Towards Carbon-Neutrality for 6G Networks

White Paper

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CHEDDAR

Durham University

UNIVERSITY of York

Executive Summary

The information and communication technology (ICT) sector accounted for between 1.5% and 4% of global greenhouse gas emissions in 2023. The use cases and performance demands of future sixth-generation (6G) networks are expected to increase energy consumption and carbon emissions over comparable coverage areas, primarily due to reliance on higher-frequency bands and ultra-dense infrastructure, unless mitigated through energy-efficient design and carbon-aware network optimisation. At the same time, there is a growing agreement on the importance of developing more sustainable systems driven by the environmental impact of carbon emissions, concerns about the exhaustion of non-renewable energy sources, and the drive for cost-effectiveness.

In order to achieve carbon-neutral 6G networks and meet the carbon emission targets set by the Paris Agreement and ITU, design and development of energy-efficient and sustainable 6G networks are essential. In this white paper, we highlight the barriers to achieving carbon-neutrality and discuss promising energy-efficient technologies for future 6G networks. We also present a model that estimates the energy consumption of 6G base stations (BSs) and compares it with that of 4G and 5G BSs. Furthermore, we introduce key performance metrics related to energy consumption and carbon emissions, which are crucial for identifying opportunities to reduce emissions, optimise energy consumption, and enhance network sustainability. Finally, we highlight that the challenges to achieving carbon-neutral 6G extend beyond technological innovation and demand coordinated action from governments, standardisation bodies, regulators, policymakers, industry, and the research community. These insights offer guidance for developing energy-efficient and carbon-neutral 6G networks and beyond.

Contributors

Ahmad Massud Tota Khel | Durham University, U.K. | ahmad.m.tota-khel@durham.ac.uk

Olufemi Isaac Olayiwola | University of York, U.K. | olufemi.olayiwola@york.ac.uk

Anas Abubakar Bisu | Durham University, U.K. | anas.a.bisu@durham.ac.uk

Hongjian Sun | Durham University, U.K. | hongjian.sun@durham.ac.uk

Poonam Yadav | University of York, U.K. | poonam.yadav@york.ac.uk

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Contents

1 Introduction

Carbon-neutrality in the information and communication technology (ICT) sector refers to balancing greenhouse gas (GHG) emissions from network operations (such as powering cell sites, radio access networks (RAN), core networks, data centres, and other infrastructure) with efforts to reduce or offset these emissions, ultimately aiming to achieve net-zero emissions [1], [2]. Mobile networks have become a fundamental pillar in modern society, influencing numerous sectors, including healthcare [3], transportation [4], education [5], agriculture [6], and entertainment [7]. Since these industries increasingly rely on mobile connectivity, the evolution of network technologies continues to shape the way they operate, innovate, and expand. Beyond its own emissions reduction efforts, the ICT sector plays a vital role in enabling other industries to achieve their sustainability goals. By leveraging advanced digital techniques and technologies, such as cloud computing, artificial intelligence (AI), and the Internet-of-Things (IoT), ICT can optimise the energy consumption and improve efficiency of several sectors like manufacturing, transportation, and agriculture, ultimately driving significant reductions in global carbon emissions [8], [9], [10].

In order to develop sustainable sixth-generation (6G) networks, it is crucial to understand the current energy consumption and carbon emissions of telecom networks, the efforts of standardisation bodies and the industry, global sustainability targets, and the challenges and need for carbon-neutrality in 6G networks.

1.1 Current Energy Consumption and Carbon Emissions of Telecom Networks

Over the past few years, digitisation, the number of network-enabled devices, and demand for ultra-high data rates and low latency, among others, have drastically increased, requiring more energy and thereby contributing to a rise in GHG emissions [2]. Various studies estimate that the ICT sector accounts for between 1.5 and 4 percent of global GHG emissions [11]. According to a recent joint report by the International Telecommunication Union (ITU) and the World Bank, the estimated carbon emissions of the telecom sector in 2020, 2021, and 2022 were 135, 134, and 133 million tonnes of CO_2 equivalent (tCO_2e), respectively [2].

The energy consumption of wireless communication networks poses a significant challenge for operators, as it not only increases the operational expenses (OPEX) but also causes carbon emissions [12]. Moreover, with the growing recognition of the detrimental effects of carbon emissions on the environment and the depletion of non-renewable energy sources, there is growing agreement on the importance of developing more energy-efficient communication systems [13].

The increasing proportion of renewable energy and power saving in mobile operators' overall electricity consumption has been the most crucial factor in reducing carbon emissions to date. For instance, British Telecom (BT) already utilises 100% renewable energy in its network operations in the UK [14]. Nokia Bell Labs reports that the telecommunications sector currently accounts for approximately 1% of global energy consumption [15]. Without any changes, the anticipated rise in data traffic and infrastructure could potentially double or triple this percentage by the end of the decade [15].

The GSMA Intelligence Telco Energy Benchmark studies [14], [16], [17] have outlined the energy consumption in various parts of wireless communication networks, including:

- The energy consumption of the RAN segment, which consists of base stations (BS) and all associated infrastructure such as rectifiers, inverters, and cooling systems;
- The core network and data centre, which include the radio network controller (RNC), mobile switching centre (MSC), home location register (HLR), serving gateways, hosting sites for operators, intranet infrastructure, and all associated infrastructure; and
- The energy consumed for other operations such as offices, branches, and transportation activities.

As illustrated in Figure 1, both the 2021 and 2024 energy consumption reports show that the RAN part consumes 73% and 76% of the energy, respectively, making it the most significant percentage of the total energy consumed in wireless networks [14], [16]. The reduction in energy consumption in core networks and data centres can be attributed to their move towards virtualisation and software applications. In contrast, the increase in energy consumption of RAN in 2024 compared to 2021 can be attributed to the expansion of coverage area through further deployment of BSs and the shift towards higher frequency bands, such as the millimetre-wave band.

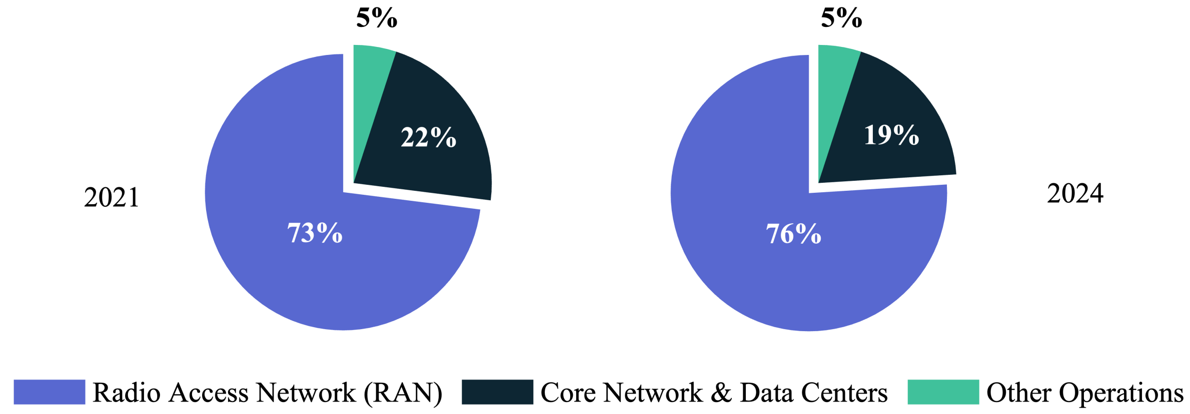


Figure 1 Energy Consumption of Wireless Networks.

Energy Consumption and GHG Emissions of BT

We examine the energy consumption and GHG emissions of the BT group, the leading telecommunications company in the United Kingdom (UK). From its annual report [18], we observe that the GHG emissions for a single user under the current fourth generation (4G) and fifth generation (5G) networks blend are non-negligible. Figure 2(a–d) summarises BT's energy usage and emissions, with (a), (b), and (d) showing data from 2017 to 2023, and (c) presenting data for 2023 only.

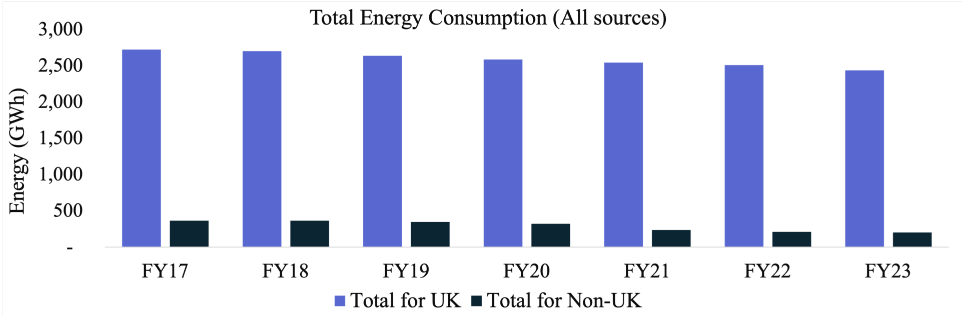
The plots in Figure 2 show high amounts of energy consumption comparable to 1% of total electrical energy generated within the UK in a year. The equivalent GHG emission was analysed and is shown to have started an uptick trend, which can be closely associated with increased use of advanced computing platforms and data centres. A close look at the sources of the GHG emissions indicates that aside from the total supply chain analysis, which accounts for the external production and consumption variables, the direct electrical energy usage for various activities such as data centres, BSs, and heating facilities accounts for the highest energy usage and therefore GHG emissions. This places emphasis on continuous operational energy efficiency (EE) along the whole telecoms equipment supply and operations chain, if carbon-neutrality is to be achieved.

With the advent of 6G, which promises improved connectivity, higher data rates, and advanced processing capabilities, these energy consumption values are envisaged to further increase [19]. A 6G network may require more energy than its predecessors due to the higher bandwidth, increased data processing requirements, and the increased number of connected devices. As a result, the energy consumption of mobile networks is becoming a critical issue that must be addressed to ensure the sustainability of future telecom infrastructures.

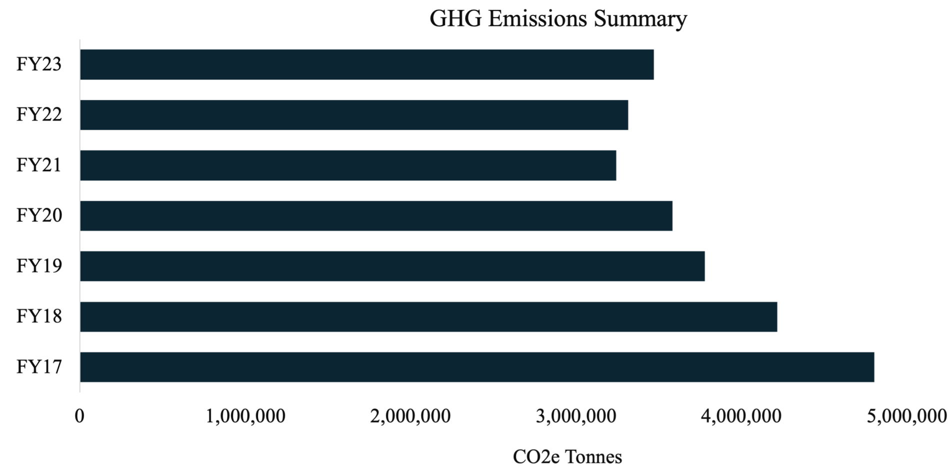
1.2 Global Targets and Commitments to Sustainability in ICT

In order to reduce carbon emissions and advance towards carbon-neutrality, governments worldwide committed in the 2015 Paris Agreement to limit the increase in global temperatures to well below 2 °C, with the aim of striving for a 1.5 °C limit [20]. The Science Based Targets initiative (SBTi) indicates that, in alignment with the Paris Agreement, carbon emissions should be reduced by 50% by 2030 and reach net zero by 2050 [21]. Accordingly, in 2020, the ITU established a target to cut emissions from the ICT sector by 45% by 2030, supporting global efforts to mitigate climate change in line with the 1.5 °C pathway [2].

