NEXT G ALLIANCE
An ATIS Initiative

6G

Next G Alliance Report: **Sustainable 6G Connectivity — A Powerful Means of Doing Good**

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FOREWORD

As a leading technology and solutions development organization, the Alliance for Telecommunications Industry Solutions (ATIS) brings together the top global ICT companies to advance the industry's business priorities. ATIS' 150 member companies are currently working to address network reliability, 5G, robocall mitigation, smart cities, artificial intelligence (AI)-enabled networks, distributed ledger/blockchain technology, cybersecurity, IoT, emergency services, quality of service, billing support, operations and much more. These priorities follow a fast-track development lifecycle from design and innovation through standards, specifications, requirements, business use cases, software toolkits, open-source solutions, and interoperability testing.

ATIS is accredited by the American National Standards Institute (ANSI). ATIS is the North American Organizational Partner for the 3rd Generation Partnership Project (3GPP), a founding Partner of the oneM2M global initiative, a member of the International Telecommunication Union (ITU), as well as a member of the Inter-American Telecommunication Commission (CITEL).

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The ATIS Next G Alliance is an initiative to advance North American wireless technology leadership over the next decade through private sector-led efforts. With a strong emphasis on technology commercialization, the work will encompass the full lifecycle of research and development, manufacturing, standardization, and market readiness.

EXECUTIVE SUMMARY

Sustainability is deeply woven into the mission of the Next G Alliance (NGA) to establish North American leadership in 6G and beyond. It is one of the six audacious goals of the National 6G Roadmap working group and as such addresses key North American imperatives. It is also one of NGA's research priorities, meant to confront driving forces, both globally and in North American communities, as they pertain to technological, economical, and increasingly social and environmental needs and demands.

This paper surveys the research and technology directions required to make the vision of a sustainable 6G system a reality. The overarching mandate is to increase energy efficiency and to reduce energy consumption in the pursuit of significantly lower, ideally net-zero greenhouse gas emissions. The advocated approach, however, is intrinsically holistic, covering the entire gamut of the information and communications technology (ICT) sector's environmental impact, including the usage and pollution of air, water, and land through ICT technologies.

The path toward a realizable and sustainable 6G system laid out in this paper tackles the two key challenges to mankind as they relate to climate change, global temperature increase, and biodiversity loss. This path spans the entire life cycle of ICT technologies, from material sourcing and mining, to manufacturing and supply chain, operation and maintenance, and ultimately waste management.

1 INTRODUCTION

The Next G Alliance (NGA), in its goal of building the foundation for North American leadership in 6G and beyond, created an entire working group — the Green G working group — solely tasked with positioning North America as the global leader in environmental sustainability as it relates to future generations of wireless technology. This focus on the environmental impacts is complemented by the Societal and Economic Needs (SEN) working group, which, amongst other things, is concerned with the social and economic demands and needs for a sustainable 6G business case. Together, the Green G and SEN working groups thus frame the case for a sustainable 6G system. By posing the "why" question, they inspire innovation and large-scale change in the "what" and "how."

Societal Impact	• Food and water security • Quality of life, health, and well-being • Reduced inequalities • Improved education • Peace
Economic Impact	• Growth • Infrastructure and climate resiliency • Innovation • Circular economy • Reduced poverty
Environmental Impact	• Sustainable land/water use • Clean air, water, and energy sources • Reduced CO_2 emissions • Sustainable waste management, material sourcing, and mining

Figure 1: Societal, economic, and environmental needs framing the case for sustainable 6G systems

The SEN working group identified and prioritized societal demands for a sustainable 6G business case such as food and water security, health, an overall improved quality of life, and reduced digital inequality. Similarly, for the economic needs, 6G needs to drive growth, infrastructure and climate resiliency, innovation, and a circular economy. Together, they can help reduce poverty, foster equality, improve education and reduce the learning gap, help provide decent work for everyone, and ultimately strengthen the establishment of peace and justice.

On the environmental side, 6G must ensure sustainable land usage to counter biodiversity loss, which many scientists regard equally threatening to humanity as the global temperature increase through greenhouse gas (GHG) emissions [21]. That said, eliminating GHG emissions is also extremely important and a goal that 6G systems can achieve through renewable energy sources and significantly lower energy consumption. In addition, 6G systems must address water consumption, as well as air, water, and ground pollution through sustainable waste management, material sourcing, and mining (Figure 1).

The importance and relevance for North America, its local communities, and humanity as a whole are self-evident. A 6G system can align with the United Nations (UN) Sustainable Development Goals (SDGs) "for peace and prosperity for people and the planet, now and into the future" [1] by:

> Being financially affordable, physically accessible, and geographically available

> Being trusted by its users

> Helping avoid climate catastrophe.

> Yielding economic growth

> Improving quality of life through health care, education, safety, and security

Since the NGA Green G working group published *The Path Toward Sustainable 6G* in [1], NGA announced its initial 6G research priorities, with sustainability prominently featured because it is also one of the audacious goals of the National 6G Roadmap in NGA [23]. In this context, this white paper discusses research and technology directions toward a sustainable 6G system, with an eye on driving forces and a path to realization specific to North America.

2 DRIVING FORCES AND NORTH AMERICAN IMPERATIVES

Sustainability, in the context of 6G, is always twofold. On the one hand, the 6G system itself must be sustainable. The ICT sector accounts for several percentage points of global electricity consumption [1]. It generates tens of millions of metric tons of electronic waste every year [1]. Mining the elements for its network equipment and cooling them during operation consume hundreds of billions of liters of water [1]. At the same time, ICT could help reduce global carbon emissions — by some estimates, up to 15% by 2030 [2]. Hence, 6G must be sustainable for its own sake while enabling other industries to be more sustainable, as well. Smart cities, smart buildings, smart grids, and smart homes all will benefit from innovative ICT solutions that enable cooperation and advanced sensing and monitoring toward the goal of overall reduced GHG emissions. There are further opportunities in supply chains, manufacturing, and agriculture.

