0.2ms and this interval is too short to meaningfully deactivate the components during symbol intervals. Consequently, the opportunities for switching off these active components end up being limited, and this limits the amount of power that can be saved. This is, however, resolved in 5G by reducing the load of signals that go into idle mode. (ITU-T, 2022), (Xiao Yao et al., 2025) (Taehyoung Kim et al, 2020).

Spatial domain

Spatial domain energy saving category refers to the adjustment of the coverage area of a base station based on traffic demand. This is achieved by reducing the number of active antenna elements or transmission beams when demand is low. In systems with advanced antenna technologies such as massive MIMO, coverage area may be dynamically shaped by deactivating parts of the antenna array or limiting the number of active transmission elements. Reducing the active coverage area or the number of active transmission elements, fewer components are required to operate. This allows parts of the antenna system and any associated hardware like the power amplifier to be switched off or operated at lower power levels. These components are among the most energy-intensive parts of the base station therefore this reduces their activity and leads to overall energy consumption. Additionally limiting spatial transmission reduces unnecessary signal transmission into areas with little or no user activity. This results in improved overall efficiency of the use of resources. Spatial domain energy saving impacts coverage and service quality. Reducing the number of active elements results in a weaker signal strength, reduced data rates and results in potential gaps in coverage, especially at the edge of the cell (ITU-T, 2022) (Xiao Yao et al, 2025)

Frequency domain

Frequency domain energy saving category refers to techniques that reduce energy consumption by adjusting how radio spectrum resources are allocated. Instead of having the available bandwidth and carriers operate continuously, the network can reduce the transmission bandwidth based on traffic demand and conditions of the network dynamically. An important strategy is base station on/off switching, where unnecessary base stations or capacity-booster cells may be temporarily deactivated when traffic demand is low. Other techniques in this domain include carrier adaptation and bandwidth part adaptation. Frequency domain energy saving enhances energy efficiency by switching off an entire carrier or by adjusting the specifications of the carrier to be affected. In the first case, when a carrier is shut down, the hardware can also be shut down, reducing power consumption of the equipment and the transmission. However, in the latter case, the device cannot be shut down since the frequency is also active, therefore certain frequency parameters are adjusted to save energy. Where the carrier stays active, the hardware cannot be fully shut off hence there is limiting power saved. A constraint is that

when one carrier is switched off, traffic might need to be moved to another carrier which will require increasing transmit power to maintain coverage and service quality. (ITU-T, 2022) (Xiao Yao et al, 2025).

Power domain

Power-domain energy saving category refers to techniques that reduce the transmission power by reducing the output power of the power amplifier and dynamically adjusting the transmission power of signals and channels depending on the traffic. Beam optimization increases the precision of the transmitted signal between the base station and the user device. When carried out by software, it increases precision of the beam, and this reduces wasted transmit power on beams directed towards wrong directions. Additionally, antennas are designed with higher antenna gain which allows the same signal strength to be transmitted with less power. This enables network coverage to be maintained while reducing overall power consumption. Reducing transmission power directly affects signal coverage and link quality between the base station and the UE. Therefore, power reduction must be managed so as not to affect the network negatively (3GPP, 2025), (Xiao Yao et al., 2025).

4.2 Identified techniques

There are many different techniques which help improve energy efficiency of mobile communication networks. The following techniques were identified in this study to increase energy efficiency of the mobile communication networks:

- AI/ML optimization
- Switch-off capabilities
- Near-zero communication
- Energy harvesting
- Energy management systems
- RAN sharing
- Edge computing
- Virtualization
- Intent-based management
- Cooling technologies

AI/ML Optimization

AI/ML optimization refers to the use of AI and ML algorithms in the networks deployed by the MNOs to analyse large volumes of network data, identify traffic and usage patterns and then dynamically adjust network operations in real time to enable operators to manage resources responsibly, improve network design, automate processes, and improve energy efficiency. AI/ML

models can analyse traffic patterns and predict demand so that network resources can dynamically match the actual load. It also helps by automating schedules, network planning and optimizing network operations. AI/ML optimization by using resources efficiently, automating resources and network activities and proactively managing activities that will lead to downtime, can also reduce the need for human intervention. However, AI/ML systems require large volumes of data for training, which takes large computational resources. The specialized hardware required to run these tasks include e.g., Graphics Processing Units (GPUs), Field Programmable Gate Arrays (FPGA), Application Specific Integrated Circuits (ASICs), which consume a lot of energy. As a result, the energy saved by optimization is reduced due to the running of AI/ML techniques (ITU-R, 2022) (Martins Odiameni et al, 2024). AI/ML optimization techniques can be considered to fall under all energy-saving domains (time, spatial, frequency and power domains).