A worldwide initiative has started to meet these carbon emission targets, with over 70 leading countries, such as the UK, the United States, China, and the European Union, committing to reach net-zero emissions [22], [23]. Furthermore, more than 1,200 companies, 1,000 educational institutions, and 400 financial organisations have promised to take immediate and substantial



(a)



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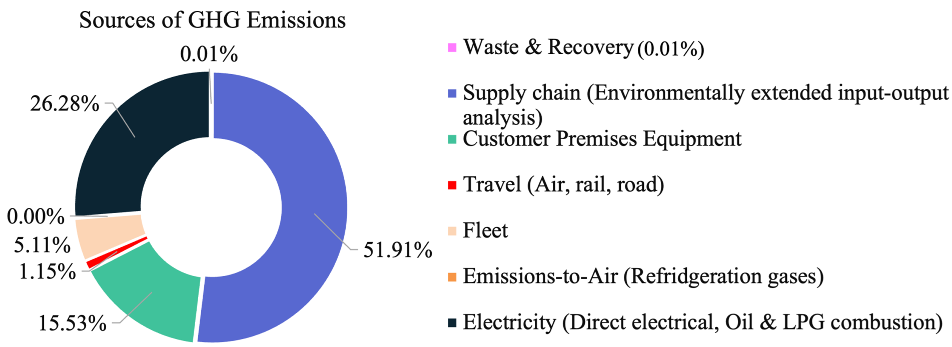

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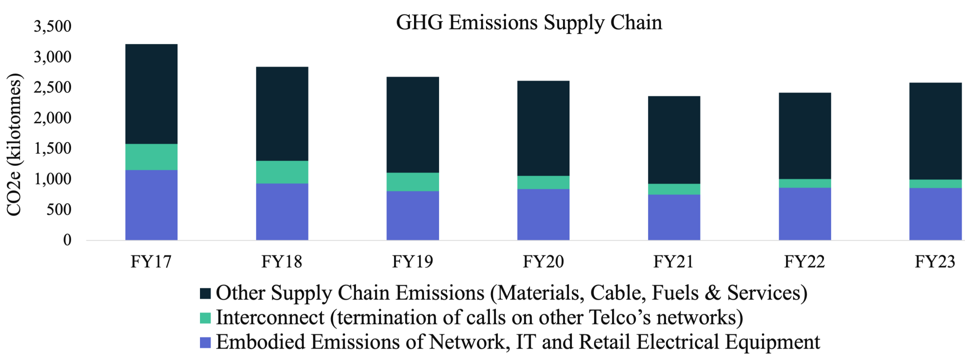

(d)

Figure 2 BT 2023 Report [18]: (a) Total Energy Consumption Worldwide, (b) Annual GHG Emissions, (c) Breakdown by Emission Sources, and (d) Supply Chain GHG Emissions.

actions to cut global emissions by 50% by 2030 [22], [23]. In addition to academia and industry, several standardisation bodies, such as the ITU, the European Telecommunications Standards Institute (ETSI), and the 3rd Generation Partnership Project (3GPP), are actively developing standards, frameworks, and methodologies to support sustainable telecommunications. Some of their efforts can be briefly summarised as follows.

ITU–T L.1470, L.1331, and L.1333 Standards

These standards collectively demonstrate the ITU's commitment to guiding the ICT sector towards EE and carbon-neutrality. **L.1470** defines GHG emissions trajectories for the ICT sector, aligning reduction pathways with the temperature goals of the Paris Agreement and providing methodologies for achieving long-term carbon-neutrality. **L.1331** establishes key performance indicators (KPIs) and assessment methods for evaluating the EE of mobile networks, while **L.1333** specifies methodologies for assessing GHG emissions from ICT infrastructure based on spatial and temporal parameters. Together, these standards provide a unified framework for improving EE, quantifying emissions, and promoting sustainability across next-generation communication networks [24], [25], [26].

3GPP Releases 16–19

These releases collectively reinforce the standardisation community's commitment to improving EE and sustainability across wireless networks. **Release 16** introduced foundational energy-saving and optimisation features, including management specifications for EE and power-saving enhancements for user equipment (UE). **Release 17** extended UE power-saving functions and provided methods for evaluating network-level EE. **Release 18** advanced network-side energy optimisation through RAN work on network energy savings and low-power wake-up signalling. **Release 19**, currently under development, continues this trajectory with a dedicated focus on EE and energy saving as a service (EaaS), including new KPIs, measurement methods, and management frameworks. Together, these releases establish a strong foundation for developing energy-efficient and carbon-aware 6G systems [27], [28], [29], [30].

ETSI ES 202 706

This standard specifies methods for measuring the EE of BSs and other radio access equipment under different load conditions. By providing a standardised framework for assessing and comparing BS energy performance, it enables operators and manufacturers to identify and implement optimisation opportunities that reduce the carbon footprint of wireless networks, thereby supporting the transition towards more sustainable communication systems [31].

1.3 The Need for Carbon-Neutral 6G Networks

There is a growing agreement on the importance of developing more sustainable systems, driven by the environmental impact of GHG emissions, concerns about the exhaustion of non-renewable energy sources, and the drive for cost-effectiveness [13]. Moreover, to meet the carbon emission targets set by the Paris Agreement and the ITU, it is essential to develop energy-efficient and sustainable infrastructure for future 6G networks. Furthermore, according to the ITU, 5.4 billion people, equivalent to 67 percent of the world's population, are now connected online, while approximately 2.6 billion people, or one-third of the global population, still lack internet access [2]. In addition, the ITU projected a significant rise in global mobile traffic by 2030, as shown in Figure 3. Therefore, accommodating the expected rise in global mobile traffic and facilitating internet access for the unconnected population requires additional infrastructure and devices, increasing the demand for the limited available energy resources and potentially raising carbon emissions unless targeted measures are implemented [2], [12].

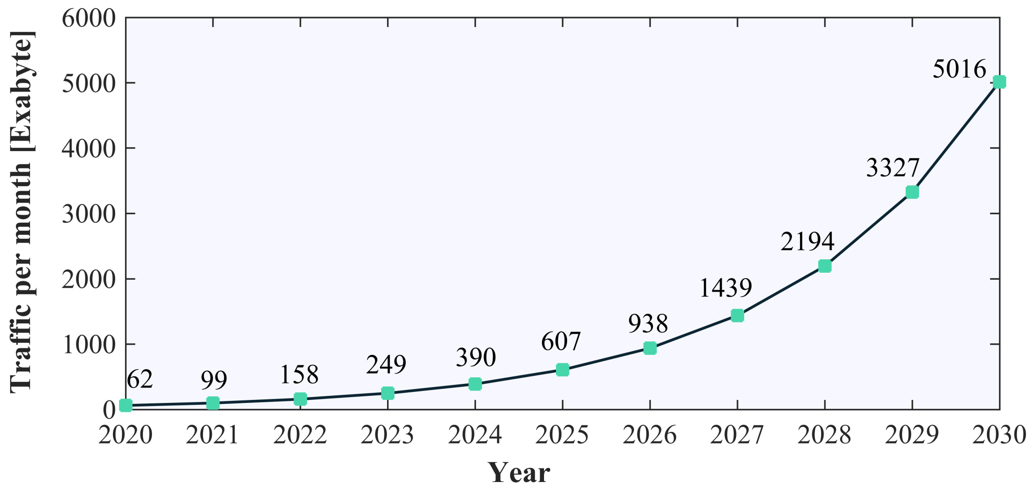

Figure 3 Global Mobile Traffic Estimates from 2020 to 2023 [32].

The ITU-R envisions that future 6G communication networks will enable transformative capabilities and support a wide range of usage scenarios [33], as demonstrated in Figure 4 and Figure 5. These diverse capabilities and usage scenarios, along with the emission targets, present significant challenges in achieving carbon-neutral 6G networks. For instance, high-demand use cases of 6G, such as immersive communication, hyper-reliable and low-latency transmission, and massive connectivity, significantly increase the energy consumption due to the shift towards the terahertz (THz) band for ultra-high data rates and real-time information processing. Similarly, core 6G capabilities, including ultra-high data rates and AI-driven network management, also pose energy challenges. While these capabilities and technologies improve the efficiency and reliability, they significantly increase the energy consumption if not properly optimised and aligned with sustainability objectives. The development of 6G networks will also drive the large-scale adoption and implementation of AI models across various applications, with carbon emissions from data centres expected to increase by more than 400 percent between 2022 and 2030 [22], [23]. Additionally, ensuring ubiquitous connectivity and low-latency communication across urban and remote areas through terrestrial and non-terrestrial networks (NTN) requires energy-intensive infrastructure, such as advanced BSs, satellites, and IoT networks.

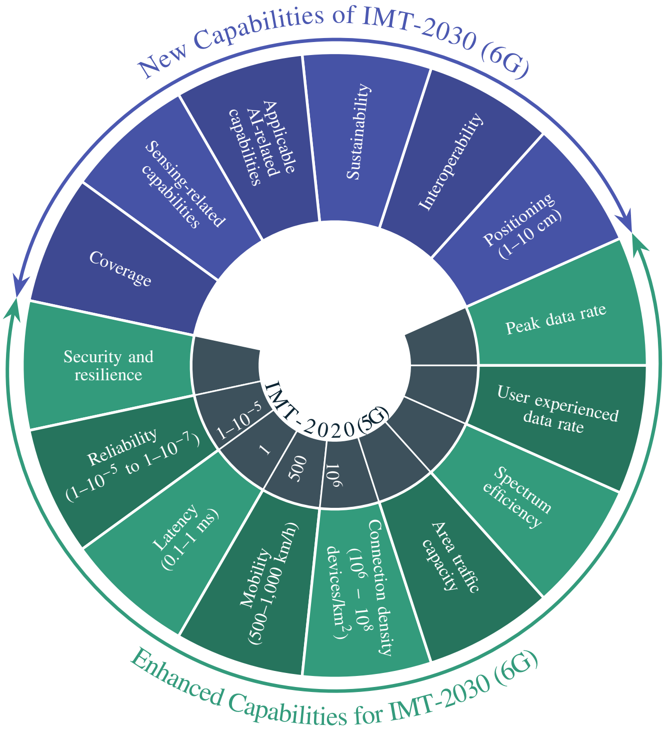

Figure 4 Extended and New Capabilities of Future 6G Networks [33].

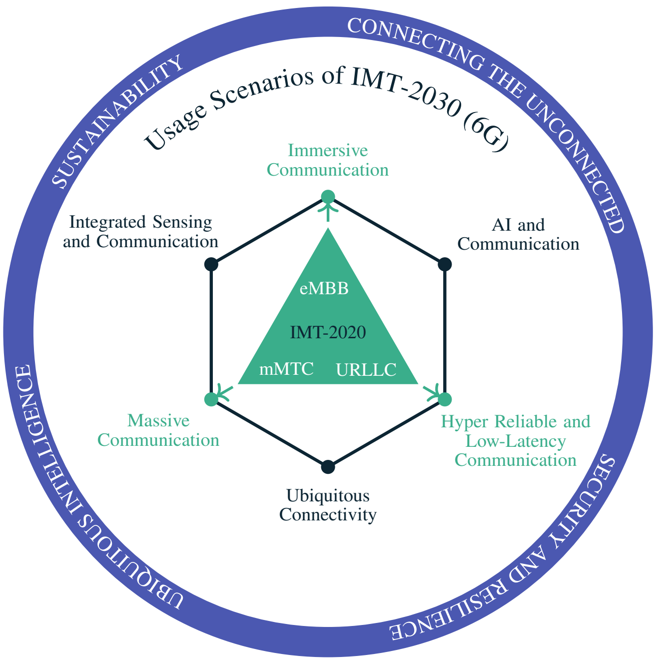

Figure 5 Extended and New Usage Scenarios of Future 6G Networks [33].