Raw and rare materials are increasingly becoming a matter of national security, making their recovery and the redesign of manufacturing processes to use recycled components all crucial goals. This means shifting from the current linear economic models to circular economy principles that rely on reuse of waste, recovery of materials and components, and renewable products resulting in little to no waste.

According to estimates, U.S. electricity demand could double by 2050 to power electric cars, heat pumps, industrial processes, and clean hydrogen production [3]. Direct land use for solar farms in a 100% carbon-free, net-zero scenario is estimated to range from the equivalent area of Connecticut to that of Virginia. For wind farms, the visual footprint is even larger and ranges from the equivalent area of Illinois and Indiana to that of Arkansas, Iowa, Kansas, Missouri, Nebraska, and Oklahoma combined [3]. 6G thus should establish energy consumption as a first-class metric advocating for renewable energy, energy harvesting, and groundbreaking network designs. In addition, 6G will enhance AI/machine learning (ML)-powered network energy consumption reduction models, as well as robust and granular real-time monitoring to achieve sustainable operation. Such optimizations make 6G a sustainable system and will span every aspect of the network, from user equipment to the radio access and core networks, data centers, and the software they use. They will increasingly rely on virtualization and disaggregation and will be cloud and AI native for utmost power efficiency and automated power management.

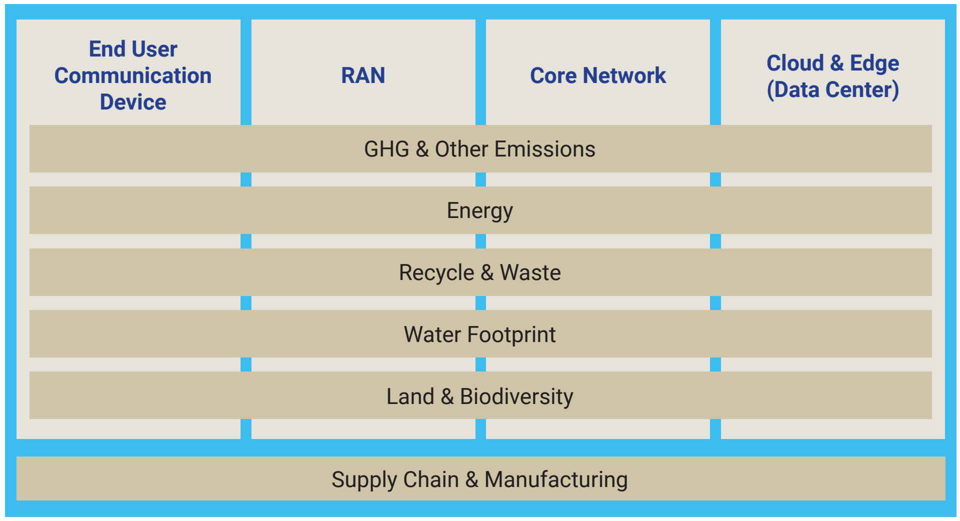

Figure 2: Optimizations that make 6G a sustainable system will span every aspect of the network

Lastly, 6G will consider the entire supply chain to reduce its environmental impact, from material sourcing to end-of-life. For example, over 80% of a smartphone's carbon footprint comes from manufacturing [1]. 6G requires a sustainable supply chain. The importance of raw materials was previously discussed, and cleaner production and manufacturing processes can make a large contribution toward that goal. To help reduce the use of rare, limited, and non-renewable natural resources, manufacturing processes and delivery logistics must thus be altered. The common goal of decarbonization will require collaboration across the entire value and supply chain, as well as new product designs and manufacturing processes that embrace circular economy ideas. When supply chain, operation, and waste management are fully circular and optimized, the promise of a sustainable 6G ecosystem that enables decarbonization of other industries will come true and with it the anticipated impacts on society, the economy, and the environment.

3 RESEARCH AND TECHNOLOGY DIRECTIONS

To create a sustainable 6G ecosystem, the NGA has published the following research priorities for sustainability:

1. Reuse and recycling of water, waste, and materials
2. Sustainable network planning and optimization
3. Sustainable supply chain
4. Sustainable operations
5. Enabling decarbonization

The following sections discuss research and technology directions in alignment with these priorities.

3.1 Increased Energy Efficiency and Reduced Energy Consumption

Component technologies: Component-level integration is a key enabler to build high-performance radios without driving up their size, weight, and power consumption. As more spectrum is introduced for 5G and beyond, requirements to support increasing bandwidth, often within the existing space at a cell site, become critical for energy efficiency and total cost of ownership (TCO).

This means that radio performance and efficiency must be improved without increasing the physical size and weight. More spectrum from multiple frequency bands needs to be managed by the same unit. Full realization of the benefits of increased bandwidth requires increased output power to maintain cell size and coverage. This creates a need for more power amplifiers, cooling, and supply power.

However, traditional hardware designs will be challenged to meet these additional requirements because current components will not physically fit into the existing available space.

Radios need to have higher levels of integration, replacing multiple components with single ones and implementing physical components that contain hardware, control interfaces, and software. All of this will reduce complexity and make configuration and maintenance more self-contained.

