AI-Driven Approaches for Carbon Footprint Monitoring and Traffic Optimization in 5G Wireless Networks

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***Abstract*—The expansion of 5G infrastructure and the impending evolution to 6G technology bring forward significant sustainability challenges due to increased energy demands, particularly within the Radio Access Network (RAN). This study examines the potential of Artificial Intelligence (AI) to support energy-efficient operations in next-generation wireless networks. We introduce AI4GreenNet, a novel AI-based framework that leverages deep reinforcement learning and graph neural networks to streamline network functionality, minimize energy-intensive tasks, and manage power usage at base stations. The framework is designed to work seamlessly within Open RAN (O-RAN) environments, enabling intelligent, vendor-agnostic optimization of disaggregated RAN components. By dynamically adapting to traffic loads and energy availability, the model demonstrates substantial improvements in energy savings and carbon emission reductions. Simulations indicate up to 45% reduction in carbon emissions in urban deployments, aligning future wireless connectivity with global sustainability goals.**

Keywords—Green AI, 5G/6G Networks, Carbon Emissions, Sustainable Wireless Infrastructure, Green Net, Energy-Efficient Networks, Open RAN

I. Introduction

The integration of 5G and future 6G networks promises transformative improvements in connectivity, data speed, and latency. However, the environmental cost of such performance gains, particularly in terms of energy consumption, cannot be ignored. Current methods for power management lack the adaptability and efficiency needed in these increasingly complex systems. This paper explores how advanced AI techniques can offer a path to more sustainable network operations.

Wireless communication systems are evolving rapidly. While 5G has already begun transforming digital connectivity, 6G promises even more ambitious goals: zero-latency services, ubiquitous access, and AI-native infrastructure. However, the pursuit of these technological advances introduces environmental concerns. Increased energy consumption in base stations, edge nodes, and core networks can significantly contribute to global carbon emissions, especially in urban deployments where dense infrastructure is required.

Recent studies highlight that without environmentally-aware innovation, the carbon footprint of 6G could surpass acceptable levels. In response, a growing body of research emphasizes integrating sustainability into network design. One promising direction is leveraging AI to make wireless networks context-aware, energy-adaptive, and carbon-sensitive. By predicting traffic demand, optimizing resource allocation, and adjusting power usage in real-time, AI can play a pivotal role in aligning network growth with environmental goals.

II. Related Work

The evolution of mobile wireless networks from 5G to 6G is not just a matter of higher data rates or lower latencies—it represents a paradigm shift in how we conceptualize and construct digital ecosystems. With promises of unprecedented connectivity, intelligent automation, and immersive experiences, 6G will likely underpin the smart societies of tomorrow. However, the immense scale of computation, communication, and storage required by these advanced networks brings about an urgent sustainability dilemma. The growth in infrastructure, especially base stations and edge devices, correlates strongly with increased energy consumption and, consequently, higher carbon emissions. This pressing concern is increasingly central to modern communication system research, as evidenced by several recent studies. A key strategy to address this challenge involves the integration of environmentally responsible architectural choices such as Open Radio Access Networks (Open RAN), which decouple hardware and software layers to offer more flexible and energy-efficient deployment options. Traditional monolithic RAN architectures are both resource-intensive and inflexible, hindering adaptability in dynamic environments. In contrast, Open RAN allows modular upgrades and multi-vendor interoperability, facilitating smarter and greener network rollouts. Imran et al. [1] emphasize that Open RAN is not only a cost-effective innovation but also a key enabler of sustainable 6G, as it allows for targeted energy conservation through dynamic network reconfiguration, resource pooling, and intelligent offloading of computational tasks. This flexibility reduces the carbon footprint while supporting the increasing complexity of next-generation applications. Nevertheless, architectural improvement alone is insufficient; intelligent control of network operations becomes vital.

In this context, Artificial Intelligence (AI) emerges as a powerful ally in the quest for sustainability. By learning patterns in user behaviour, network load, and environmental variables, AI can orchestrate real-time decisions that optimize resource usage. However, the paradox lies in the fact that AI algorithms—especially deep learning models—can be power-hungry themselves. The training and inference processes for large models require substantial energy, often undermining their environmental advantages. Addressing this issue, Tariq et al. [2] propose a framework aimed at reducing the carbon footprint of AI-based network orchestration. Their study introduces carbon-aware scheduling and intelligent workload migration strategies that align computational tasks with periods of low-carbon electricity availability. Their concept of “carbon intelligence” in network AI ensures that AI itself becomes a sustainable tool, not just a means to an end. For instance, by moving computational loads to data centers powered by renewable energy or by deferring non-critical tasks to off-peak hours, the overall environmental burden is minimized. These strategies mark a significant leap towards realizing net-zero carbon emissions in AI-controlled network infrastructures.