Switch-off capabilities

Switch-off capabilities refer to the ability of network elements to either fully or partially be deactivated during periods of low traffic to reduce energy consumption. During periods of low traffic, base stations for instance continue to consume significant energy regardless of whether users are being served, due to fixed static power of components. By switching off the underutilized base stations, energy that would have been used to run the base station is conserved. A constraint of switch-off capabilities is that there is usually a trade-off between energy savings and performance. This can result in degraded quality of service, increased latency and reduced throughput for users (Adrian Ichimescu et al, 2024). Switch-off capabilities be considered to fall under all energy-saving domains (time, spatial, frequency and power domains).

Near-zero energy communication

Near-zero energy communication refers to the use of devices that operate using energy harvested from natural and man-made sources like solar energy, thermal energy, wind power, salinity gradient. Due to the small amount of energy required to operate the devices, these devices do not require batteries and therefore can be deployed in places where replacing batteries would be difficult. Near-zero energy devices use ultra-low-power radio circuits, such as nano-Watt receivers that require very small amounts of power to operate. These circuits harvest energy from the environment. These make them deployable in areas where power availability is an issue. As a result, energy is not drawn from the grid. Harvested energy is usually insufficient and not stable enough for continuous harvesting. Therefore near-zero communication is not sufficient for advanced computational needs, which limits the usage scenarios, and they cannot be deployed on a large scale (R. Citroni et al, 2024), (3GPP, 2025) (NGA, 2023a), (NGA, 2023c). Near-zero communication is considered to belong to time and power domain energy saving categories.

Energy harvesting

Energy harvesting refers to the techniques that allow devices to obtain energy for their operations from natural or man-made sources like radio-frequency signals, body heat, light, sun, wind, friction, temperature fluctuations and vibrations. Energy harvesting systems include circuits that capture small amounts of energy from the environment where they exist and convert it to electrical power that can be used by the device. This eliminates the need for batteries, meaning the devices can be miniaturized further. This makes them consume less energy. In addition, there is no energy drawn from the grid and energy consumption is reduced. The amount of energy that can be harvested is usually limited and not continuously available. Therefore, this makes it exploitable only by low-powered devices. In addition, the rectifiers that convert signals to direct current power are not usually very efficient, but they keep improving (ITU-R, 2022) (Peter Sevcik et al, 2025), (R. Citroni et al, 2024). Energy harvesting is considered to belong to time and power domain energy saving categories.

Energy management systems

Energy management systems refer to the methods used in mobile communication networks to plan and control how energy is obtained and used across the network. They help in the selection of cost-effective energy sources including low-carbon electricity purchased through wholesale agreements and renewable energy generated on sites. They also coordinate battery charging and discharging when electricity is at its cheapest. Energy management systems combine information about energy demand, electricity prices and renewable energy production and determine the most efficient energy supply strategy tailored to each site. This ensures there is no energy waste based on a uniform application of energy needs for sites that are varied. Weather forecast data is used to predict the production of renewable energy, allowing operators to plan energy consumption in advance, and when to integrate renewable energy into their network. For energy management systems to operate effectively, they require high volumes of real-time data and accurate forecasting. Additionally, the data they require comes from multiple sources which are layered, e.g. data from site-level, data from network-level, data from the grid and so on. To use all this effectively, they could benefit from AI/ML, which in turn is power hungry. Also, some energy sources, like solar and wind are not consistent and reliable and cheap energy may not be available when demand is high (NGMN, 2025a). Energy management systems are considered to belong to all four (time, frequency, spatial and power domain) energy saving categories.

RAN sharing

RAN sharing refers to an arrangement where two or more operators use the same network infrastructure instead of each operating its own network. Different RAN sharing models exist, whereof one is the multi-operator core network (MOCN), which supports sharing spectrum assets. Another is

the multi-operator radio access network (MORAN), which support sharing of broadband resources. The third model is the gateway core network (GWCN) where some of the core network elements are shared. Sharing infrastructure between operators reduces and/or eliminates the number of network elements that need to remain active to provide communication services. Duplication of infrastructure is also avoided. This lowers the energy that all the operators would otherwise consume, whether from the grid or from other sources. RAN sharing requires that the operators coordinate in areas like managing traffic, quality of service, use of spectrum and how faults are handled. These activities increase the complexity of managing the network. Infrastructure sharing may be limited by differences in spectrum between operators. For example, in MORAN, spectrum cannot be shared which means radios cannot be shared. This limits the amount of energy savings that can be made. Differences in propagation characteristics and bandwidth availability may require additional network densification. This results in increase in capital expenditure (CAPEX), operational expenditure (OPEX) and energy consumption. Additionally, RAN sharing increases the risk of transparency, reliability, privacy and other concerns (5G Americas, 2023) (ITU-R, 2022). RAN sharing is considered to belong to all four (time, frequency, spatial and power domain) energy saving categories.