Achieving carbon-neutrality for 6G networks, in light of these challenges, requires a comprehensive strategy encompassing energy-efficient communication technologies and techniques, AI-driven energy-saving approaches, integration of energy-efficient terrestrial and non-terrestrial technologies, developing strategies for carbon-aware networks, renewable energy integration, and efficient energy storage and cooling solutions, among others. By addressing these challenges holistically, 6G networks can fulfil their transformative potential, minimise environmental impacts, and achieve carbon-neutrality.

2 Performance Metrics for Sustainable Wireless Networks

To support sustainable development in wireless communication networks, various performance metrics have been developed to assess EE, environmental impact, and renewable energy integration. These metrics are crucial for identifying opportunities to reduce carbon emissions, optimise energy consumption, and enhance network sustainability. The following key metrics evaluate the environmental and EE of wireless networks, focusing on energy consumption, carbon emissions, and renewable energy.

2.1 Energy Efficiency (EE)

EE is a crucial performance metric that is linked to carbon emissions. By improving the EE of communication networks, the overall energy consumption can be significantly reduced, thereby potentially decreasing carbon emissions. In the context of communication systems, EE can be defined in several ways, depending on the evaluation objective, such as throughput-based, data volume-based, or coverage-based efficiency. These can be mathematically formulated as [26] [34]

$$\mathrm{EE}_1 = \frac{\text{Data Volume (bits)}}{\text{Total Energy Consumption (Joule)}}$$

$$\mathrm{EE}_2 = \frac{\text{Data Throughput (bits/sec)}}{\text{Total Power Consumption (Watts)}}$$

$$\mathrm{EE}_3 = \frac{\text{Coverage Area (m}^2\text{)}}{\text{Total Energy Consumption (Joule)}}$$

These formulations characterise different aspects of how efficiently a communication network uses energy: (i) EE_1 reflects how much energy is required to deliver a certain amount of data, (ii) EE_2 represents how effectively power is converted into data transmission performance, and (iii) EE_3 describes how efficiently energy is used to provide coverage across a geographical area.

2.2 Total Carbon Emissions (TCE)

Total carbon emissions (TCE) quantify the overall GHG emissions that result from the energy consumed by a communication network. This provides a comprehensive measure of the network's environmental impact. In essence, total emissions increase with both the amount of energy consumed and the carbon intensity of the energy supply. This metric can be mathematically expressed as

$$\text{TCE} = \sum_t \text{Energy Consumption}_t\,(\text{kWh}) \times \text{Emission Factor}\,(\text{kgCO}_2\text{e/kWh}),$$

where the emission factor (EF) represents the carbon emissions per kWh of electricity generated by the grid and auxiliary energy sources, including both traditional and green energy [26]. It is noteworthy that in 2023, the UK's average EF for the electricity consumed, including grid losses, was about 0.19323 $\text{kgCO}_2\text{e/kWh}$ [35].

2.3 Network Carbon Intensity (NCIe)

Network carbon intensity (NCIe) is another key performance metric that measures the GHG emissions caused by the energy consumption for data transmission by a communication network [26]. It shows how much carbon is emitted for every unit of data transferred, providing a clear indication of the network's environmental efficiency. A lower NCIe value means that the network can deliver more data with less associated carbon emissions. It can be mathematically expressed as

$$\text{NCIe} = \frac{\text{TCE (kgCO2e)}}{\text{Total Data Traffic (TB)}}.$$

2.4 Renewable Energy Utilisation Rate (REUR)

Renewable energy utilisation rate (REUR) is a critical performance metric, particularly as communication networks increasingly integrate renewable energy sources [34]. It indicates the proportion of a network's total energy consumption that is supplied by renewable sources and reflects how effectively clean energy is incorporated into network operations. A higher REUR value represents greater dependence on renewable energy, thereby reducing reliance on fossil fuels and contributing to a more sustainable and environmentally responsible network. The REUR can be calculated as [34]

$$\text{REUR}\,(\%) = \frac{\text{Renewable Energy Used (kWh)}}{\text{Total Energy Consumption (kWh)}} \times 100.$$

2.5 Renewable Energy Carbon Offset Factor (RECOF)

Renewable energy carbon offset factor (RECOF) is an important performance metric that quantifies the amount of GHG emissions avoided for every unit of renewable energy used in a communication network. It reflects the effectiveness of renewable energy in reducing the network's carbon footprint by offsetting emissions that would otherwise have resulted from conventional energy sources. The RECOF can be calculated as

$$\text{RECOF} = \frac{\text{GHG Emissions Reduced by Renewable Energy (kgCO2e)}}{\text{Total Renewable Energy Used (kWh)}}.$$

3 Estimated Energy Consumption of 6G Base Stations

As illustrated earlier in Figure 1, the RAN accounts for the largest share of total energy consumption in wireless networks. Within the RAN, the BS represents the primary energy-consuming element, as it performs the core radio transmission and signal processing functions that link user devices to the network infrastructure. Therefore, understanding the energy profile of BSs is essential for evaluating the sustainability of 6G networks. This section estimates the energy consumption of 6G BSs using established power models and compares it with that of 4G and 5G networks. The analysis provides insights into how network design, deployment density, and technological evolution influence overall energy demand and the resulting GHG emissions.

3.1 Flexible Power Model

The BS here is defined in terms of the ETSI standard [36] as the network component that serves one cell or more cells and interfaces the user terminal (through air interface) and a RAN infrastructure. According to the standard, the BS is composed of several items and can be largely subdivided into BS radio equipment and other site equipment. To analyse the energy consumption at the BS level of the network, we apply the macro BS model studied in [37]. In this approach, the power consumption is split between the baseband unit P_{BB}, the radio unit P_{RF}, the power amplifier P_{PA} and the overhead costs P_{PA}, which are associated with power conversion and cooling the hardware. The total power consumption is given by,

$$P_{\text{Total}} = P_{\text{BB}} + P_{\text{RF}} + P_{\text{PA}} + P_{\text{PA}} \quad (1)$$

It is noteworthy that both P_{BB} and P_{RF} are calculated by breaking each down into a series of sub-components, each of which consumes a given amount of power depending on five parameters. These parameters are the transmission bandwidth, number of antennas, modulation scheme,

Table 1: Comparison of Network Generation Features

Network Generation	Frequency Range (GHz)	Typical MIMO Configuration	Modulation	Antenna Type	Key Feature
4G LTE	0.8–2.6	$\leq 4 \times 4$	Up to 256-QAM	Passive panel antennas	Sectorised coverage
5G NR	3.3–3.6	$> 4 \times 4$	Up to 1024-QAM	Active phased array	Beamforming & spatial multiplexing
6G (Expected)	6.425–7.025	$\geq 256 \times 256$	Beyond 1024-QAM	Metasurface & AI-controlled antennas	Dynamic reconfigurable beams

coding rate, and load which is split into time and frequency domain duty cycling. As the parameters are increased, the energy consumption of some or all components increases, with the manner in which they increase depending on a predefined scaling.

We also include the efficiency improvement factor, E, which describes the change in efficiency between each generation of mobile networks. Moreover, let D describe the increase in demand for network usage, which can be scaled linearly or super-linearly with data demand. Here, we assume a linear scaling for D, and thus our model is given by

$$P_{\text{Total}} = (E \times D) \times (P_{\text{BB}} + P_{\text{RF}} + P_{\text{PA}} + P_{\text{PA}}) \quad (2)$$

This is a simplistic model for the 4G model, and it was further developed to provide comprehensive information for the advanced multiple-input multiple-output (MIMO) 5G & 6G. In this model, the demand factor is initially set to 14.88. This is in line with fundamental industry research indicating that the total demand from mobile networks over 10 years (2018 - 2028) will increase by a factor of 14.88 [38]. Also, the efficiency factor is initially set to 0.1, based on industry evidence that 5G networks are 90% more efficient than 4G networks [39].

To provide an equivalent comparison of the energy consumption by BSs of each network generation, we apply a case study scenario, where we consider approved network frequencies and suburban data transmission efficiency in the UK. In Table 1, we acknowledge that various technologies are being considered for improved energy consumption in 6G; however, pending the full implementation of the modifications, we utilise operational parameters and technologies for the various generations, which have been verified in [40], [41], [42], [43], [44], [45].

In Figure 6, the power consumption of a single BS of 4G, 5G, and 6G networks is compared not in isolation but vis-a-vis the energy efficiency of the data throughput. This is essential because, while the 6G BS may appear to consume more energy due to the higher operating frequency requirement, it in turn outputs more data per time compared to the previous generations. From the figure, it is clear that while the 6G is significantly more energy efficient per data

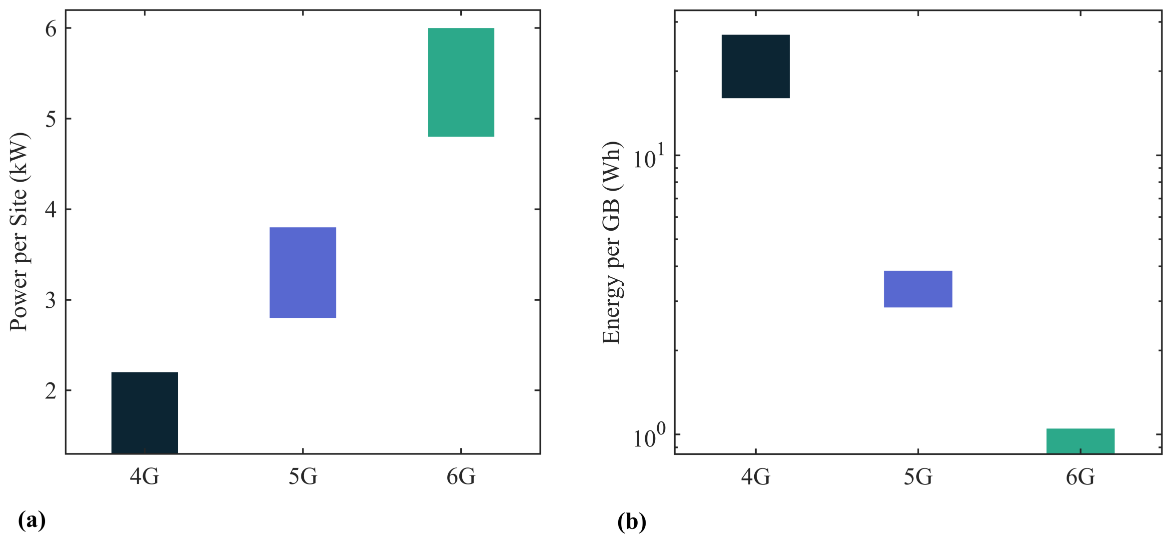

Figure 6 (a) Energy Consumed by a Single 4G, 5G, and 6G BS and (b) Corresponding Data Efficiency (Energy per Gigabyte - GB).

throughput, it consumes more energy per actual measured instance using energy meters.

Similar to previous estimates [37], [43], [44], [45], the 4G BS has a power consumption between 1300W and 2200W, the 5G BS has a power consumption between 2800W and 3800W, and the 6G BS has a power consumption between 4800W and 6000W. The greater range of values seen in the 6G case is due to the more significant variation in frequencies available and potential sleep mode. Higher frequencies will likely be reserved for specialised systems that require such speed that can only be enabled with 6G. This emphasises the need for a final implementation of 6G networks, which will include better energy-efficient components and smarter energy consumption via AI controls.