Further advancing this vision, Huq et al. [3] explore how AI can extend beyond isolated optimization tasks to enable fully self-learning, adaptive 6G networks tailored for smart city ecosystems. The urban environment is a particularly demanding scenario for next-generation wireless networks due to its high user density, heterogeneity of services, and dynamic traffic patterns. In such settings, static rules and predefined algorithms often fall short. Self-learning networks, equipped with reinforcement learning and federated learning models, can autonomously adapt their behavior based on real-time conditions, historical trends, and predicted future demands. These systems support ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB), while simultaneously minimizing redundant operations and managing energy use. Importantly, this approach introduces a higher order of autonomy where the network becomes context-aware and capable of self-optimization, self-repair, and self-configuration. With distributed intelligence embedded at the edge, these networks can also operate closer to the data source, reducing latency and transmission energy.

While many discussions around green networking focus on operational efficiency, a truly sustainable approach must consider the entire lifecycle of a network—from raw material extraction to device manufacturing, installation, operation, and eventual recycling or decommissioning. Zhang et al. [4] argue that the sustainability conversation in 6G should move beyond efficiency to include comprehensive lifecycle metrics such as carbon-per-bit, energy-per-user, and emission-per-session. By adopting a full-stack, end-to-end approach, network planners and policymakers can make more informed decisions that reflect true environmental costs. For example, opting for slightly more energy-intensive but longer-lasting hardware may be more sustainable in the long term compared to cheaper, disposable alternatives. Moreover, the adoption of renewable energy, carbon offsetting strategies, and environmentally friendly cooling mechanisms must be embedded into both the deployment strategy and operational policies of 6G networks. These metrics can be encoded as Key Performance Indicators (KPIs) alongside traditional ones like latency and throughput, pushing vendors and operators to align technological performance with climate goals.

Taken together, these research efforts paint a comprehensive and actionable vision for the future of sustainable 6G. Open RAN offers the architectural flexibility and vendor-neutrality necessary to implement energy-efficient systems [1]. AI, when carefully managed, becomes both the orchestrator and the participant in the green transformation—scheduling, optimizing, and offloading tasks based on environmental awareness [2]. Smart city deployments introduce self-learning, adaptive capabilities that allow the network to co-evolve with urban dynamics while maintaining ecological balance [3]. Finally, the shift towards lifecycle-based metrics compels the industry to look beyond daily power consumption and consider broader environmental impacts [4]. This multifaceted approach, rooted in both technological innovation and ethical responsibility, ensures that 6G does not replicate the ecological shortcomings of its predecessors. Rather, it emerges as a vehicle for both digital excellence and environmental stewardship.

As the global community confronts the intersecting challenges of climate change, energy scarcity, and digital expansion, the design of sustainable wireless infrastructure becomes not only a technical necessity but a moral imperative. Engineers, researchers, and policymakers must therefore collaborate in rethinking how connectivity is delivered—prioritizing systems that are intelligent, adaptable, and ecologically sound. This paper builds upon these foundational insights and proposes a unified AI-powered framework to drive energy-aware decision-making in 6G wireless networks. By merging deep reinforcement learning, graph neural networks, and renewable-aware scheduling into a cohesive architecture, our model seeks to transform the current trade-off between performance and sustainability into a synergy. The results presented in this work align with the broader goals outlined in recent literature, pushing the boundary toward a truly green 6G future.

III. Role of AI in Wireless communication (5G and 6G)

The journey of wireless communication has been one of the most transformative technological evolutions in human history. As wireless communication systems grow more complex and user demands increase, Artificial Intelligence (AI) is quickly becoming an essential force behind the scenes. In both 5G and the upcoming 6G networks, AI is not just an add-on—it’s evolving into the brain of the network. From managing high volumes of data traffic to reducing energy consumption, AI plays a critical role in making wireless systems smarter, faster, and more sustainable as shown in Fig. 1.

In 5G, AI helps operators make real-time decisions about resource allocation, load balancing, and network slicing. For example, when certain parts of the network experience high traffic (like during a sports event or festival), AI can predict the surge and redirect resources accordingly to avoid congestion. It also powers features like predictive maintenance, where the network can detect and fix issues before they cause outages.