Edge computing

Edge computing refers to a form of cloud computing in which part of the processing and data storage is shifted from the central cloud to the nodes at the edge of the network. This technique is used in instances where clients request low-latency service. Edge computing can also involve split where computing resources are moved from the user device to the network. By offloading the workload and splitting computing processes, transport costs are reduced when data is processed at the edge instead of the core. This reduces use of energy. In cases where energy-intensive processing is shifted from the user device to the edge, the battery of the device is extended. Additionally, the flexible distribution of workloads allows networks to optimize resources and avoid over-provisioning of computing devices. Edge computing requires deployment of additional infrastructure at the edge. These come with additional processing requirements such as additional power and cooling requirements. Therefore, while energy is being saved through distributing processes to the edge of the network, this additional deployment can increase overall energy consumption (ETSI, 2023) (ITU-R, 2022), (NGA, 2023a), (Muhammad Ilyas Khattak et al, 2025). Edge computing is considered to belong to time domain, spatial domain and power domain energy saving categories.

Virtualization

Network function virtualization (NFV) refers to the separation of network functions from dedicated hardware and implementing them as software on general computing transforms and are referred to as virtualized network functions (VNFs). It is closely associated with software defined networking (SDN). By running multiple VNFs on shared servers, hardware that would have otherwise

been used can be shut down, thus saving energy. Similarly, NFV enables the dynamic scaling of VNF instances such that resources are only allocated, when necessary, thus reducing energy consumption (Z. Ezzeddine et al, 2024), (Josip Lorincz et al., 2024). Virtualization introduces computational overheads when multiple VNFs are executed. The competition for resources degrades the efficiency of processes in the servers and increases energy cost per function. This results in partially offsetting energy savings made (ETSI, 2014) (Josip Lorincz et al, 2024) (Z. Ezzeddine et al, 2024). Virtualization is considered to belong to time domain and power domain energy saving categories.

Intent-based management

Intent-based management functions refer to software functions that control network operations based on predefined goals like improved energy efficiency. In cloud-based systems, these functions run on components deployed on general-purpose processors like application-specific integrated circuits. AI/ML-enabled power management evaluates network conditions, the weather forecast and the temperature of the surrounding when determining how workloads should be executed. Based on the information obtained, workloads can be prioritized so that network functions are operated in towards predefined intents which in this case is energy efficiency. AI/ML is also used to automate these processes in a cloud-native RAN environment. Intent-based management functions rely on AI/ML which requires continuous monitoring and processing of collected data. Performing analysis of this data are energy intensive processes and this reduces the amount of energy that can be saved (Adrian Ichimescu et al., 2024) (NGA, 2023a), (SUSTAIN 6G, 2025). Intent based management is considered to belong to all four (time, frequency, spatial and power domain) energy saving categories.

Cooling technologies

Cooling technologies refer to methods that remove excess heat generated by telecommunication equipment to reduce the energy consumption of the network equipment. Inefficient cooling directly increases network's energy consumption. Cooling technologies include e.g. fresh air water or liquid cooling systems, improved fan technologies and thermal management. Cooling technologies operate in different ways. When fresh-air cooling is used, no energy is used to operate machines that will cool the equipment rooms. Water or liquid systems conduct heat more effectively than air. Thus, they require less energy to move a given volume of coolant. When fans are used for cooling more energy efficient fans can be used to lower the energy consumed. Alternatively, the temperature of the equipment room can be fixed, and then gradually increased to a point where free cooling can be used. Also, temperatures can be adjusted depending on the season of the year. Cooling systems that run on electricity increase the energy consumption of network operators. In addition, some of the cooling methods have environmental impact, for instance, use of water and refrigerants (NGMN, 2023b), (Narjes Lassoued et al, 2026). Cooling technologies are considered to belong to time domain and power domain energy saving categories.

5

Design principles to improve energy efficiency



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5 Design principles to improve energy efficiency

Energy efficiency will be most effectively achieved when it is considered a requirement of network design rather than an add-on feature after deployment. When energy-saving features are added onto an already deployed network, this typically adds extra costs and technical complexity. Networks need to be designed with sufficient allowance to accommodate unforeseen changes in traffic patterns, technology, and operations without compromising the uptime, the quality and the energy efficiency of the network. In this chapter we propose eight design principles that will embed energy efficiency into the mobile communication network right from the beginning. Figure 5.1 shows the proposed design principles of energy-efficient networks, which are explained in more detail in the following.