3.2 The Effect of the Number of Base Stations

As previously highlighted, 6G BSs will require more energy than their 5G counterparts due to the higher frequencies and greater demand that a 6G network will support. In addition, another consequence of using shorter wavelength electromagnetic waves for these high speeds is a reduction in range compared to the electromagnetic waves used in 5G. As such, in a 6G network, more radio towers are needed to cover the same area as a 5G network.

To quantify this, we examine the coverage area of a single network BS for each of the generations. Again, this comparison cannot be isolated, considering that the data throughput of each network generation varies. An assessment of the coverage area of each network is determined, considering the spectral efficiency, bandwidth, free-space path-loss (FSPL), and radius of coverage across the network generations. The visual representation is provided in Figure 7. For lower frequency (< 1GHz) 4G waves, the estimated coverage radius is around 15 miles; while the 6G coverage radius at approved Ofcom frequencies is in the range of 0.7 miles.

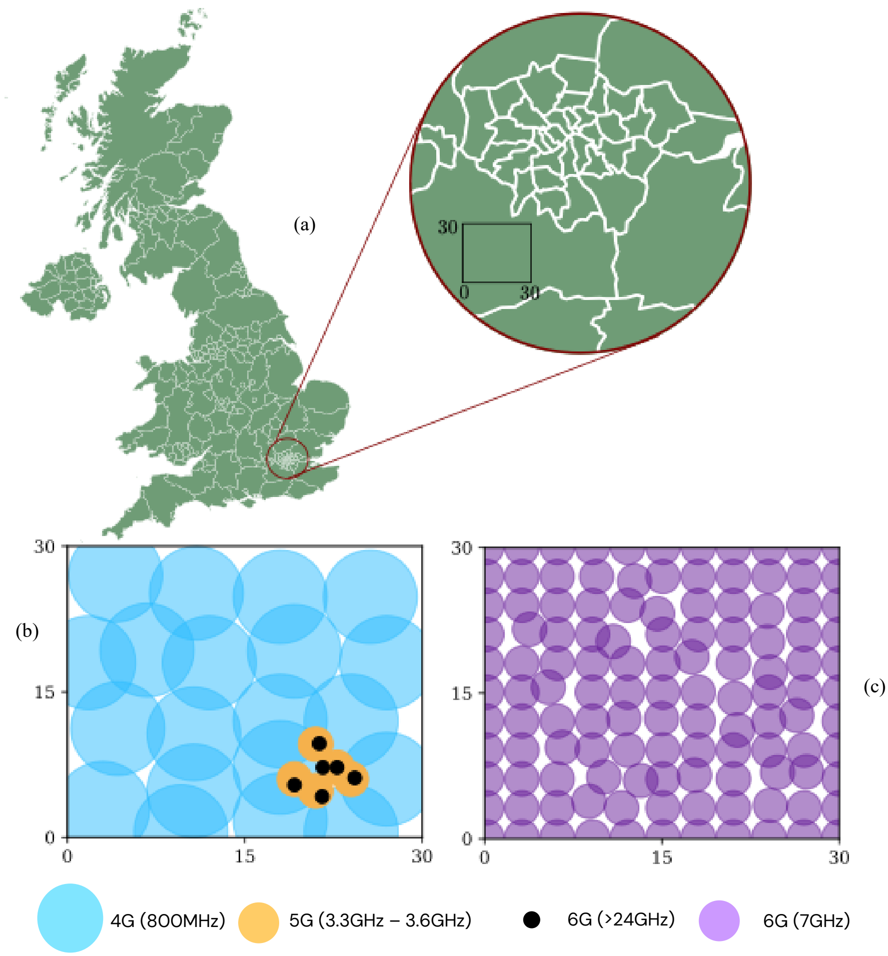

Figure 7 An Example of Cell Site Coverage (*a*) Over a 30 Mile by 30 Mile Area (*b*) Using Combination of Different Networks and Frequency Bands (*c*) Only 6G Network at Approved UK Frequencies of about 7 GHz.

This is significant to determining the phase out of the 4G antennas for replacement with 6G antennas in urban areas where the shorter latency and higher bandwidth of the 6G are required. In Figure 7(*b*-*c*), we consider a 30 mile by 30 mile area and estimate the energy per unit area using,

$$E_{\mathrm{PA}} = \frac{\sum_{t_0}^{t_1} \sum_{1}^{N_{\mathrm{BS}}} P_{\mathrm{Total}}}{A}, \tag{3}$$

where E_{PA} is the energy per unit area, N_{BS} is the number of BSs, and A is the area.

We compare the energy required by each of the network generations to deliver the same data-throughput on one hand, and the energy required to cover the same area when equivalent coverage is required. From Figure 8, we observe that while 4G will requires a lot of energy to deliver the same data throughput, the energy required for the number of 6G BSs to cover the same area is also significant. While there is a general perception that an individual 6G BS may utilise less power, using advanced components and intelligence techniques, the energy required to cover

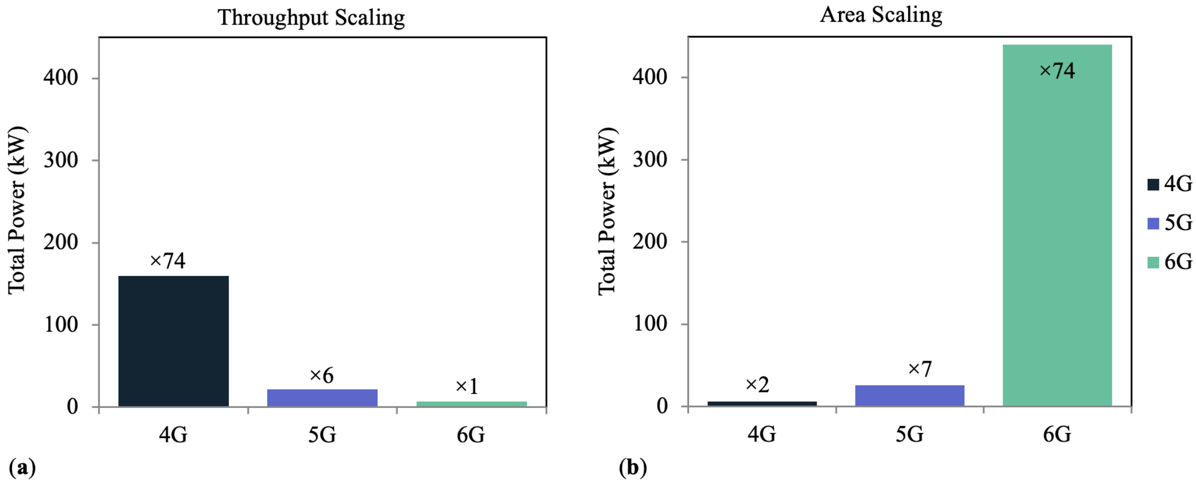

Figure 8 Estimated Energy Consumed by 4G, 5G, and 6G BSs Under the Same (a) Data Throughput and (b) Coverage Area.

the same area compared to other generations may be significant and must be carefully considered in the roll-out. In addition, the EE of 6G networks is expected to be approximately five times greater than that of 5G. This is because the 6G network is expected to deliver significantly higher data rates per antenna. The EE of a network is defined as the data rate per unit of power since the use of ultra-massive MIMO antenna configuration in 6G networks enables the delivery of a much higher data rate per antenna.

Consequently, the energy consumption of 6G networks becomes a critical consideration requiring an optimal balance in the number of antennas required to cover a specific area (due to the higher path loss) and the data rate sufficient for activities within a specified area. Note that the model and subsequent analysis presented in this paper demonstrate a worst-case scenario where various EE approaches proposed for 6G networks have not been implemented. Despite this, it does show, in principle, that 6G networks will require more energy than 5G networks.

3.3 GHG Emissions and Network Transition

The energy required to operate a BS is typically drawn from the national grid. The 2024 figures in the UK were estimated at 29% from fossil fuels, 13% from nuclear, 45% from renewable sources, and 11% from imports. This results in carbon intensity of about 124 g CO_2/kWh [46]. As we transition from 5G to 6G, it is envisaged that the initial deployment of 6G networks will involve either the simultaneous installation of 6G BSs alongside 5G or the replacement of a limited number of 5G BSs in dense areas. Then, for each passing year, the percentage of the network that 6G BSs cover will increase, and the percentage covered by 4G and 5G BSs will decrease depending on the use. As may be expected, this will increase energy demand by telcos significantly. With respect to the above, it is considered that there will be more emphasis on the proper estimation of energy utilisation and GHG emissions with respect to spatial or temporal

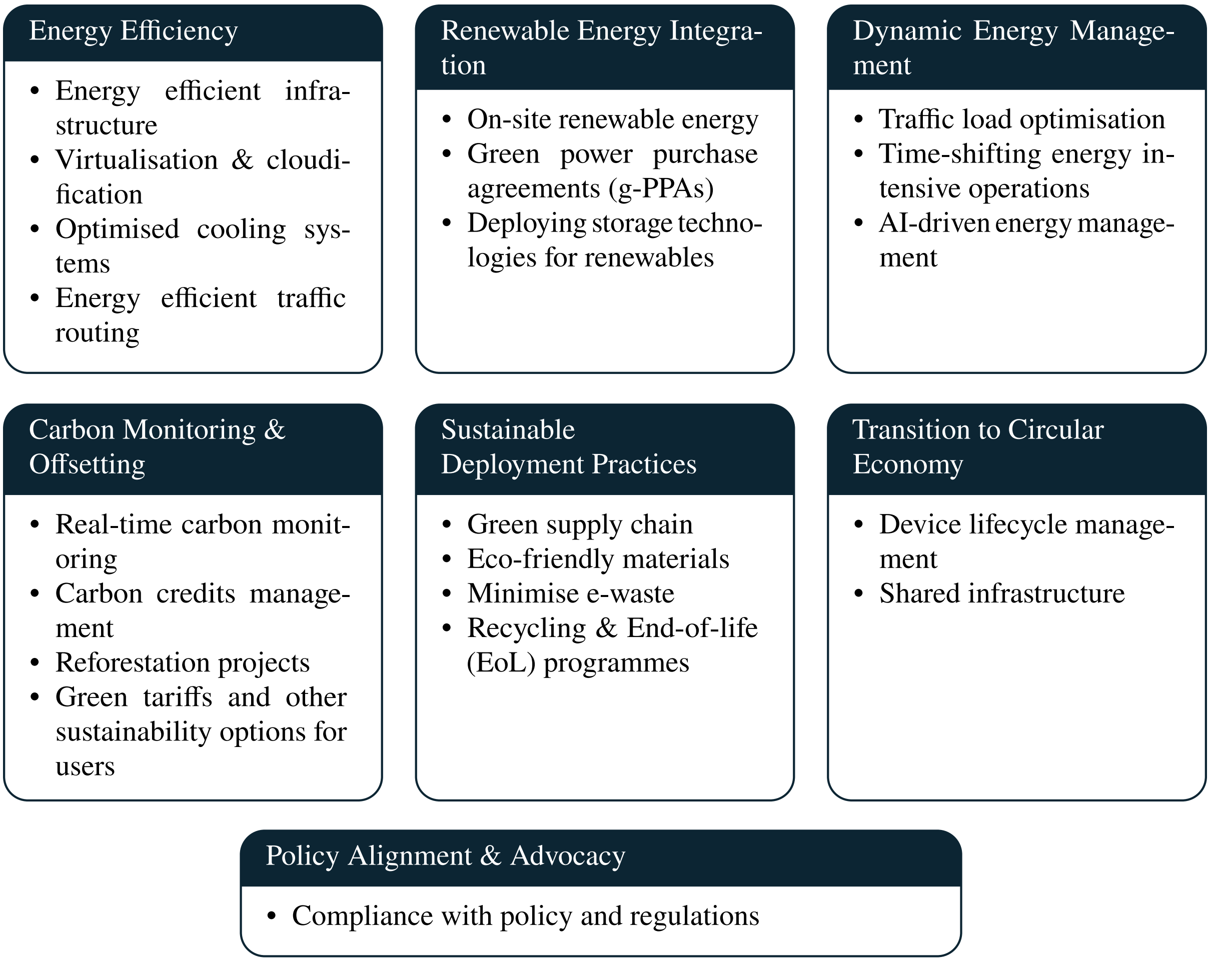

Figure 9 Net-Zero Emission Strategies for Communication Networks.

classification. This is consistent with recommendations of the ITU standards [26] using metrics that relate carbon emissions to the emission location.