The radio's power amplifier (PA) is a crucial component for achieving energy efficiency in the Radio Access Network (RAN). Typically, the PA accounts for over 60% of the radio's power consumption, although this naturally varies across products [6]. Some examples of this integration-driven design philosophy include PA solutions that can handle more power and bandwidth and fit into a given space by integrating several discrete functions into a single package. Therefore, the efficiency of the radio hardware can be optimized for the specific output power or configuration used by continuously integrating more discrete steps into a single package.

Using transistor technologies such as Gallium Nitride (GaN) is an example of where higher power densities, higher supply voltage, and higher thermal conductivity will lead to system benefits such as higher efficiency and smaller circuits with less losses. These benefits become transformational for higher frequencies, which will be a key factor for a sustainable 6G. Note that innovations are needed to address the non-linearity challenges faced by GaN-based PAs.

This also applies to low-level radio frequency and signal processing, which have also been partly shifted into the digital domain to utilize the latest semiconductor processing technologies.

The tighter integration increases the density of the dissipated power. Therefore, new robust designs and innovative cooling solutions and management functionality need to be introduced. Network providers need to work closely with device suppliers to continue finding more innovative solutions to tackle these challenges.

By moving some of the advanced functionality like beamforming into the radio, RAN transport requirements can be reduced and the radio can adapt quicker to the constantly changing radio channel conditions. This enables significant improvements in performance, size, and energy efficiency. To do this, advanced application specific integrated circuits (ASICs) with specialized signal processors (DSPs), accelerators, and other logic elements that provide advanced processing capabilities need to be available.

Radio technologies and protocols: The radio's energy consumption occurs from fixed overhead forming a static consumption, as well as dynamic consumption that is highly correlated with data activity. Energy consumption can be reduced by selectively entering dimensions in time, frequency, and space into a dormant mode. The responsiveness of the network or device directly impacts the perceived user experience: The "deeper" a dormant mode, the larger the energy savings, but at the expense of longer "wake-up" times that return the base station or device back into active mode.

As a result, the potential magnitude for energy savings in 6G radio networks will depend on the exact operating point in the aforementioned multi-dimensionality comprising ever larger numbers of carriers, antennas, use cases, and many more, each of them capable of being dynamically turned on and off. Finding these operating points and understanding their trade-offs between energy consumption — as well as more traditional KPIs like throughput, latency, and reliability — is as much an important research area as finding the technologies that allow the system to operate at these operating points. Specifically, 6G systems are expected to dynamically allow at runtime for different trade-offs to balance the needs of an agile and responsive network with the associated environmental impact.

Although such on/off techniques offer great potential for enhancements in next-generation networks, another, more recent line of research/technology tackles power consumption in the radio more directly by deliberately introducing non-linearities in the transmission chain. This has been tremendously successful for PAs in conjunction with digital pre-distortion (DPD) technology. 6G radios will further leverage pre- and post-distortion techniques in the system design beyond the PA subsystem.

However, there are two major issues when transmitting signals through a non-linear PA. First, the signals will be distorted, resulting in poor signal error vector magnitude (EVM), and the receiver may not be able to demodulate the signal. Second, the non-linearity will result in higher out-of-band emissions. The first of these issues is beginning to be addressed using receiver processing based on ML. It has been shown that the ML receiver can cope with non-linearity through special processing of the signal in the time domain, followed by FFT operation and then followed by ML-based demodulation techniques.

The second problem is fundamentally introduced by the non-linearity and can be addressed to a certain extent through DPD techniques. However, that requires additional processing power at the transmitter and also limits the extent to which the PA can operate in the non-linear regime. One approach to address this second problem would be to relax the requirements at the expense of increased out-of-band emissions whenever possible. Although allowing distortions is desirable for lower energy consumption, they have adverse side effects (e.g., on out-of-band emissions and other important link- and systems-level KPIs). Novel concepts need to be developed that can accompany such energy reduction techniques and limit the effects on spectral efficiency.

5G has achieved hundreds of megahertz of bandwidth (e.g., in the millimeter wave bands above 24 GHz), has introduced shorter transmission time intervals through larger subcarrier spacings in OFDMA-based systems, and is the first cellular technology deploying massive antenna systems. However, these technological breakthroughs have resulted in significantly increased complexities, especially in the lower layers, as evident in Figure 3 [5]. 6G systems are expected to significantly reduce layer 1 (PHY) and beamforming-related processing needs for significantly improved energy efficiency. These complexity reductions are crucial to enable all kinds of novel 6G technologies, as detailed in the *Next G Alliance Report: 6G Technologies* [10], while keeping its promise to be a sustainable and cost-efficient system.

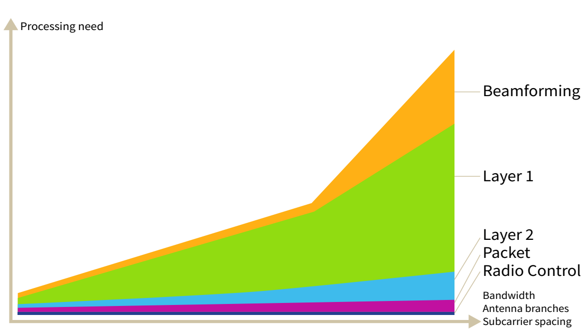

Figure 3: Exponential increase of processing need in layer 1 and beamforming — scales with bandwidth and branches [5]

Finally, 6G is expected to enable net-zero energy communication over cellular networks where the energy required to power a device is scavenged from the RF environment. Featuring ultra-low power radio circuits, such "zero-energy" devices enable novel applications and use cases in places where power supply is a concern or constraint. The introduction of such techniques requires advances in all aspects of the system, starting at the circuit level, but also including signaling aspects, waveform design, modulation, and coding, as well as protocol and networking aspects. These devices' unprecedented sensing and monitoring capabilities, and the use cases they enable, are expected to play a crucial role in the decarbonization of other industries outside the ICT sector. Thus, they are yet another example of how a greener ICT technology can unleash turbo effects that enable other industries to be more sustainable, as well.