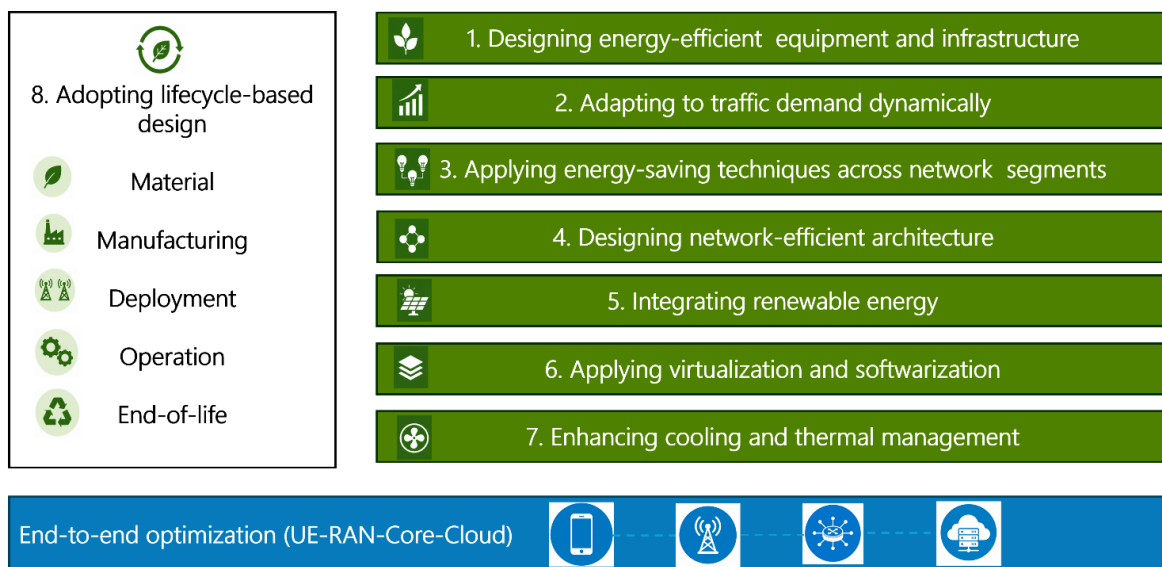


Figure 5.1: Proposed design principles for energy efficient networks

5.1 Designing energy efficient equipment and infrastructure

Energy consumption in mobile networks is influenced by the performance of hardware and supporting infrastructure. This means inefficiencies at this level will be scaled across the whole network. Designing energy-efficient equipment and infrastructure is a key design principle for energy-efficient networks. Energy efficiency of the network must start with its components. Since network equipment

operate continuously and is the basis of all network functions, improving design of equipment and infrastructure will have a scalable impact on the overall energy efficiency of networks (ITU-T, 2022). This means designing and deploying energy efficient equipment and infrastructure. It also means using passive infrastructure like fibre optics cables and simplifying the site architecture. The concept of zero-energy devices is helpful (NGA, 2023a) as these devices do not use conventional energy to operate, but harvest energy from their surroundings to operate.

Using energy efficient hardware (NGMN, 2023b), deploying AI accelerators (Hexa X II, 2025; ITU-R, 2022; Hexa X II, 2025; ITU-R, 2022), and using high-voltage direct current on site (NGMN, 2021a) can help with energy management. One component that is vital for managing the energy efficiency of the radio is the power amplifier (NGMN, 2021a) as 60% of the radio's power consumption is attributed to the power amplifier. RF devices, which include power amplifiers, are responsible for 60% approximately of the energy consumption on site (Huawei, 2021). Semiconductor materials and circuits are being designed to be more energy efficient (NGMN, 2021a). Other semiconductor materials and design of circuits are improving as well, improving the energy efficiency of the radio as well. Gallium nitride (GaN) is one such material that is used in transistors due to its higher power density, higher supply voltage and higher thermal conductivity (NGMN, 2021a; NGA, 2022b; NGMN, 2023b; NGA, 2023c). Gallium nitride amplifiers are widely used in 5G equipment, and this makes them have higher power efficiency than 2G/3G/4G equipment.

Besides using better materials as described above, integration of functions into single components can help to improve energy efficiency. For instance, the same power amplifiers can be designed to integrate several discrete functions into a single package (NGMN, 2021a). Multi-band technology can improve energy efficiency, size and weight of equipment (Ericsson, 2022; Ericsson 2024). Transceivers can address energy efficiency through using energy-efficient hardware like Application Specific Standard Products (ASSPs) and Application-Specific Integrated Circuits (ASICs) (NGMN, 2023b). Simplifying sites also makes the RAN more energy efficient. This means reducing the amount of equipment in a room, which leads to less use of air conditioning (Huawei, 2021). Another example would be to move sites from indoor to outdoor for the same reason, using less cooling equipment by taking advantage of outdoor cooling (NGMN, 2023b). Enhanced cooling methods can be used, including heat exchangers and heat pipes (ITU-T, 2016). Part of site simplification includes deploying bulk DC feeds closer to the radios on the tower instead of multiple feeds (NGMN, 2023a) or deploying high voltage direct current (NGMN, 2021a) which is more efficient as it reduces the number of conversion stages compared to AC. This reduces losses due to the changes, making it more energy efficient.

5.2 Adapting to traffic demand dynamically

The second design principle is to adapt the networks to traffic demand dynamically. Networks are usually sized to handle peak traffic, but for much of the time they operate well below that level, which means some resources remain active without being fully used (Narjes Lassoued et al, 2026); (NGMN, 2021a). The result is ongoing energy consumption even when demand is low. Dynamic adaptation addresses this problem by matching network operation more closely to actual traffic conditions. Instead of keeping capacity fixed at a constant level, modern networks can adjust resource allocation in response to real-time or predicted demand (A. De Domenico et al, 2026). This allows network elements to be scaled, reconfigured, or temporarily switched off when traffic is light.