4 Carbon-Aware 6G Networks

We define carbon-aware networks (CANs) as the effective monitoring and management of telecommunication networks, focusing on EE and reducing carbon emissions while maintaining an optimal user experience. Recent discussions on carbon awareness of networks have gained significant attention among researchers [47], [48] on carbon emissions reduction towards net-zero emissions strategies. While this is crucial, the user experience cannot be under-emphasised as recent emerging technologies demand ultra-low latency and exceptional user experience.

As a backdrop of the Kyoto Protocol and the Paris Agreement [1] on carbon emissions, various strategies have been implemented to enable the achievement of the net-zero emission targets. Some are incentive-based regulations, tax reductions, an increase in renewable energy system installation, and most recently, an incursion into carbon-aware communication networks, as illustrated in Figure 9.

Data Acquisition

- Real-time and historical carbon intensity and emissions data collection (from grid, carbon data providers)
- In-network telemetry
- Regional/National data collection
- Spatial and temporal data
- Third-party integrations

Low-Carbon Integration

- Renewable energy sources integration (solar, wind, and more)
- Energy efficient hardware & infrastructure
- Energy efficient cooling
- Low-power servers and network devices
- Shared cloud and data centre integration
- Smart grid connectivity
- Battery storage & load balancing

Decision Engine

- Carbon & cost intelligent routing
- Tasks scheduling
- Resources allocation
- Predictive analysis for future carbon emissions trends
- Workload & traffic management
- Traffic shifting mechanisms through lower-carbon pathways
- Renewable energy utilisation prioritisation

Monitoring & Analytics

- Continuous monitoring of the carbon-aware strategies
- Tools to track energy consumption and carbon emissions
- Visualisation
- Carbon footprint reporting
- Spatial and temporal trend analysis

Policy & Governance

- Training & certification for operators
- Policies for sustainable practices
- Metrics standardisation
- Knowledge sharing
- Documentations
- Risk analysis
- Safety practices
- Green operational standards
- Avoid double counting
- Trustworthy evaluation

Figure 10 Carbon-Aware Network Planning.

The concept of CAN becomes vital due to the complexity of the temporal and spatial utilisation of telecommunication components and resources. This is largely due to mobile network nodes and variability in data transmission packets based on usage. In addition, 6G networks have been shown to have higher energy demand than the existing 4G and 5G networks.

This highlights the critical nature of carbon awareness required going forward. In view of this, we present critical aspects of a carbon-aware 6G network, as illustrated in Figure 10.

4.1 Carbon-Aware Data Acquisition

Decision-making in CANs is highly dependent on the accuracy, timeliness, and granularity of the spatial and temporal information collected over the network between the receiver and sender. The study in [47] attempted to capture this process as an end-to-end data movement that considered EE not only for the nationwide network but also global network. This emphasises the need for certain data types sharing by networks globally and not just at the national level. This process is realistic via a standardised in-band network telemetry which allows real-time data collection and reporting on the status of a network or associated parameters.

4.2 Low-Carbon Integration

This is considered the integration of low-carbon technologies and infrastructure of various types in the 6G network. A major component is the use of renewables such as geothermal, hydro, wind, solar, marine, nuclear energy, and more in the new 6G networks. This is not targeted at only the BS operations, this is targeted at the whole infrastructure chain or life cycle analysis of the network [49]. For example, low-carbon transport technologies for installation and maintenance, new energy-efficient hardware, low-power servers, and shared data centres are key considerations to enable the realisation of low-carbon integration in 6G networks.

4.3 Carbon-Aware Decision Engine

At the core of the 6G CAN is the decision-making engine. This additional processing layer while consuming negligible power is expected to make planning more efficient, considering that the 6G network without optimisation would utilise more energy than existing networks. At present, several studies (e.g., [50], [51]) have considered modelling scenarios for decision-making systems that prioritise data transmission via a route with the lowest carbon emission. While they provide successful carbon emissions reductions, they have the potential to overload certain routes at specific times of the day. Thus, such models need to be dynamically implemented to ensure that traffic overload is avoided and user experience is not negatively impacted.

4.4 Carbon-Aware Monitoring & Analytics

The monitoring of the overall performance of 6G CAN is to provide information to both operators and policymakers on the cost-benefit of the carbon awareness layer. This involves the use of standardised tools by each telecommunications company as well as policy regulators to provide visualisation and make accurate accounts of their carbon footprint. This involves both high-level and low-level visualization of all BSs, data flows across devices, density maps, and more. This provides feedback to operators on their carbon creditworthiness and future areas for optimisation.

4.5 Carbon-Aware Policy & Governance

Reports presented by [52] and [53] indicate that implementation of CAN requires a high level of standardisation, particularly in the metrics applied to carbon emissions measurement for 6G networks. This emphasises the role of the regulator to ensure both national and global standardised metrics. This would further enable the implementation of incentives and punitive measures for defaulters while ensuring trustworthiness in the approaches applied. Net-Zero strategy achievement is only achievable via formidable public-private partnerships (PPP) when properly managed.

5 Potential Technologies for Carbon-Neutral 6G Networks

This section briefly describes some of the most promising energy-efficient techniques and technologies to support the realisation of carbon-neutral 6G networks. These include effective RAN architectures, cell-free massive multiple-input multiple-output (mMIMO), cell-sleep and energy-saving methods, reconfigurable intelligent surfaces (RISs), reconfigurable holographic surfaces (RHSs), promising multiple access and multiplexing schemes, energy harvesting (EH) and zero-energy communications, AI-driven techniques for energy and carbon emission reductions, deployment of renewable energy sources, and efficient energy storage and cooling solutions.

5.1 Cloud RAN, Fog RAN, and Open RAN

The processes of network softwarisation and cloudification, which began with 5G, should be further accelerated in the development of 6G by leveraging the latest technological innovations such as Cloud RAN (C-RAN), Fog RAN (F-RAN), and Open RAN (O-RAN). These paradigms enable the virtualization and decoupling of network functions from dedicated hardware, while enhancing automation, flexibility, and intelligence within the network. Such advancements contribute to reduced energy consumption and lower both operational costs and environmental impact [54]. As illustrated in Figure 11, four potential RAN architectures can be employed in wireless networks. Distributed RAN (D-RAN) is a traditional RAN architecture where the remote radio unit (RRU) and baseband unit (BBU) are co-located at cell sites, connected to the core network via backhaul. It enables low-latency local data processing but increases the

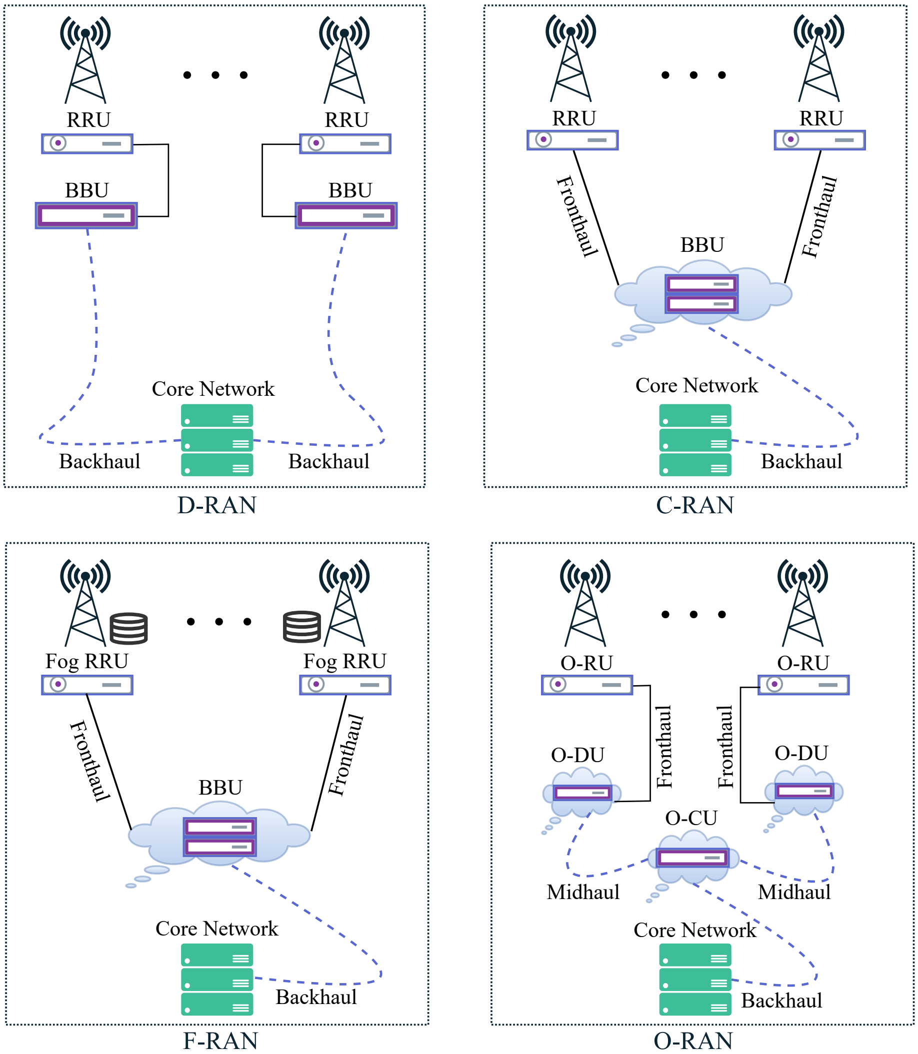

Figure 11 Generic Diagrams of Four RAN Architectures in Wireless Communication networks.

costs and energy consumption due to dedicated equipment at each site [55]. On the other hand, C-RAN, F-RAN, and O-RAN are three emerging technologies with significant potential to reduce energy consumption and contribute to carbon-neutrality in 6G networks [56], [57], [58], [59], [60]. These technologies are briefly described below, highlighting how they support the achievement of sustainable 6G networks.

- C-RAN centralises the BBUs in cloud data centres, reducing the need for costly and energy-hungry equipment at cell sites while enabling dynamic resource allocation through virtualised network functions, ensuring that power is used only when necessary [56], [57]. Therefore, this technology, with fewer physical components and more efficient data centres, results in reduced energy consumption and a significant decrease in carbon emissions.
- F-RAN decentralises the network functions to edge devices, reducing the need for long-distance data transmission and its associated energy costs [57], [58]. By processing some

of the data locally at fog RRUs and fog users, it minimises the backhaul traffic, lowers the transmission latency, and significantly reduces the energy consumption and carbon emissions, crucial for sustainability of future 6G networks.

- O-RAN enables interoperability between components from different vendors through open interfaces, allowing operators to choose energy-efficient solutions [59], [60]. In this architecture, the combination of the RRU and BBU is divided into three parts: the open radio unit (O-RU), open distributed unit (O-DU), and open centralised unit (O-CU). By separating hardware and software, it supports dynamic resource allocation and automates energy-saving features such as load balancing, traffic offloading, and powering down idle components, leading to significant reductions in energy consumption and carbon emissions in 6G networks.