Compute and storage infrastructure: A key architectural paradigm in the implementation of mobile networks is cloudification, where core and RAN functions are implemented in data centers. Centralized mobile cloud data centers allow pooling of resources, taking advantage of statistical multiplexing that leads to a more energy-efficient system compared to network functions implemented on dedicated compute resources that cannot be turned off until the last user is in the system.

Another trend is edge cloud networking for hosting services requiring low latency and high capacity. Added processing capability at the network edge is increasing the number of energy consuming data centers. To optimize energy consumption, network and application functions can be distributed between edge and centralized data centers based on load, function type, and latency requirements of the application. Furthermore, with cloud platforms being extended to implement specialized functions like radio processing and ML workloads, the hardware design of the data centers may require additional resources.

In addition to pooled general-purpose compute, data center evolution should include support of specialized hardware that can execute the specialized functions in a specialized way (e.g., use of ASICs leads to 10x less power than CPU/GPU for L1 processing). The data center design should enable marshalling of specialized hardware (e.g., accelerator, resources). It should also allow the accelerator to be shared between multiple ownership domains because the same data center may be hosting different function owners (e.g., operators) with a need to access similar kinds of accelerator resources.

Another issue for compute-intensive, multiply-accumulate operations, such as those needed for deep learning inference computations, is the power consumption of data read-write operations from memory. In particular, the hyper parameter weights are stored in memory and must be fetched for the compute operation. This operation consumes a significant amount of power. In analog compute-in-memory (CIM), a single flash transistor is used simultaneously for storing neural network weights and performing multiply-accumulate operations. Small electrical currents are steered through flash memory arrays that store neural network weights, and the matrix multiplication results are accumulated through a series of analog-to-digital converters. This provides very dense storage of neural network weights and high-performance AI processing in a single chip without the added cost of internal or external RAM and its associated components. Estimates from ongoing research suggest that savings of up to two orders of magnitude are possible using higher compute intensity per watt measured in terms of Tera operations per watt (TOPS).

Analog computing is somewhat inherently noisy. However, deep learning networks can be made robust against noise through appropriate offline training of the networks. Hence, analog CIM approaches can be leveraged better by implementing compute-intensive receiver processing through neural network models. When load is low and portions of the system-on-chip (SoC) can be powered down depending on the amount of compute power needed, scalable compute in the radio unit (RU) will allow a more flexible SoC deactivation, leading to further power savings in the RU.

Operation, administration, and maintenance (OAM), and service enablement (SE): A sustainable 6G system will fundamentally rely on sustainable operation through network optimization. This can be achieved using digital twinning of the network to enable sustainable optimization without the need of excessive drive tests. The importance of switching entirely to renewable energies manifests throughout this paper and requires key innovations such as novel backup systems that rely on batteries or fuel cells rather than diesel generators.

Availability of renewable energy may be intermittent. Matching the robustness of legacy, fossil-fuel-based energy sources requires novel network orchestration and optimization concepts and protocols that are more granular and aware of the environment in near real-time. Moreover, the performance of renewable energy must meet network performance needs during stressed conditions such as natural disasters or emergencies. OAM/SE also need to cater to the aforementioned "zero-energy" devices that similarly demand novel optimizations that ensure their robust operation absent a stable power source. In addition, their massive deployment may represent unprecedented challenges that need to be addressed in addition to ensuring secure encryption and authentication despite the devices' extremely limited computational complexity, form factor, and power supply.

6G systems will increasingly rely on software components that are deployed and operated natively in the cloud on general-purpose processors, as detailed in *6G Distributed Cloud and Communications Systems* [11]. This architectural trend makes software crucially important to maintain the same energy efficiency as purpose-built hardware with ASICs. This can be achieved through increased degrees of agility and flexibility that allow near-instantaneous provisioning of network resources and capacity and is enabled through novel AI-native protocols, as well as disaggregated hardware and software and open interfaces.

AI-native protocols are an integral part of a cognitive network. To maintain efficient and versatile future networks without accelerating cost and complexity, the level of network intelligence must be increased. These cognitive networks will enhance energy efficiency, optimize performance, and ensure service availability. This is achieved through AI/ML for difficult optimizations and AI machine reasoning (MR) for autonomous management of current system tasks. Key to this intelligence is making decisions based on data, and the more data available, the better the decisions. A data-driven architecture supports data pipelines that take care of moving, storing, processing, visualizing, and exposing data from inside service provider networks, as well as from external data sources in a format adapted for the consumer of the pipeline.

Additionally, cognitive systems must be autonomous, constantly learning and adapting to their environment through feedback from operations and performance. This continuous optimization results in a more dynamic network compared to current systems. It should also be able to predict and proactively adapt to future situations by using digital twin models fed with live operational data. Such a model can predict the impact of users, traffic, and proposed configuration actions on the system, prioritizing impacts on aspects such as energy [17].