At the radio access level, these adaptation mechanisms operate across time, frequency, spatial configuration, and transmit power. In practice, this includes sleep modes and reduced transmission levels that lower the activity of base station components during off-peak periods. By keeping transmission and processing activity closer to what is needed, these approaches reduce energy use associated with idle or underused resources (J. X. Salvat Lozano et al, 2025). Dynamic adaptation also applies to computational resources in virtualized and cloud-based network architectures. Network functions can be scaled up or down depending on traffic load, which means processing capacity does not have to remain fully provisioned. Studies show that this kind of scaling can reduce energy consumption by better matching computational resources to service demand (J. Lorincz et al, 2026). Recent work also shows that traffic-aware control strategies can outperform static configurations. When resource allocation is adjusted continuously using observed or predicted traffic conditions, networks avoid unnecessary operation of both transmission and computing resources (Xiao Yao et al, 2025). This makes adaptive control an important part of overall system efficiency.

Prediction plays an increasingly important role in this process. Artificial intelligence and data-driven methods allow networks to anticipate traffic changes and adapt more proactively (A. De Domenico et al, 2026). That shortens the gap between demand changes and system response, which improves the effectiveness of adaptation. However, dynamic adaptation also brings trade-offs. Frequent changes in configuration can affect service continuity, latency, and system stability if they are not managed carefully. Inaccurate traffic prediction can also weaken the benefits of adaptation and lead to poor resource allocation. Overall, dynamic adaptation improves energy efficiency by reducing the gap between provisioned capacity and actual demand. By aligning transmission, processing, and infrastructure activity with real usage conditions, unnecessary energy consumption can be reduced while still maintaining the required level of performance.

5.3 Applying energy-saving techniques across network segments

The third design principle is to apply energy-saving techniques across network segments. For achieving energy efficiency improvements, energy-saving techniques must be applied simultaneously across the UE, the RAN, the core and the cloud, rather than focusing on only one part of the network. Energy efficiency of network equipment should be considered from an end-to-end perspective (NGMN, 2024a; NGMN, 2025b) and everything should be considered holistically and jointly with optimization (NGA, 2023a). When transmission, computation and data transport are addressed together, networks can reduce energy consumption more effectively than through isolated optimization (Narjes Lassoued et al., 2026) (J. Lorincz et al, 2026).

The RAN has been identified as the biggest energy consumer of the network, and therefore most effort to conserve energy should be address that (GSMA Intelligence, 2026; A. De Domenico et al, 2026). Also the core and data centres/cloud within the MNO domain also provide opportunities for network energy saving. Therefore, energy-saving techniques need to be used across several domains, each targeting a different source of consumption. In the RAN, methods such as discontinuous transmission, sleep modes, antenna muting and transmit power control can reduce energy use by lowering radio and baseband activity during periods of low traffic (Narjes Lassoued et al., 2026). These measures directly cut transmission-related energy consumption, which accounts for the largest share of network energy use (NGMN, 2024b) (Xiao Yao et al, 2025).

In the core network and cloud infrastructure, energy efficiency depends heavily on how computational workloads are managed. As network functions move toward virtualized and cloud-based environments, energy demand shifts from dedicated hardware to shared computing infrastructure. Efficient workload allocation, resource consolidation and dynamic scaling are therefore needed to manage this transition and avoid unnecessary energy use (J. Lorincz et al, 2026; A. De Domenico et al, 2026). The use of AI is important for coordinating energy saving across the whole network. AI/ML algorithms that analyse traffic patterns and predict demand on the network can be used for dynamic spectrum management, interference reduction and energy-efficient network planning (NGA, 2023b; Nouri Omheni et al, 2025). Examples include AI-based communication protocol that runs across several layers of the network (Chouksey, 2025). AI can also help with fault recovery, energy optimization, optimal scheduling and network planning (ITU-R, 2022).

5.4 Designing energy-efficient network architecture

The fourth design principle is designing energy-efficient network architecture. 5G mobile network architecture is an end-to-end system made up of interconnected domains, including UE, the RAN, the core network, and cloud or data centre infrastructure of the MNO (3GPP, 2022), (ITU-R, 2022). This system-level structure shapes how network functions are distributed and how data and control move through the network. In turn, it influences where processing, transmission, and storage take place, and how efficiently resources are used across the system (A. De Domenico et al, 2026) (Bhuvaneshwar Doorgakant et al, 2025). By shaping where processing, transmission, and control take place, architectural design plays a central role in how network resources, and therefore energy, are used.

The network's functional structure rests on the separation and interaction of network functions. In the 5G core, the service-based architecture allows network functions to offer services to one another through standardized interfaces (3GPP, 2022). Since functions can be instantiated and scaled independently, resources can be adjusted more closely to demand, which affects how efficiently computing capacity is used. In the radio access network, architecture is defined by the separation of functions across different components. When base station functions can be split into distinct units that can be deployed independently (3GPP, 2022), the distribution of processing across the network can be changed. Centralizing functions can reduce duplication and improve resource sharing, but it also increases transport demands between nodes. Distributing functions closer to the edge does the opposite: it reduces transport requirements but shifts more processing to local sites (Abir Laouadi et al, 2025) (Bhuvaneshwar Doorgakant et al, 2025).