5.2 Reconfigurable Intelligent Surfaces (RISs)

In wireless communication networks, propagation effects such as scattering, diffraction, and reflection degrade the performance and necessitate higher transmission power to meet target quality of service (QoS) requirements [61], [62]. Traditionally, mitigating these effects involves deploying array of antennas and employing complex transceiver designs, which increase energy consumption and costs while failing to fully address the wireless channels' randomness [61], [63]. Reconfigurable Intelligent Surfaces (RISs) have emerged as an energy-efficient solution for creating smart wireless environments, enabling the intelligent manipulation of signal propagation [64], [65]. According to the ETSI's RIS study group, an RIS structure at least includes: (i) an RIS panel comprising a nearly passive array of low-cost reconfigurable elements that intelligently modify the signals directions, and (ii) a microcontroller to adjust these elements. RISs are categorised as reflective, transmissive, and simultaneously transmitting and reflecting RISs (STAR-RISs), with STAR-RISs enabling full-space (360^o) coverage, surpassing the 180^o limitations of the first two, as illustrated in Figure 12. RISs provide flexible deployment options and can be easily integrated into a variety of indoor and outdoor environments, including walls, ceilings, building facades, or UAVs for non-terrestrial networks (NTNs) [66]. As a nearly passive alternative to traditional relays, RISs eliminate RF chains and complex processing, significantly reducing the energy consumption and carbon emissions while improving the performance of future 6G networks [64], [65].

5.3 Cell-free Massive Multiple-Input Multiple-Output (Cell-free mMIMO)

To accommodate the expected significant increase in the number of users, additional BSs and antennas are necessary in 6G networks, potentially leading to higher energy consumption and carbon emissions. Unlike the traditional cellular and co-located mMIMO systems, a cell-free

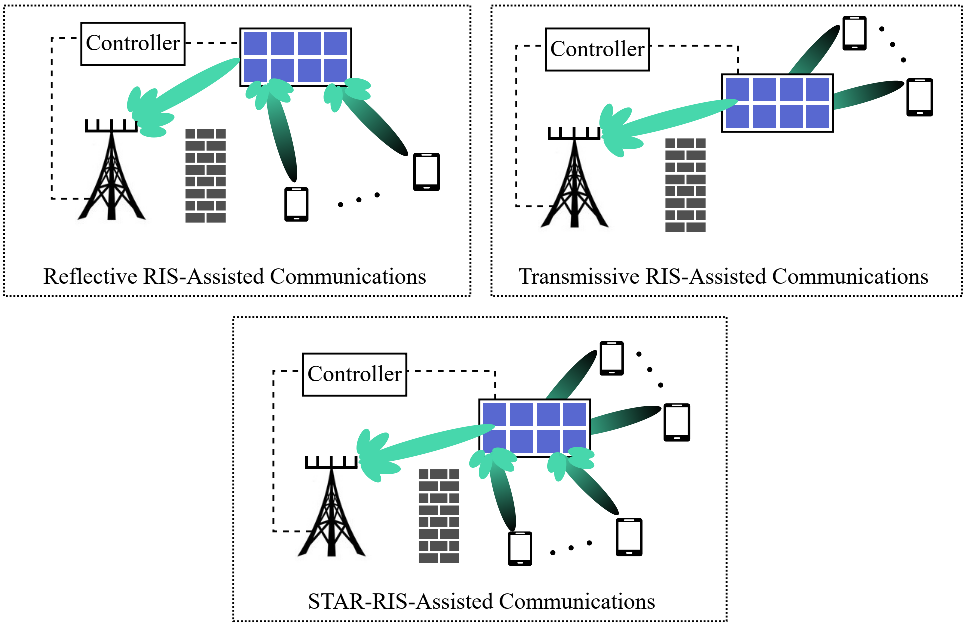

Figure 12 Wireless Communications through Three Types of RISs.

mMIMO system connects a large number of geographically distributed antennas/access points (APs) to a central processing unit (CPU), enabling spatial multiplexing to efficiently serve multiple users [67], [68]. Although deploying a large number of APs increases the energy consumption, the close proximity of APs to users results in higher channel gains, enabling the target QoS to be achieved with less transmit power. In addition, the THz band, essential for ultra-high data rates in 6G, faces challenges like beam misalignment, severe path loss, and environmental factors. Therefore, cell-free mMIMO technology can be particularly promising for future multi-user THz systems, as it will help address these challenges while improving the EE. It is noteworthy that integrating the cell-free mMIMO and RIS technologies, as shown in Figure 13, can be considered one of the most promising candidates in the RAN segment for achieving cost-effectiveness and carbon-neutrality in future 6G wireless networks [67], [68].

5.4 Reconfigurable Holographic Surfaces (RHSs)

In conventional mMIMO systems, strong beamforming is achieved by employing a large number of power amplifiers and phased arrays that depend on precise phase adjustments and controlled beamforming techniques, which significantly increase both hardware costs and energy consumption [69], [70], [71]. Therefore, to achieve carbon-neutrality and meet the use cases and capabilities of future 6G networks, it is essential to deploy energy-efficient and cost-effective antenna technologies. Recently, researchers have proposed an innovative type of metamaterial-based antennas called reconfigurable holographic surfaces (RHSs), which are envisioned as a

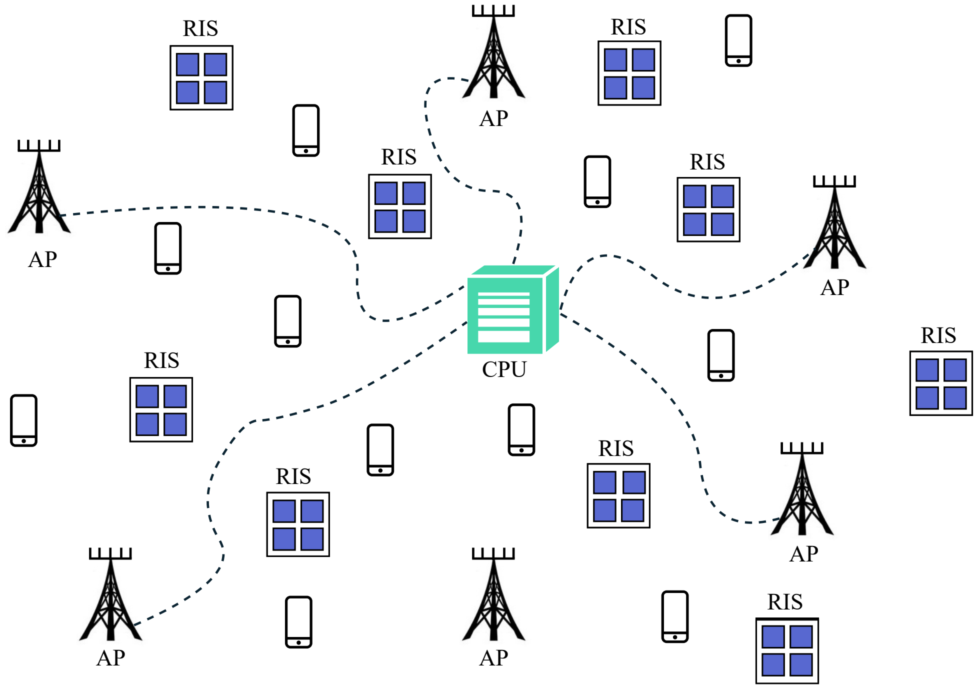

Figure 13 A Generic Architecture of RIS-Assisted Cell-Free mMIMO Wireless Communications.

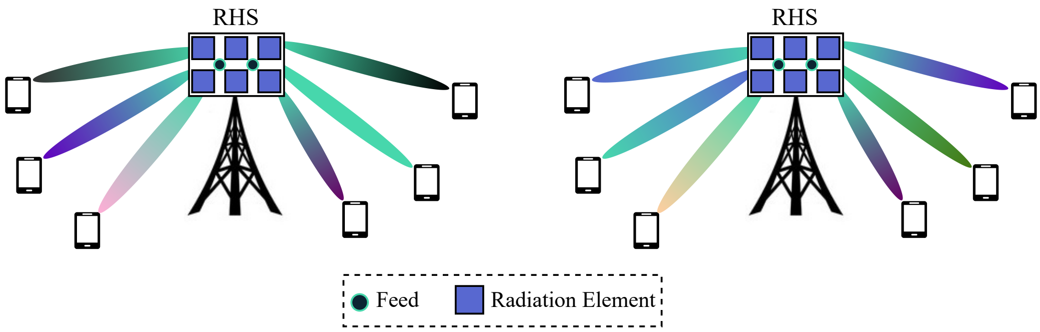

Figure 14 A Generic Model of RHSs-Assisted Wireless Communications.

strong candidate for future 6G networks to overcome the limitations of conventional mMIMO technology [69], [70], [71]. As illustrated in Figure 14, a generic RHS model consists of multiple cost-effective and low-power radiation elements and feeds. The feeds, attached to the surface, generate electromagnetic waves, and each radiation element can intelligently control the radiation amplitude to form precise holographic beams towards desired directions [69], [70], [71]. While both RISs and RHSs are cost-effective and energy-efficient technologies enabling a smart propagation environment, they serve different purposes: (i) RISs are widely considered as strong replacements for conventional relays and repeaters [64], [65], while RHSs are considered as strong replacements for conventional antenna technologies [69], [70], [71]. Therefore, the integration of these technologies can be a powerful solution for advancing towards carbon-neutrality in future 6G networks.

5.5 Energy-Efficient Ubiquitous Connectivity via Non-Terrestrial Networks (NTNs)

The integration of 6G terrestrial networks and NTNs has remarkable potential for improving the EE and reducing the carbon footprint. 6G is envisioned to support diverse use cases, ultra-dense networks, and additional usage scenarios such as ubiquitous connectivity, AI and communication, and integrated sensing and communication (ISAC), as shown in Figure 5 [33]. NTNs will complement and offer a novel approach to achieving the 6G sustainability goal by enabling improved EE and reduced carbon emissions. A key advantage of NTNs is their ability to provide ubiquitous connectivity and high capacity in underserved, unconnected, and remote areas without requiring extensive terrestrial infrastructure. Connecting rural and difficult terrain areas using terrestrial networks such as wireless cellular systems often demands extensive deployment of power-intensive BSs, usually powered by non-renewable energy sources, which increases energy consumption and carbon emissions. In contrast, NTNs powered by renewable energy sources can be used exclusively or as a complement to terrestrial networks within the 6G ecosystem to provide global coverage while requiring minimal terrestrial infrastructure. This reduces overall energy demand and carbon footprint [72].

With the deployment of large-scale satellite constellations in Low Earth Orbit (LEO), such as Starlink and other three billion constellations, NTNs integration into 6G networks enables ubiquitous connectivity with fewer terrestrial installations and improved sustainability. The strategic integration of NTNs within the 6G architecture, as shown in Figure 15, is essential for achieving global connectivity in a more energy-efficient and environmentally conscious manner. In addition, the massive construction and maintenance activities associated with terrestrial infrastructure, including the use of materials, transportation, and wired networks such as fibre optics—are linked to high carbon emissions and environmental degradation. Minimizing reliance on such terrestrial infrastructure helps not only reduce the cost but also the carbon footprint of network operations. NTN exhibits great potential in realising the 6G vision considering the new capabilities that will be offered only by 6G and beyond, such as sustainability, coverage, positioning, sensing, interoperability, and AI-related functions, as shown in Figure 4 [33].

5.6 Energy-Efficient Multiple Access and Multiplexing Schemes

As discussed, future 6G networks aim to achieve unprecedented targets, including massive connectivity, ultra-reliable low-latency communications, and ultra-high data rates [33]. They are also expected to simultaneously support diverse applications like communication, sensing, and computation for various network entities based on their needs [73]. To meet these goals while ensuring spectrum efficiency and sustainability, advanced multiple access and multiplexing techniques are essential.