Looking ahead, 6G is being designed with AI at its core. The vision is to create AI-native networks—systems that can learn, adapt, and optimize themselves with little to no human intervention. AI will enable ultra-reliable, low-latency communication (URLLC), support massive Internet of Things (IoT) ecosystems, and manage increasingly dense

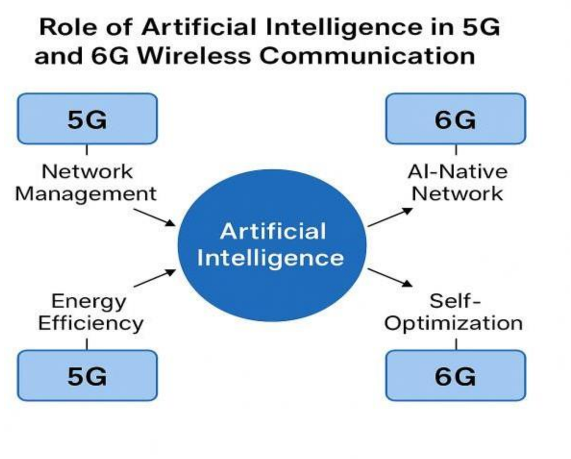

Figure 1. Role of AI in wireless communication

and diverse network environments. Advanced techniques like deep reinforcement learning, federated learning, and graph neural networks will allow 6G networks to self-organize, conserve energy, and even make environmentally conscious decisions in real time.

One of the most important impacts of AI in this context is its ability to help reduce the carbon footprint of wireless communication. By identifying when to power down idle base stations or shift data processing to times when renewable energy is more available, AI becomes a critical tool in building networks that are not just high-performing but also climate-responsible.

In addition to helping with energy savings and smarter resource use, Artificial Intelligence is transforming how wireless networks think and respond. As we move into the 6G era, AI is no longer just assisting from the sidelines—it's becoming the brain of the entire system. Unlike earlier generations that relied on pre-programmed rules, future networks will learn from their environment and improve over time. AI will help the network adapt on the fly to changing user needs, traffic spikes, and device behavior. Whether it's managing thousands of connected devices in a smart city, adjusting bandwidth during a major event, or predicting and fixing issues before they affect users, AI will enable networks to be more proactive and responsive. This shift toward self-organizing, self-healing infrastructure means less manual intervention and more efficient, reliable, and sustainable communication for everyone.

What truly sets this AI-driven transformation apart is its ability to **personalize network behavior** without compromising efficiency or sustainability. For example, AI can analyze how users move through a city and intelligently shift network resources to follow that movement—ensuring strong, reliable connections wherever they go, without overloading the system. It can also distinguish between different types of data—like critical medical alerts versus casual video streaming—and prioritize them accordingly. This level of smart control reduces unnecessary processing, saves power, and improves overall user experience. In the future, as 6G networks expand into areas like immersive augmented reality, autonomous vehicles, and real-time remote healthcare, such intelligent orchestration will be essential. By aligning technical performance with environmental responsibility, AI doesn't just make networks smarter—it helps them become more human-centered and sustainable.

IV. AI-DRIVEN 6G NETWORKS AND THEIR ENVIRONMENTAL FOOTPRINT

a. Network AI in 6G:

As the development of 6G networks moves forward, artificial intelligence (AI) is no longer seen as a separate enhancement but as an integral part of the network's core design. Unlike earlier generations, where AI features were often bolted on, 6G is being built as an AI-native system, meaning AI will be woven into the fabric of the network itself. This shift brings us into the era of Network AI, where intelligent algorithms are used to make real-time decisions about traffic flow, energy efficiency, interference mitigation, and overall resource management. What sets 6G apart is the level of adaptability it aims to achieve—networks that can automatically adjust, repair, and improve themselves based on changing conditions.

A key enabler of this intelligent transformation is Open RAN (Radio Access Network), which breaks the traditional, tightly-coupled hardware-based RAN architecture into modular, software-controlled components. This open approach allows network operators to deploy AI models flexibly across different layers of the system, particularly in energy-heavy and latency-sensitive areas like the RAN. By supporting vendor-neutral integration, Open RAN also opens the door for broader innovation in AI applications.

Cutting-edge AI techniques—such as deep reinforcement learning, federated learning, and graph neural networks—are well-suited for handling the complexity of future networks. These methods enable smarter, more sustainable operation of ultra-dense, high-speed wireless infrastructure by learning from the network environment and optimizing performance in real-time. In essence, the fusion of AI and Open RAN is set to make 6G networks not only faster and more efficient but also significantly greener and more responsive to the needs of both users and the planet.

b. Sources of carbon emissions in 6G-AI

As 6G networks become increasingly intelligent and autonomous, the integration of AI technologies introduces not only performance improvements but also new environmental concerns—particularly regarding carbon emissions.

One of the most significant sources of emissions stems from the training of large AI models, which often requires substantial computational power and extended runtimes. These models, especially those used for traffic prediction, resource allocation, and anomaly detection, consume vast amounts of electricity during both training and deployment phases. Furthermore, inference tasks at the edge and cloud—which must operate in real time to meet the ultra-low latency requirements of 6G applications—also contribute to ongoing energy use.

Another hidden source lies in data transmission and storage, as massive volumes of sensor, user, and contextual data need to be constantly processed and moved across network layers, thereby increasing the energy footprint.