Enablement, control, and optimization, however, are not limited to the network itself anymore. They must also monitor the environment to achieve the sustainable operation envisioned for 6G. AI/ML-enabled power management not only optimizes the energy consumption but also the water consumption and how to most effectively use a given energy mix of renewables. Workloads can be optimized based on their priority and taking into account the weather forecast, ambient air temperature, or conditions of nearby lakes and rivers that supply water for cooling. Sustainable 6G systems thus rely on precise metrics for energy consumption, carbon footprint, water consumption, and the overall environment. In addition to traditional concepts like traffic forecasting, AI/ML techniques are key in realizing these sustainable future networks. The training and maintenance of AI/ML models can be extremely energy intensive, so a benefit analysis is important.

Intent-based management is an important aspect that can help improve sustainability. Intent-based management functions are software functions that control the operation based on specific goals, such as optimizing for energy efficiency in the network. These functions require a higher level of abstraction in the human-machine interface and the ability for the system to interpret and reason around these goals. AI/ML can be used to create a RAN automation solution where functionality can work together toward intents by utilizing the flexibility of a cloud-native RAN implementation. For example, if target KPIs are met and there are still resources available, the system can have additional intents such as optimizing for peak throughput or energy efficiency. These rules determine how the system should behave in situations when all KPIs are met and there are still free resources in the system (e.g., during low traffic periods in coverage cells), as well as how to prioritize between KPIs when there are not enough resources to meet all KPIs (e.g., during traffic peak periods) [17].

System and network architecture: 6G networks must accommodate a wide range of new and emerging services. Metrics such as data rates, latency, and capacity may be augmented with new capabilities that may be more subjective in nature.

Trustworthiness, sustainability, automation and AI, and limitless connectivity are projected to be key drivers for future networks to support the imperatives shown in Figure 4. Triggered by these drivers, new application areas will require new capabilities. To support these capabilities, many components from cloud systems to applications and from diverse devices to industrial systems need to be addressed together by the 6G future network platform.

For 6G networks, a broad range of promising technology areas should be considered. The study of these potential elements identified below will be a key topic of research in the coming years [17].

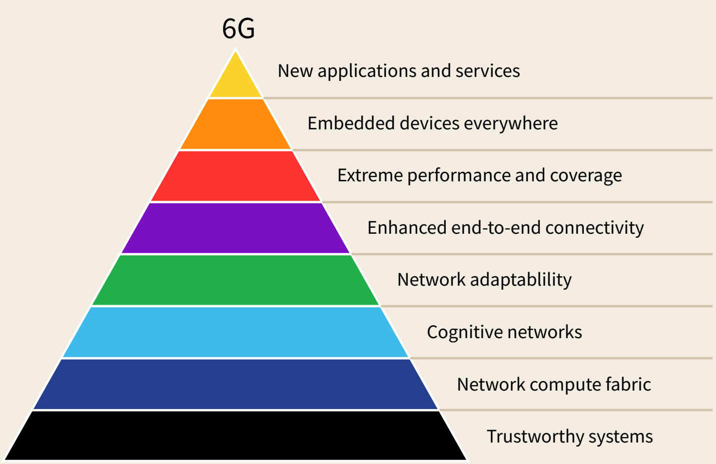

Figure 4: Connecting a cyber-physical world [17]

In order to support these, a 6G system needs to support:

> Communication services with very challenging requirements on a system level.

> Critical communication (covering sensitive needs in society and industries).

> Immersive communication (covering the future of intense human and machine interaction).

> Massive communication (covering the future of large-scale digital twins).

This calls for a system with low latencies, high data rates and capacity, and the ability to provide assurances on coverage and services. Some of the architectural solutions underpinning such a 6G system will pose additional challenges for achieving sustainability goals, while other solutions will provide tools that enhance the ability to improve sustainability. For instance, 6G systems will need architectural solutions that provide high levels of steerability and observability throughout the network, enabling efficient and versatile actions to be taken. These solutions can and should also prioritize energy efficiency and cost-effective dense deployments.

Similarly, the future network platform must be able to support new services beyond communication, such as navigation and spatial awareness, which require an architecture with functions for data collection and distribution via localization, sensing, mapping, and time synchronization; compute offloading for low latency and battery-limited applications; and distributed training, execution, and management of AI models. Although many of the required solutions will increase the challenges for sustainability, the new services will make the network more agile, which also provide opportunities to improve sustainability of the overall network. For instance, these solutions will necessitate advanced processing in the network, which can be achieved through the use of advanced ASICs in the architecture to maintain energy efficiency while supporting these functionalities.

To achieve the goals for 6G, the 6G architecture needs to enable an AI-native cognitive network with intent-based orchestration that is cloud-driven and data-driven, which provides significant opportunities for enhanced energy efficiency. However, this needs to be achieved while accommodating the considerations of cloud-native infrastructure and edge, and on-premise infrastructure. In a multi-cloud environment, where different cloud infrastructure vendors are used, the RAN software must be able to be deployed on multiple vendor cloud infrastructures. The service management and orchestration (SMO) should orchestrate multiple vendor cloud infrastructures while considering aspects such as energy efficiency.

New use cases that require low latency are becoming more common. This means that the cloud infrastructure must be able to be deployed near the antennas and at enterprises' and other organizations' own premises, with a focus on being lightweight, compact, energy-efficient, and cost-effective. The large scale of these edge cloud deployments highlights the need for homogeneous, unified infrastructure management in order to manage energy-efficiency considerations.