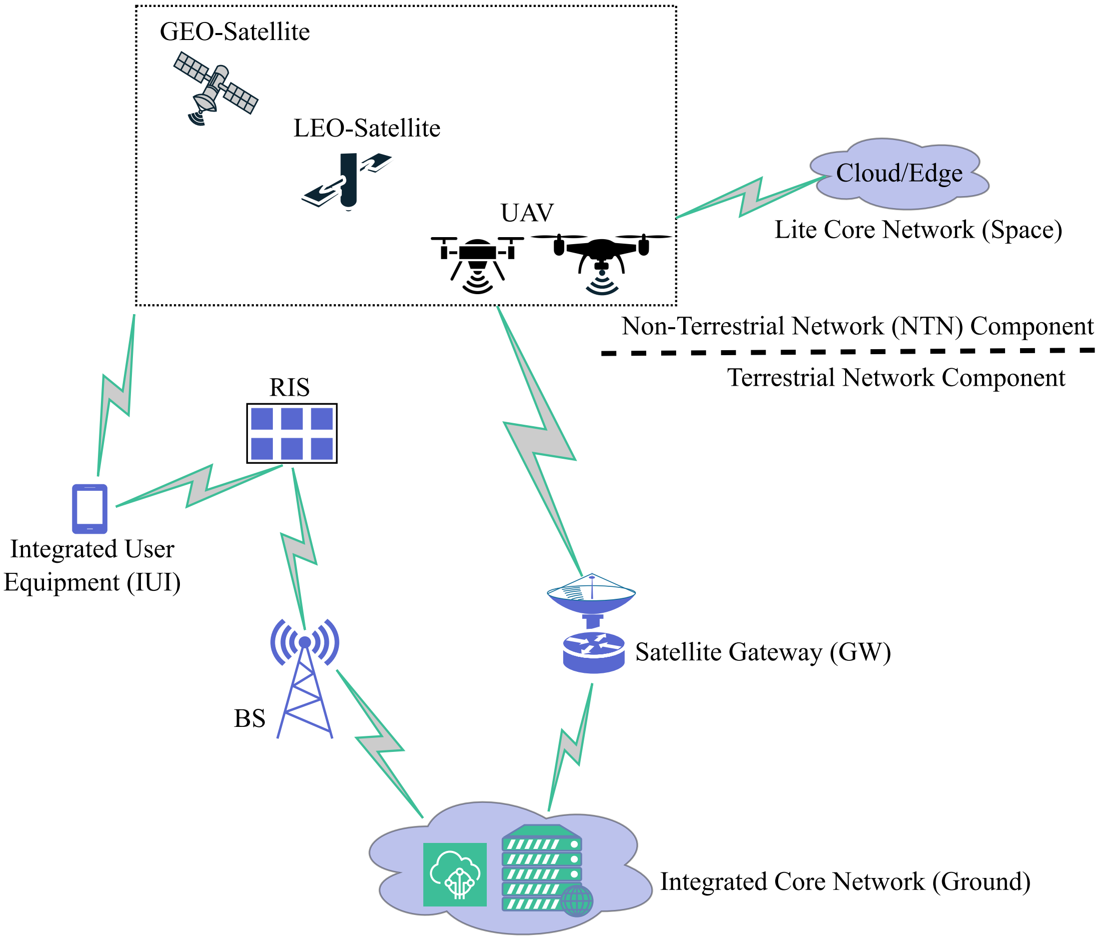

Figure 15 Proposed Architecture of Space-Air-Ground Integrated NTN and 6G Network.

Multiple Access Schemes

Conventional orthogonal multiple access (OMA) schemes, which allocate separate resources to users, are unlikely to meet the demands of 6G networks, especially given the anticipated drastic increase in the number of users, low-latency requirement, and the scarcity of frequency spectrum [73]. Thus, non-orthogonal multiple access (NOMA) and rate-splitting multiple access (RSMA), both of which are non-orthogonal transmission schemes, are envisioned as promising and energy-efficient solutions to address these challenges and support the use cases and capabilities of 6G networks [73]. As identified in the ITU-R, NOMA significantly enhances the radio interface of future wireless networks by enabling multiple users to simultaneously exploit the same resource blocks, either through the power domain or the code domain [33]. Similarly, the RSMA scheme also enables multiple users to simultaneously exploit the same resource blocks without increasing the transmission bandwidth and energy consumption, while outperforming the NOMA scheme in terms of implementation simplicity and interference suppression [74], [75]. Additionally, employing hybrid multiple access schemes, such as hybrid NOMA-OMA and hybrid RSMA-OMA, can further improve the spectral and energy efficiencies, particularly in large-scale setups, such as the massive number of users anticipated in 6G networks [76], [77]. Thus, the integration of these techniques with RISs can be considered key enablers for advancing towards carbon-neutrality in large-scale 6G wireless networks [78], [79].

Multiplexing Schemes

Conventional multiplexing schemes, such as time division multiplexing (TDM), frequency division multiplexing (FDM), code division multiplexing (CDM), and orthogonal frequency division multiplexing (OFDM), use waves with uniform phases and rely on limited resources like frequency, time, and space, offering restricted degrees of freedom. As a result, they fall short of meeting 6G network requirements, such as ultra-high data rates, massive connectivity, and sustainability. In contrast, orbital angular momentum (OAM) multiplexing leverages helical-phase waves to create additional transmission channels, enabling resource sharing without causing interference and improving the spectral and energy efficiencies, particularly in short-range applications like THz systems [73], [80], [81]. However, conventional OAM-based systems face challenges like beam divergence, atmospheric turbulence, and path loss [81], [82]. These issues can be mitigated through energy-efficient techniques, such as adaptive OAM multiplexing, which adjusts OAM modes based on channel conditions, and integrating RISs to enhance beamforming and eliminate divergence. Combining RISs with adaptive OAM multiplexing offers a promising path to improving spectral and energy efficiencies, supporting carbon-neutrality and advanced use cases of 6G networks [80].

5.7 Energy Harvesting and Zero-Energy Communications

EH and zero-energy communication technologies are expected to play a key role in enabling carbon-neutral 6G networks [83], [84]. Unlike earlier generations, 6G aims to support large-scale, self-sustainable deployments of distributed devices, reconfigurable surfaces, and intelligent network components, many of which will operate under stringent energy constraints [83], [84]. These include not only traditional IoT sensors, but also future 6G use cases such as intelligent wearables, autonomous drones, and AI-powered edge nodes [85], [86], [87], [88].

To support these deployments without a corresponding increase in energy consumption, 6G research emphasises integrating EH techniques. Devices can harvest energy from ambient sources such as radio frequency (RF) signals, solar radiation, mechanical vibrations, wind, and thermal energy, thus reducing dependency on non-renewable energy sources and extending operational lifetimes [85], [87], [89], [90]. By minimizing the need for battery replacement or manual recharging, especially in remote or inaccessible locations, EH directly supports the sustainability goals of 6G networks [87], [88], [90].

In addition, RISs can also be used to harvest energy for their self-sustainability. Although RISs consume significantly less power compared to traditional mMIMO and relay technologies, employing EH techniques at the RIS through RIS partitioning can enable zero-energy RISs, further advancing towards carbon-neutrality [83], [84], [91]. Additionally, zero-energy communication schemes such as thermal noise modulation offer promising pathways for ultra-low-power 6G communications [84]. In these systems, information is conveyed by modulating the intrinsic thermal noise produced by passive circuit components like resistors, switches, and capacitors, eliminating the need for active RF transmission or external energy sources [92], [93], [94]. It is important to note that, in certain situations, the harvested energy or the thermal noise power of devices may be insufficient to support reliable and low-latency communications [84], [87]. In such cases, the integration of zero-energy RISs with these techniques presents a viable solution to overcome these limitations, paving the way for scalable, energy-efficient, and sustainable communications in future 6G networks.

5.8 Sleep Mode and Energy Saving Techniques

The sleep mode technique reduces the energy consumption during low-traffic periods by deactivating underutilised BSs, while neighbouring BSs maintain coverage and service quality [95]. In the existing literature, it has been demonstrated that employing various sleep mode and energy saving techniques can significantly reduce the energy consumption of wireless communication networks [96], [97], [98]. In addition, the BT Group in the UK has recently implemented the sleep mode technique across its mobile sites, which is estimated to lead to a significant reduction of 4.5 million kWh annually in the network's overall energy consumption [99]. Due to the high energy consumption of the RAN segment (Figure 1), the projected growth in global mobile traffic (Figure 3), and the expected densification of BSs driven by THz-band deployment, it is essential to implement advanced sleep modes and energy-saving techniques to reduce the energy consumption and support carbon-neutrality in future 6G networks.

5.9 AI Techniques for Energy and Carbon Emission Reductions

AI and machine learning (ML) techniques play a crucial role in intelligently reducing the energy consumption and carbon emissions of future 6G networks. Some examples of AI and ML applications aimed at improving the EE and reducing the carbon footprint of wireless communication networks are given as follows.

- AI models can accurately predict traffic demand and dynamically allocate resources to ensure that idle network components are powered down during low-demand periods, significantly reducing the energy consumption and carbon emissions of wireless networks [100], [101].

- ML-driven adaptive network slicing is another example that enables dynamic resource allocation based on real-time traffic demands. This prevents over-provisioning, and minimises unnecessary load and energy consumption, especially in dense and heterogeneous communication scenarios, as expected in 6G networks [102], [103].
- AI techniques can also be used in 6G networks to predict channel conditions in real time and dynamically adjust the wireless networks' parameters, such as transmission power, beamforming directions, and modulation schemes, among others [104], [105]. This enables more efficient resource utilisation, optimised connectivity, and enhanced EE during data transmission, which are critical for meeting the high demands of 6G networks.
- Integrating AI at edge devices in 6G networks reduces the energy-intensive data transmission to central servers [88], [106]. Moreover, ML algorithms optimise the task scheduling and processing at the edge, minimizing the overall network energy consumption and supporting the low-latency and high-efficiency requirements of 6G networks [88], [107], [108], [109].
- In addition, implementing distributed ML techniques can further reduce the energy consumption by dividing the learning and computational tasks across devices and network nodes, reducing reliance on centralised servers and further advancing towards carbon-neutrality in future 6G networks [88], [110], [111].

5.10 Efficient Techniques for Physical Sites and Data Centres

In order to achieve carbon-neutral 6G networks, it is crucial not only to implement energy-efficient AI and communication techniques and technologies, as previously discussed, but also to decarbonise their power supply alongside efficient cooling systems. Therefore, some promising techniques that can be implemented in physical cell sites and data centres are described below.

Renewable Energy

There are various types of renewable energy sources, such as solar, wind, hydroelectric, geothermal, biomass, wave, ocean current, and tidal power, which can be used for the sustainability of 6G networks, as they provide the significant clean energy needed to support 6G networks and reduce the carbon footprint of network operations [112], [113], [114], [115]. Renewable energy sources, e.g., solar and wind, are particularly suitable for powering remote cell sites and data centres, enabling decentralised energy generation and improving the network resilience [115].

Integration of Renewable Energy and 6G in Smart Grids

By incorporating renewable energy and 6G into smart grids, network operators can manage energy flows more efficiently, reducing energy waste and adapting to changes in network demand, thereby further supporting the sustainability of 6G networks [116], [117], [118].

Energy Storage

Integrating renewable energy sources and storage solutions further accelerates the achievement of carbon-neutral 6G networks, ensuring a reliable power supply and reducing dependence on fossil fuels [119], [120], [121]. Lithium-ion batteries are commonly used to store significant amounts of renewable energy, ensuring a steady power supply during low-generation periods and thus reducing the need for backup fossil fuel-based power sources [122], [123]. In addition, emerging storage technologies, such as flow batteries, offer scalable and long-duration storage for larger operations [124], while supercapacitors provide high power density and rapid charge/discharge capabilities for short-term use and during peak demands [125]. Together, these technologies create efficient systems that enable reliable, sustainable, and resilient power management for telecom infrastructure, particularly in off-grid or renewable-powered setups [126], [127]. Therefore, integrating these energy storage systems improves the efficiency and resilience of 6G networks, accelerating the transition towards carbon-neutrality.