Open and disaggregated architectures add another layer of flexibility. Open RAN uses open interfaces between components, making it easier to integrate network elements in a modular way (Michele Polese et al, 2024). That modularity supports independent deployment and scaling, but it can also create extra coordination and signalling overhead. As a result, system resources may be used more flexibly, but not always more efficiently (Sotiris Chatziiltis et al, 2025; Ahmed Al-Tahmeesschi et al, 2025). A further design choice concerns where functions are placed across centralized and distributed environments. Cloud RAN and edge computing represent different ways of locating processing resources within the network (J. Lorincz et al, 2026). Centralized architecture tends to improve sharing and utilization, while distributed architecture reduces transport requirements and latency. These choices determine where energy-intensive tasks such as processing and data transmission occur (Bhuvaneshwar Doorgakant et al, 2025). (NGA, 2022a)

Edge computing extends this logic by bringing processing closer to the radio access network. Multi-access edge computing allows applications and services to run near the network edge (Shi-Yu Zhang et al, 2025). That reduces long-distance data transport, but it also increases the computational burden at distributed sites, shifting energy use rather than eliminating it. Network slicing adds a logical

layer to the architecture, allowing multiple virtual networks to run on shared infrastructure (3GPP, 2022). This can improve resource allocation by matching capacity more closely to service requirements. At the same time, operating multiple logical networks creates extra management and coordination demands, which can affect overall efficiency (Josip Lorincz et al., 2024) (M. Weng et al, 2025).

5.5 Integrating renewable energy

The fifth design principle is integrating renewable energy. Mobile operators are increasingly committing net-zero emissions, and the shift to renewable energy is widely seen as one of the main ways to reduce the carbon footprint of network operations (GSMA Intelligence, 2026). In that sense, renewable energy is both an operational measure and a strategic priority. Overall, renewable energy integration supports network sustainability by reducing dependence on carbon-intensive electricity while still maintaining reliable operation through storage and intelligent control.

Consequently, reducing the carbon intensity of energy supply is essential to improving the environmental sustainability of mobile communication networks, which makes renewable energy integration important. Energy efficiency improvements can lower total energy consumption, but the environmental impact of network operation still depends on the source of that energy. Recent research treats the shift to renewable energy as a key step in reducing GHG emissions from mobile networks (A. De Domenico, 2026).

Operators have reported that they have sourced all electricity from renewable energy since (Deutsche Telekom, 2024) or are developing solutions to support the transition to renewable energy in telecom networks (Elisa, 2025; Telia, 2024). These examples show a broader industry shift toward lower-carbon network operation. However, renewable energy integration also brings challenges because solar and wind generation are variable by nature. This can create a mismatch between energy supply and network demand, especially as energy systems become more decentralized. As a result, telecom networks need new approaches to energy management that can handle intermittency more effectively (Y. Zhong et al, 2025). Energy storage systems are central to that effort. Batteries can store excess renewable energy and provide backup when generation is low, improving reliability and making better use of renewable supply (NGMN, 2023a). Hybrid energy systems that combine renewables, storage, and grid supply also give networks more flexibility in balancing energy availability with demand.

The effectiveness of renewable energy integration is further strengthened by intelligent energy management. Machine learning and optimization methods can help predict traffic demand and renewable generation, allowing networks to better align energy use with available renewable supply (K. Ukoba et al, 2024; A. De Domenico et al, 2026). In practice, this means energy management systems can use weather forecasts and grid conditions to improve how renewable energy is scheduled and used

(A. De Domenico et al, 2026). Beyond operational gains, renewable energy integration is also important for long-term sustainability targets.

5.6 Applying virtualization and softwarization

The sixth design principle is applying virtualization and softwarization. Ultimately, virtualization and softwarization improve energy performance by making better use of computing resources and reducing the need for rigid hardware. By matching processing activity to current demand and consolidating functions onto shared infrastructure, these methods create a more adaptive and energy-aware network. Rigid, hardware-based deployments often lead to inefficient use of computing resources, which makes virtualization and softwarization a central principle for improving energy performance. By decoupling network functions from proprietary hardware and running them as software on shared, general-purpose infrastructure, virtualization changes how capacity is provisioned and utilized across the network (NGMN, 2023a; J. Lorincz et al, 2026). This shift allows for more efficient operation through workload consolidation and dynamic allocation. Instead of running functions on dedicated equipment that stays underutilized for long periods, virtualized environments allow multiple tasks to share the same physical hardware. Evidence suggests that consolidating these workloads onto fewer servers reduces the total number of active processing units, which in turn lowers overall energy demand (NGMN, 2023a; J. Lorincz et al, 2026)

Softwarization also enables much greater flexibility in resource management. Network functions can be instantiated, scaled, or migrated on demand, which ensures that computational capacity stays in line with traffic. This cuts back on unnecessary processing during quiet periods (A. De Domenico et al, 2026; J. Lorincz et al, 2026). When combined with software-defined networking, this flexibility allows for more centralized control and optimization of network-wide resources (J. Lorincz, 2026). The impact of this approach is especially clear in the radio access network. Virtualized RAN (vRAN) and disaggregated architectures allow base station functions to run on shared computing platforms rather than specialized hardware. Research indicates that this can improve utilization and allow for more flexible placement of processing tasks. Depending on local conditions, these functions can be centralized or distributed to optimize how energy is consumed across the site (A. Kalia et al, 2025).