It is also important to consider the impact of centralized versus distributed RAN architectures for energy-efficient future systems. The common view is that centralized RAN (C-RAN) is inherently better for lower power consumption solutions than a distributed RAN (D-RAN) deployment. Mobile networks are dimensioned for peak traffic, so resources are often over-allocated in certain areas of the network. With C-RAN, processing resources can be shared in a common pool, leading to more efficient cooling, power-supply, and energy-storage solutions. However, it is crucial to understand which parts of a network can realistically be centralized in a C-RAN deployment and under what conditions. C-RAN deployments typically use off-the-shelf hardware, which allows adding value with custom-made silicon that can deliver higher load dependence and lower energy consumption. Latency considerations will limit the centralization of time-critical and power-consuming lower-layer processing, such as the digital frontend. The analog (radio) parts must also remain distributed in a C-RAN deployment to serve users distributed over the coverage area [18].

In conclusion, traditionally networks have been designed primarily to maximize performance for mobile broadband (MBB) users. However, new use cases and priorities in 6G may lead to different and additional optimization goals in network design, performance, and implementation beyond enhanced MBB (eMBB). As indicated in this section, programmability of networks and devices, centralization of resources, RAN acceleration for cloud implementation, and the ability to turn cells on/off with densified networks are all important trends that will impact 6G that can also be used to enhance energy efficiency. Furthermore, aspects such as resilience, security and trust, and edge computing that are important to 6G will need to be addressed while managing the impacts to energy efficiency.

Device diversity considerations: As new services and applications emerge, the number of devices will increase exponentially and the variety of devices will diversify. These devices, which will connect to the 6G platform to enhance the quality of experience (QoE) for end users, will augment existing solutions, such as new types of devices in the industrial domain, zero-energy devices, bio-degradable devices, etc. These device types cater to ecosystems that are either evolving in broad use-case categories such as eMBB, IoT, and URLLC/critical services or could be disruptive types of devices with new capabilities that could influence the device-edge-cloud split for tasks and even lead to seamless task migration. The network architecture must be able to support these capabilities in an energy-efficient manner. Based on the bulk of emissions of devices coming from their manufacturing process and the need to increase their lifecycle, enhanced frameworks to update and manage the device capabilities throughout their lifecycle should be adopted at least for critical energy-impacting features.

3.2 Reduced Environmental Impact

Today, biodiversity loss is mostly the result of clearing lands and forests for urban development or farmland and over-fishing the oceans. However, scientists expect that climate change will become the leading cause of biodiversity loss if not limited to 1.5º Celsius [7]. Eventually, the ICT sector may contribute as much as 20% of the global energy consumption, up from less than 5% today. More important than its relative share or even absolute consumption in terawatt-hours (TWh) are the ICT sector's greenhouse gas emissions in metric ton of carbon dioxide equivalent (Mt CO_2e), which already appear to decorrelate from energy consumption and data growth as Figure 5 illustrates [1][4][8]. Because 80% of the ICT sector's carbon footprint stems from electricity usage [9], switching entirely to renewable energy sources would thus readily reduce the industry's emissions by 80%.

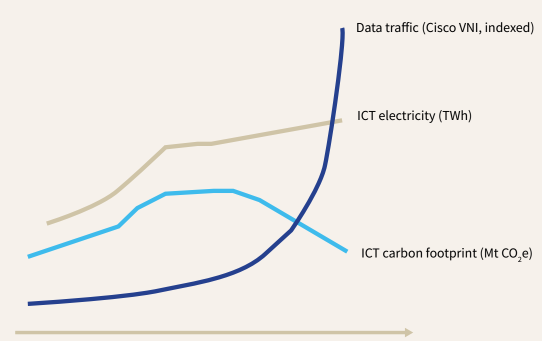

Figure 5: The ICT sector's carbon footprint [4]

Beyond carbon footprint, there are additional reasons to significantly lower electricity consumption. Land use from solar and wind energy is forecasted to be significant [3]. Drastically reducing the electricity consumption of 6G systems will help ease the demands on generation and distribution of renewable energy in a carbon-free, net-zero North American scenario. This will benefit the environment through substantially reduced land use and embodied GHG emissions in infrastructure, as well as the economy and taxpayers by lowering the burden of funding and building the related infrastructure. Reduced energy consumption is thus a prime example of how "green" 6G systems can unleash turbo effects far beyond the ICT sector's influence itself. There is a tremendous economic, societal, and environmental upside, and accounting for such secondary effects is key to a holistic approach to environmental sustainability.

It is moreover crucial to assess the environmental impact of a 6G system by category, namely Figure 2, and in addition whether it mainly stems from operation or manufacturing. For example, the land use of a base station may be rather small but is significant for a data center. Similarly, water use is irrelevant to a smartphone during operation but mining just the ore for 1.4 billion smartphones uses 100 billion liters of water [1]. For a data center, on the other hand, operational water usage can amount to 3-5 million gallons a day, which is the equivalent of an entire small city [1]. These examples demonstrate that both within and across network elements, the environmental impact can significantly vary between manufacturing and operation.

Last but not least, any consideration of environmental sustainability of 6G systems must also be end-to-end by taking into account waste management of 6G components. For instance, 54 million metric tons of electronic waste were generated in 2019 alone [1]. 6G systems must be deeply rooted in circular economy principles, with near-zero waste products reliant on high degrees of reuse and recycling through renewable or recovered components and materials. This departure from current economic models will necessitate innovations in the supply chain and manufacturing because a circular economy, unlike a linear one, has no defined endpoint. Innovative, novel recovery and manufacturing processes are needed that can efficiently and sustainably use renewable and recycled components and materials. Software will be increasingly important not only in the design and optimization of these processes, but also to prolong the lifecycle of deployed hardware.