Efficient Cooling Systems

Traditional air cooling systems in cell sites and data centres require complex infrastructure and consume large amounts of energy, thus increasing their carbon footprint [12], [128]. In contrast, direct liquid cooling systems offer a more cost-effective solution by circulating coolant directly around the heat-producing components [128], [129]. This method provides a much higher cooling efficiency than conventional air-based systems, making it a promising approach to create sustainable networks [12], [129].

Efficient Power Conversion Systems

Conventional alternating current (AC) and direct current (DC) conversion and power supply systems, especially those with silicon-based semiconductors, are often less efficient [130], [131]. This inefficiency leads to significant energy losses and higher cooling requirements, creating challenges for future networks with dense cell sites and data centres. On the other hand, systems based on silicon carbide (SiC) and gallium nitride (GaN) offer a solution by achieving conversion efficiencies of up to 97.5% [131]. These systems minimise energy losses, reduce the need for complex cooling, and lower operational costs, as they can operate at higher voltages and temperatures compared to traditional silicon-based systems [130], [131].

6 Challenges to Achieving Carbon-Neutral 6G Networks

Achieving carbon-neutral 6G networks extends beyond technological advancements and requires coordinated efforts across standardisation bodies, regulatory authorities, policymakers, industry stakeholders, and the research community. International targets such as the ITU's goal of a 45% reduction in the ICT sector's carbon emissions by 2030 and the SBTi's net-zero framework provide an ambitious policy foundation [2], [21]. However, progress towards carbon-neutral 6G remains constrained by several gaps, such as the lack of a standardised end-to-end 6G architecture, harmonised carbon metrics, and effective governance mechanisms. At the same time, technical advances from ITU, ETSI, and 3GPP, along with major research initiatives such as Hexa-X and the 6G Infrastructure Association (6G-IA), have begun to integrate sustainability into 6G roadmaps [132], [133]. Nevertheless, achieving true carbon-neutrality will require systematic measurement, transparent reporting, and strong international alignment. Therefore, several key challenges to achieving carbon-neutral 6G networks are outlined below, though others may also emerge as the technology evolves.

Lack of Policy and Interoperability Frameworks

While the emerging technologies discussed earlier offer promising avenues for improving EE and achieving carbon-neutrality, their integration should be guided by comprehensive frameworks that ensure policy alignment, standardised carbon metrics, and global interoperability. Without effective cross-sector collaboration and consistent benchmarks, the potential of 6G to support carbon-neutrality could be significantly diminished.

Lack of End-to-End Carbon Accountability

Despite ongoing work on sustainability metrics, there is currently no integrated framework for end-to-end carbon accountability in 6G networks. Existing guidance, such as ITU-T L.1470 [24], provides baseline direction; however, the lack of a standardised end-to-end 6G network architecture makes it difficult to align carbon footprint tracking throughout the network components and lifecycle. This challenge will become even more complex as 6G relies on large numbers of distributed edge nodes to support latency-sensitive and data-intensive applications. Without systematic measurement and reporting, the cumulative carbon emissions of these nodes may not be fully captured in sustainability assessments, weakening transparency and the effectiveness of management strategies. Addressing this requires standardisation bodies to define clear monitoring requirements, regulators to enforce transparent reporting, and operators to implement consistent carbon accounting across both centralised and edge infrastructure.

Inconsistent Carbon Reporting Practices

Telecom operators and vendors worldwide use inconsistent methods to report their networks' carbon footprints, leading to misalignment in reporting scopes, levels of data detail, and verification practices [134]. Although frameworks like GSMA's ESG indicators are emerging [134], the absence of internationally mandatory standards limits transparency and comparability in current reporting efforts, an issue that needs to be addressed to truly achieve meaningful progress towards carbon-neutral 6G networks.

Carbon Cost of AI Workloads

AI is expected to play a key role in improving EE and reducing the carbon footprint of 6G networks. However, AI itself consumes significant energy and produces emissions, particularly through model training, large-scale deployment, and real-time inference, which are often overlooked in current assessments [135]. Therefore, without holistic carbon accounting that includes AI workloads, evaluations of 6G sustainability may be misleading and overstate AI's contribution to carbon-neutrality. Addressing this challenge requires coordinated efforts by researchers, standardisation bodies, and policymakers to ensure that AI supports, rather than undermines, 6G's sustainability targets.

Unequal Access to Clean Energy

A major barrier to carbon-neutral 6G is the unequal global access to clean energy. While some countries advance rapidly with renewables, others remain dependent on fossil fuels due to infrastructure, investment, or geographic limitations [136]. Bridging the gap will require coordinated efforts: governments need to invest in sustainable energy systems, telecom operators need to align growth with environmental goals, and international organisations, such as the UN, ITU, and development banks, should support funding and knowledge transfer. Decentralised energy solutions, like mini-grids and off-grid solar, can play a vital role, especially in remote or underserved areas where extending the traditional grid is not practical. The UK, with its strong climate commitments and leadership in innovation, can play a valuable role in advancing these efforts through global partnerships, research collaboration, and capacity-building.

Lack of Lifecycle Carbon Accounting in ICT Supply Chains

ICT procurement processes do not yet consistently account for the embodied carbon emissions of network equipment, focusing instead on capital and operational costs. Overlooking lifecycle emissions from material extraction, hardware manufacturing, transport, deployment, and end-of-life management will pose a critical barrier to carbon-neutral 6G. Addressing this requires coordinated actions: regulators and standardisation bodies should define lifecycle-based sustainability criteria, while operators and vendors must embed them systematically into procurement and supply chain frameworks.

Connectivity Expansion in Fossil-Heavy Regions

Expanding connectivity to underserved regions is essential for digital inclusion, but this expansion risks raising carbon emissions in areas reliant on fossil-heavy grids. Without frameworks that integrate clean energy access into connectivity planning, carbon-neutral 6G cannot be achieved across all regions. Addressing this requires governments to prioritise renewable energy deployment in parallel with digital expansion, operators to adopt low-carbon network design principles, and international organisations, including standardisation bodies, development banks, and multilateral agencies, to provide guidance, funding, and coordination for inclusive and sustainable infrastructure deployment.

Financial Barriers to Low-Carbon Investment

Achieving carbon-neutral 6G will require substantial investment in low-carbon infrastructure, which often involves higher upfront costs than conventional deployments. Without strong economic mechanisms, operators may deprioritise sustainability in favour of short-term cost efficiency, slowing the transition to carbon-neutral 6G networks. Addressing this challenge requires governments and regulators to introduce supportive measures, such as carbon pricing, tax incentives, and green procurement mandates, while financial institutions and development banks expand access to sustainability-related funding. Industry players should also embed carbon performance into investment decisions to accelerate the adoption of carbon-neutral technologies.

Spectrum Allocation and Energy Efficiency

Spectrum allocation strongly affects the carbon footprint of 6G networks. For instance, small or uncoordinated spectrum blocks force operators to deploy more sites and equipment, raising the energy consumption and carbon emissions. By contrast, larger and harmonised blocks as well as spectrum sharing can reduce duplication and improve efficiency [137], [138]. Addressing this challenge requires regulators and standardisation bodies to integrate sustainability goals into spectrum policy.

7 Conclusion

In conclusion, this white paper underscores the urgent need for achieving carbon-neutrality in the ICT sector, particularly in the context of evolving 6G networks, which are poised to deliver unprecedented capabilities but also pose significant energy consumption and carbon emission challenges. By presenting a comprehensive analysis of energy consumption patterns, power models, and performance metrics, we have highlighted the critical areas where interventions are needed to reduce GHG emissions, optimise the energy consumption, and enhance the sustainability of 6G networks.

The exploration of energy-efficient solutions, spanning terrestrial and non-terrestrial networks, advanced communication technologies, AI-driven optimisation, renewable energy integration, and innovative energy management techniques, offers a roadmap to carbon-neutral 6G networks. These solutions, coupled with adherence to international standards such as those from the ITU, ETSI, and 3GPP, demonstrate that sustainable development in telecommunications is both feasible and essential. However, as highlighted in Section 6, realising carbon-neutral 6G networks will also depend on addressing ongoing challenges in policy, standardisation, financing, and equitable access to clean energy.

The transition to carbon-neutral 6G networks is not just a technological imperative but also a societal need, aligning with global commitments. By integrating renewable energy, adopting energy-saving innovations, and fostering collaboration among industry, academia, and standardisation bodies, the ICT sector can play a pivotal role in reducing its carbon footprint and achieving a sustainable future. The findings and recommendations outlined here aim to guide stakeholders in realising energy-efficient, carbon-neutral 6G networks that support the twin goals of connectivity expansion and environmental preservation.

List of Abbreviations and Acronyms

3GPP	3rd-Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
6G-IA	6G Infrastructure Association
AC	Alternating Current
AI	Artificial Intelligence
AP	Access Point
BBU	Baseband Unit
BS	Base Station
BT	BT Group (formerly British Telecom)
CAN	Carbon-Aware Network
CDM	Code Division Multiplexing
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CPU	Central Processing Unit
C-RAN	Cloud Radio Access Network
D-RAN	Distributed Radio Access Network
DC	Direct Current
EaaS	Energy Saving as a Service
EE	Energy Efficiency
EF	Emission Factor
EH	Energy Harvesting
EoL	End-of-Life
ETSI	European Telecommunications Standards Institute
FDM	Frequency Division Multiplexing
F-RAN	Fog Radio Access Network
FSPL	Free-Space Path Loss
GaN	Gallium Nitride
GB	Gigabyte
GHz	Gigahertz
GHG	Greenhouse Gas
g-PPA	Green Power Purchase Agreement
GSMA	GSM Association
Hexa-X	EU 6G Research Project (Hexa-X Initiative)
HLR	Home Location Register
ICT	Information and Communication Technology
IMT	International Mobile Telecommunications
IoT	Internet-of-Things

ISAC	Integrated Sensing and Communication
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
ITU-SCC	ITU Study Group on Spectrum, Communication and Coding
ITU-T	ITU Telecommunication Standardisation Sector
kWh	Kilowatt-hour
LEO	Low Earth Orbit
mMIMO	Massive Multiple-Input Multiple-Output
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MSC	Mobile Switching Centre
NCIe	Network Carbon Intensity (Emissions)
NOMA	Non-Orthogonal Multiple Access
NR	New Radio (5G)
NTN	Non-Terrestrial Network
OAM	Orbital Angular Momentum
O-CU	O-RAN Centralised Unit
O-DU	O-RAN Distributed Unit
OPEX	Operational Expenditure / Expenses
O-RAN	Open Radio Access Network
O-RU	O-RAN Radio Unit
Ofcom	Office of Communications (UK telecom regulator)
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PPP	Public-Private Partnership
QoS	Quality of Service
RAN	Radio Access Network
RECOF	Renewable Energy Carbon Offset Factor
REUR	Renewable Energy Utilisation Rate
RF	Radio Frequency
RHS	Reconfigurable Holographic Surface
RIS	Reconfigurable Intelligent Surface
RNC	Radio Network Controller
RSMA	Rate-Splitting Multiple Access
RSPG	Radio Spectrum Policy Group (EU)
SBTi	Science Based Targets initiative
Si	Silicon
SiC	Silicon Carbide
STAR-RIS	Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface
TCE	Total Carbon Emissions
TDM	Time Division Multiplexing
THz	Terahertz
tCO_2e	Tonnes of Carbon Dioxide Equivalent

TB	Terabyte
UE	User Equipment
UAV	Unmanned Aerial Vehicle
UN	United Nations

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CHEDDAR

Durham University

University of York