However, virtualization does involve trade-offs. General-purpose servers can be less efficient than specialized hardware for certain high-speed tasks, and the processing overhead required to manage virtualized environments can sometimes offset energy savings. Furthermore, the data centres that support these functions require significant energy for both computation and cooling, effectively shifting the energy burden from dedicated network equipment to centralized cloud infrastructure (A. De Domenico et al, 2026). Despite these challenges, a shift toward softwarization is clearly moving the industry toward more flexible and efficient operation. By enabling dynamic allocation, reducing

hardware redundancy, and supporting centralized optimization, these strategies provide a pathway to better efficiency if they are managed effectively (NGMN, 2024a; J. Lorincz et al, 2026).

5.7 Enhancing cooling and thermal management

The seventh design principle is to enhance cooling and thermal management. Thermal management is a significant hidden cost in mobile networks, as a substantial share of total energy use is dedicated to heat dissipation. As processing intensity and traffic loads grow, heat generation from radio units, baseband processing, and computing hardware also climbs, which forces cooling requirements upward (NGMN, 2023a; T, Dbouk et al 2025; A. De Domenico et al, 2026). Cooling efficiency is therefore a major factor in the total energy performance of any network. Ultimately, better thermal management improves energy efficiency by directly reducing the power needed to handle heat. By blending efficient hardware solutions with intelligent, thermal-aware operations, networks can shrink their energy footprint while keeping hardware reliable (NGMN, 2023a; A. De Domenico et al, 2026).

Enhancing cooling and thermal management require both minimizing the need for active cooling and upgrading the technologies used to remove heat. "Free cooling" is one prominent approach, which uses ambient conditions such as external air or low temperatures to dissipate heat. By cutting the need for mechanical air conditioning, free cooling can sharply lower the energy demand for thermal management (ITU-T, 2022). Its effectiveness, however, is tethered to geography and climate, which can limit its use in warmer or more humid regions (Dlzar Al Kez et al, 2025). Liquid cooling offers an alternative for high-density environments like data centres. Because liquids transfer heat far more efficiently than air, these systems can remove heat from dense processing units much more effectively (NGMN, 2023a; D. Zhou et al, 2025). This helps maintain safe operating temperatures even when processors are under heavy, sustained load.

Beyond physical cooling equipment, thermal-aware operations are also essential. By distributing workloads strategically to avoid "hot spots," networks can reduce peak thermal loads and the strain on cooling infrastructure (NGMN, 2024a). This shows that cooling efficiency is a result of both hardware performance and how network resources are scheduled and utilized. Stable cooling also extends equipment life by reducing thermal stress on components. Lower failure rates indirectly boost energy efficiency by reducing the frequency of hardware replacements and the associated environmental footprint (A. De Domenico et al, 2026). These improvements do come with trade-offs. Advanced methods like liquid cooling often increase system complexity and initial deployment costs (D. Zhou et al, 2025). Conversely, passive methods like free cooling remain limited by local environmental factors (NGMN, 2024a; Dlzar Al Kez et al, 2025).

AI can enhance cooling and thermal management where AI-driven control systems can optimize cooling by dynamically adjusting intensity based on real-time workloads, internal temperature maps,

and external weather data (Xiyong Li et al, 2025; Shrenik Jadhav et al, 2026). In data centres, machine learning models are already being used to improve airflow management and predict thermal surges before they occur. This shift suggests that thermal management is moving away from purely physical solutions toward intelligent, data-driven optimization.

5.8 Adopting lifecycle-based design

Finally, the eighth design principle is about adopting lifecycle-based design. Assessing the environmental impact of mobile communication networks therefore requires accounting for energy use and emissions across all the lifecycle stages (A. Furberg et al, 2026). Energy efficiency must be considered across the entire lifecycle of the network, from material sourcing to manufacturing, to operation, decommissioning and recycling. Network equipment operates continuously, and its use phase is where the bulk of the emissions arise (L. Williams et al, 2022; NGMN, 2021b). The embodied energy of network equipment is in the extraction of raw materials and thus must be reduced. Similarly, the same must be done for manufacturing processes, by using energy-efficient processes to convert raw material into finished products, especially in semiconductor fabrication and energy-intensive components (NGMN, 2021b).