3.3 Observability Improvements and Consumer Choice

The most obvious and maybe most important step for the ICT sector to take immediately is reducing its carbon footprint. However, meaningful KPIs can be defined for additional environmental impacts the ICT sector is responsible for, as summarized in Figure 2. Sustainability KPIs are important because they can be recorded, which is the first step in the path toward a sustainable 6G system. Recording KPIs enables analysis of the environmental impact and subsequently the design of solutions alleviating it. For some industries, the relationship between KPIs is very straightforward. An automotive supplier can easily assess the impact of a new part on fuel consumption by its weight. According to business lore, American Airlines famously saved tens of thousands of dollars by reducing the number of olives on a passenger's salad plate [22]. Due to the highly distributed nature of modern communication networks, such relationships are not always as straightforward. Improved modeling and reporting of key sustainability metrics are needed to understand ICT's impact on the environment and provide insight to drive the design of technologies and actions toward reducing its environmental impact.

For example, the ICT sector is often heralded for enabling efficient work from home during the COVID-19 pandemic. But whether working from home reduces the overall carbon footprint is not always easily quantifiable due to so-called rebound effects [12]. Let's assume a worker saves a certain amount of time and GHG emissions by not commuting between their home and work. Whether this reduces GHG emissions overall strongly depends on how they use the time saved by not driving to work. If they replace the commute with an activity whose equivalent carbon footprint is larger than that of the commute, ICT did not, in fact, reduce GHG emissions. Such considerations are subject of current research. The ICT sector's goal is to significantly contribute to the reduction of GHG emissions by enabling smart buildings, fleet management, and so forth [2][8][12].

This leads to the second step on the path toward sustainable 6G systems: reporting, which also introduces accountability. Twenty-nine operators are already committed to reduce emissions by at least 45% between 2020 and 2030 [1]. But simple reporting of sustainability KPIs can also have a tremendous impact on consumer behavior. For example, one study [14] showed that hotel guests take shorter showers simply by being made aware of how much water they use. This can be further leveraged through more direct means such as green credentials and ECO rating, which allow consumers, similar to fair trade coffee, to make purchasing or usage decisions based on such labels that facilitate improved observability at the end customer.

Recording and reporting sustainability KPIs thus directly or indirectly enable the reduction of the ICT sector's impact on the environment (Figure 2). They allow for a proper and quantifiable understanding of the problems that need to be addressed and inform possible solution directions. They establish accountability and can influence or enable consumer choice. Last but not least, quantifiable KPIs and metrics may be crucial to the adoption of other, future 6G technologies like blockchain and AI/ML, and the proliferation of billions of IoT devices. The explosion of complexity observed in 5G (Figure 3) is not a promising trajectory for 6G systems. The operation, administration, and maintenance, and possibly even the feasibility of these and other technologies, may rely on the availability of detailed, reliable, real-time information. Similar to the rebound effects discussed previously, if a given AI/ML algorithm enables an optimization that reduces the energy consumption by X, but the execution of the AI/ML algorithm itself consumes Y, nothing is gained overall. The goals of 6G, especially as they pertain to sustainability, can thus only be achieved with much improved observability as outlined in this section.

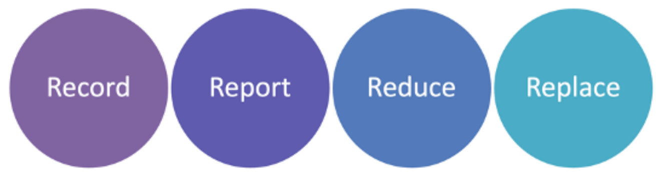

Figure 6: The path to sustainable 6G (Credit: [13])

4 PATH TO REALIZATION

In 2018, the Intergovernmental Panel on Climate Change (IPCC) confirmed that in order to limit global warming to 1.5°Celsius, the world needs to halve CO_2 emissions by around 2030 relative to 2015 levels and reach net-zero CO_2 emissions by mid-century [24]. The IPCC defines net zero as that point when "anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period." However, recent IPCC reports indicate that human activities are estimated to have caused approximately 1.0º Celsius of global warming above pre-industrial levels. [17][18]. Achieving these goals will require close collaboration between public and private stakeholders.

Government has a big role in preparing the ICT ecosystem and beneficiary industries for revolutionary technological changes such as 6G. The U.S. government's CHIPS and Science Act promotes U.S. innovation in wireless supply chains. This includes $1.5 billion for promoting and deploying wireless technologies that use open and interoperable RANs. This investment will boost U.S. leadership in wireless technologies and their supply chains [15]. The important aspects of 6G policy are summarized in [16]. Additionally, governments can support decarbonization efforts by providing financial incentives for adopting green technologies like renewable energy production, battery storage, and electric vehicles. The U.S. Inflation Reduction Act of 2022 includes $370 billion to support these technologies [20]. U.S wireless leadership can be further advanced with proof of concepts, which would lead to quicker commercialization of technologies needed for sustainable 6G. The U.S. has set a goal to achieve net-zero emissions economy by 2050 [19].

A sustainable 6G system requires specifications that define the system architecture and design guidelines to enable implementations leading to improved energy efficiency and sustainability. This means that the specifications enable flexibility to achieve energy efficiency and optimizations. In general, the specifications should enable the possibility for modules to be turned off as much as possible when not being used and facilitate the most efficient forms of communication to be energy efficient when in use. In past generations, sustainability has often been seen as a secondary consideration. For 6G, specification design should take sustainability as a core constraint at all stages from the outset and specify frameworks via which performance can be traded off in favor of energy efficiency. In addition, for 6G, industry should further define metrics and evaluation methodologies for energy consumption and energy efficiency, along with frameworks enabling the exposure of this data.

The International Telecommunications Union (ITU) has developed a standard that provides ICT sector organizations guidance on setting net-zero targets and strategies to achieve decarbonization toward achieving net-zero emissions [9]. This standard defines net zero as a state reached by an organization when it has reduced its value chain emissions (scope 1, scope 2, and scope 3 emissions) following science-based pathways, with any remaining residual GHG emissions attributable to that organization being fully neutralized by like-for-like removals (e.g., permanent removals for fossil carbon emissions) exclusively claimed by that organization. ICT sector companies can adopt the guidance and strategies outlined in this standard. The ITU standard addresses emissions from a company's entire value chain and outlines the following criteria:

- Reach net-zero emissions no later than 2050; 2040 is recommended.
- Reduction of Scope 1, 2, and 3 emissions is the priority towards net-zero.[1]
- Adhere to robust social and environmental principles in deploying net-zero strategies.

Powering ICT infrastructure with energy from renewable sources is critical to achieving net-zero emissions. The ICT sector's carbon footprint can be reduced by 80% if all the electricity it consumed came from renewable energy sources [9]. Multiple strategies are available for ICT sector companies to source renewable energy, as shown in Figure 7, such as installing onsite renewable sources like solar panels and entering into large-scale renewable electricity power purchase agreements.

OPERATING ENERGY-EFFICIENT NETWORK

1. Multiple power saving features
2. Alternative energy supply
3. Consolidation and virtualization
4. Free cooling and location optimization

EFFICIENCY IN BUILDINGS AND SERVICES

5. Monitoring solutions for efficient buildings
6. Focus on energy conservation measures
7. Alternative mobility concepts
8. Video conferencing and audio conferencing

ALTERNATIVE ENERGY

9. Self-production of renewable energies
10. Purchasing renewable energy, the certificate of origin, and PPA
11. Energy supply innovation

APPLICATION OF THE CIRCULAR ECONOMY PRINCIPLES

12. Eco-design of products and services
13. Reuse of network equipment
14. Optimizing the life cycle and end-of-life of customer products and services
15. Selling repairable products

Figure 7: Decarbonization measures

The path to sustainability also necessitates pursuing efficiencies throughout the design and manufacturing process and in all parts of the supply chain. Just as it is important for specification development to take sustainability considerations into account from the outset, it is also critical for the design and implementations of the various hardware and software components in the network to do the same. It is crucial to minimize energy consumption when components are not being actively used to deliver connectivity and services as well as design for efficient operation when they are active. Manufacturing practices that minimize use of resources such as water need to be aggressively pursued. Awareness of the sustainability impact of all procurement throughout the supply chain needs to be increased in order to reach sustainability goals. Finally, the application of proper waste management and application of circular economy principles with consideration to the entire lifecycle of the ecosystem is necessary to ensure that the sustainability improvements are truly achieved.

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[1] Scope 1 emissions are direct GHG emissions from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion in boilers, furnaces and vehicles). Scope 2 emissions are indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling. Although scope 2 emissions physically occur at the facility where they are generated, they are accounted for in an organization's GHG inventory because they are a result of the organization's energy use. Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly affects in its value chain. Scope 3 emissions include all sources not within an organization's scope 1 and 2 boundary. Ref: [25] [26]

5 CONCLUSION

The ICT sector is crucially important in helping mankind address and overcome the challenges of climate change. It contributes a significant share to the global energy consumption, and, to a lesser extent, to the global GHG emissions. Moreover, ICT technologies are essential to the overall decarbonization of human activity as we strive to limit global temperature increase to less than 1.5° Celsius compared to pre-industrial levels. The ICT sector can furthermore implement meaningful changes toward the conservation of biodiversity by addressing land and water usage in its effort to become more sustainable.

For 6G systems to be truly sustainable, the environmental impacts must be minimized in regard to the entire life cycle of its components, from sourcing and mining to manufacturing and supply chain, operation, and maintenance, and ultimately to waste management. This can be achieved by transitioning manufacturing processes toward a circular economy with limited to no waste, reliant on the use of recycled or renewable components and raw and rare materials. To this end, the operation and maintenance of 6G systems must be highly optimized, enabled through novel component and radio technologies and advanced compute, network, and storage infrastructure with unprecedented levels of virtualization, software enablement, disaggregation, and observability. The cloud- and AI-native implementation of protocols and system architectures will enable sustainable operation of the 6G system itself; and possibly more importantly, usher in an era of massive connectivity and digital cooperation across all industries and verticals advancing their goals toward decarbonization and environmental sustainability. The technologies and research directions surveyed in this paper will ensure that next generation networks are sustainable across all domains, from end user and IoT devices to radio access and core networks, as well as data centers, that their supply chains are sustainable, and that the overall impact on the environment is reduced, across all industries and sectors, enabled by ICT technologies.

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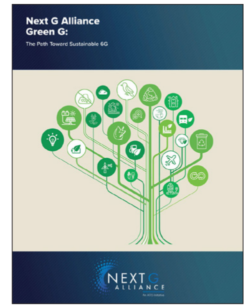

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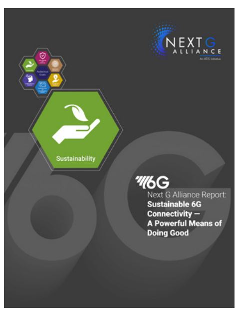

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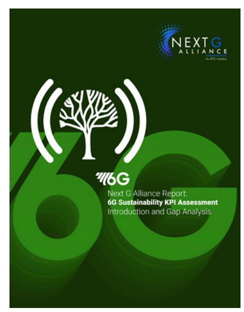

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