The end-of-life phase is what happens when equipment is decommissioned. They can be refurbished for use, disassembled for parts or recycled for materials. Extending use of equipment reduces the manufacturing of new equipment, which avoids cost of extraction, processing and production. Replacement of old equipment with newer, more efficient equipment needs to be studied case by case as the energy saving made during operation can outweigh energy used to operate an old energy intensive equipment (NGMN, 2024a).

Focusing only on the operational phase provides an incomplete picture of network energy performance, which makes lifecycle-based design a critical principle for long-term environmental sustainability. As mobile communication networks consume energy throughout their entire life—from raw material extraction and manufacturing to final disposal—efficiency must be viewed through a full-lifecycle lens rather than being limited to the "use phase" (NGMN, 2021b; NGMN, 2024b). This approach is increasingly reflected in European regulatory frameworks. Policies such as the EU Ecodesign Directive (EU, 2024a) and the Ecodesign for Sustainable Products Regulation (EU, 2024b) mandate that energy performance, durability, and recyclability be considered at the design stage. Furthermore, the EU Circular Economy Action Plan (European Commission, 2020) highlights the necessity of reducing resource use and extending product lifetimes. Together, these regulatory frameworks show that lifecycle considerations are now central to sustainability. The relative importance of these stages has also shifted. While the operational phase has long been the primary focus, recent studies indicate that "embodied energy"—the energy tied up in material extraction and manufacturing—is becoming increasingly

significant as operational efficiency gains accumulate (L. Williams et al, 2022). Thus, there is a growing need to lower energy use in upstream processes like material processing and equipment production.

In the material and manufacturing phases, energy demand stems from resource extraction and component assembly. This can be mitigated through better material efficiency, the use of recycled inputs, and cleaner manufacturing processes (NGMN, 2024b). These steps effectively lower the embodied energy of hardware before it is ever deployed in the field. During the operational phase, efficiency remains vital due to the continuous nature of network activity. Techniques like traffic adaptation, virtualization, and cooling optimization remain essential for reducing ongoing consumption (NGMN, 2021a; NGMN, 2024a) (Adrian Ichimescu et al, 2024). However, designers must be careful not to prioritize operational savings in a way that ignores the trade-offs in other lifecycle stages.

End-of-life management is also a critical regulatory focus, supported by the Waste Electrical and Electronic Equipment (WEEE) Directive (EU, 2012), which encourages the reuse and recycling of electronic components. Extending hardware lifespans through refurbishment is particularly effective, as it reduces the need for new production and avoids the significant energy costs associated with manufacturing replacement units (L. Williams et al, 2022; NGMN, 2021b). Lifecycle-based design ultimately requires balancing these trade-offs. While newer equipment can offer better operational efficiency, these gains must be weighed against the embodied energy required to manufacture and deploy that replacement hardware (NGMN, 2024b). AI can help in decision making through predictive maintenance and improved asset management by detecting equipment degradation early to extend the operational life of hardware and defer the need for premature replacement (Taimia Bitam et al, 2025).

6

Conclusions



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6 Conclusions

This report has examined how to enhance energy efficiency in mobile communication networks. The evolution of mobile communication networks through each generation has increased traffic, leading to increased energy consumption of networks. This report has presented how energy efficiency improvements can be made in mobile communication networks through different technologies including AI/ML optimization, switch-off capabilities, near-zero communications, energy harvesting, energy management systems, RAN sharing, edge computing, virtualization, intent-based management, and cooling technologies.

The report has further identified how mobile communication networks can be designed to be more energy efficient by proposing eight design principles that should be employed when designing mobile communication networks. The design principles cover the design of energy-efficient equipment and infrastructure, adapting to traffic demand dynamically, applying energy saving techniques, designing energy efficient network architecture, integration of renewable energy sources, applying virtualization and softwarization, enhancing cooling and thermal management, and adopting life-cycle based design.

In conclusion, this report equips mobile communication network operators, network infrastructure vendors and other stakeholders with additional tools, techniques and design approaches that they can adopt to make their networks more energy efficient and environmentally sustainable. Collaboration among the mobile network operators, their equipment providers, the standards and regulatory organizations, the energy providers and the researchers all contribute to improved energy efficiency efforts, while supporting technological advancements, efficient service delivery and environmental sustainability.

7

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VISIIRI – National ecosystem for Green ICT transition

The Green ICT project VISIIRI creates an overview of the impact of the Finnish ICT sector on climate and the environment. The project supports the green transition of the ICT sector by connecting the sector's actors in a national ecosystem. The ecosystem will enable the sharing of best practices and bring together Finnish industry and academia.

The project will develop methods to measure the environmental impact of the ICT sector and produce environmental awareness training materials for companies. Raising environmental awareness will reduce the carbon footprint of the ICT sector, while increasing the handprint at the same time. Green business will enable Finland's pioneer position, opening up opportunities in international markets.

Funding

The project is co-financed by European Union through the Economic Development Centre of Northern Finland.

Project duration

01.04.2024–31.05.2026

More information

tieke.fi/green-ict-visiiri (in Finnish)