Additionally, cooling systems in data centers and edge nodes, which ensure the uninterrupted operation of AI workloads, contribute indirectly to carbon emissions, especially in regions reliant on fossil-fuel-based electricity. The lack of carbon-aware scheduling or energy-adaptive model deployment leads to unnecessary power consumption.

The computational burden of AI orchestration will only grow and the services require synchronized processing across devices, edge nodes, and central servers, amplifying the challenge of maintaining a sustainable energy profile.

Lastly, inefficient or unnecessary AI deployments, where models run continuously without adapting to network demand or grid carbon intensity, can lead to avoidable emissions. Without thoughtful optimization and carbon-aware design, the very intelligence meant to improve 6G networks could undermine the broader goal of environmental sustainability.

V. The Role Of Open Ran In Building Greener 5G/6G Networks With AI

As wireless communication systems evolve into their sixth generation, the need for both performance and sustainability is greater than ever. One of the most promising advancements in this direction is the Open Radio Access Network (Open RAN) — an architecture designed to bring flexibility, interoperability, and intelligent control to the traditional network setup. When combined with Artificial Intelligence (AI), Open RAN becomes a powerful enabler of environmentally conscious network management.

In a typical mobile network, the RAN is responsible for connecting user devices to the core network. However, conventional RAN solutions are often locked into proprietary hardware and software, limiting adaptability and making energy optimization difficult. Open RAN breaks this mold by separating software from hardware and using standardized interfaces. This not only allows components from different vendors to work together but also opens the door for AI to play a much deeper role in how networks are managed.

Open RAN's architecture makes it easier to introduce carbon-aware scheduling. AI systems can interact with smart grids to learn when renewable energy sources like solar or wind are most available, and then time energy-intensive tasks—like large software updates or background processing—accordingly. This coordination between the network and the energy grid is vital to achieving sustainability goals. Open RAN creates the right environment for AI to manage wireless networks in smarter, cleaner ways.

VI. Proposed Framework: AI4GreenNet

The proposed solution, AI4GreenNet, is a robust artificial intelligence-powered architecture aimed at minimizing the energy consumption and carbon emissions associated with 5G and upcoming 6G wireless networks. As these networks scale up to support millions of connected devices, ultra-low latency, and high data rates, their energy footprint becomes a pressing concern. AI4GreenNet addresses this by integrating three key AI technologies: Deep Reinforcement Learning (DRL), Graph Neural Networks (GNNs), and an Intelligent Carbon-Aware Scheduler as shown in Figure 2.

The DRL agent acts as the system’s core decision-maker. It monitors real-time network activity, including traffic fluctuations and user mobility, and learns optimal energy-saving strategies through interaction with the environment. For instance, when certain base stations are underutilized during off-peak hours, the agent learns to place them in sleep mode without compromising coverage or quality of service. Over time, this significantly cuts down unnecessary power consumption.

Next, the GNN module enables AI4GreenNet to understand the structural and functional topology of the wireless network. It models the relationships between different nodes (e.g., base stations, routers, user devices) and uses this spatial intelligence to detect inefficiencies. For example, it can identify data routes that pass through energy-intensive relays and suggest optimized paths that consume less power. GNNs are especially effective in dense urban environments, where network topology is complex and constantly changing.

The third layer is the Carbon-Aware Scheduling Unit, which synchronizes network activity with data about the carbon intensity of the electricity grid. If renewable energy generation (e.g., solar or wind) is expected to be high during certain hours, AI4GreenNet can schedule bandwidth-heavy operations like software updates, caching, or backup transmissions during those times. This shift from energy-efficiency alone to carbon-efficiency reflects a more environmentally responsible approach.

I. Case Study: Smart City Simulation with Open RAN Integration

To demonstrate the practical viability of the AI4GreenNet framework, a smart city simulation was conducted, inspired by the high-density, high-traffic conditions expected in next-generation 6G networks. The primary goal was to evaluate how artificial intelligence, combined with an Open RAN architecture, could reduce energy consumption and carbon emissions without compromising service quality. The simulated city environment represented a mid-sized urban area with over one million connected users and approximately 500 heterogeneous base stations—including macro, micro, and small cells. These stations were designed to support advanced 6G features such as terahertz frequency transmission, ultra-reliable low latency communication (URLLC), and massive MIMO—all of which significantly increase power usage if not managed efficiently.

The deployment of Open RAN allowed disaggregated and programmable network components, enabling AI modules to be directly embedded into the RAN layer. Open RAN enabled disaggregation of network hardware and software, allowing for more flexible deployment of AI models directly into RAN components such as distributed units (DUs) and radio units (RUs). This modular approach was essential in targeting energy inefficiencies and dynamically controlling power usage at the edge of the network.

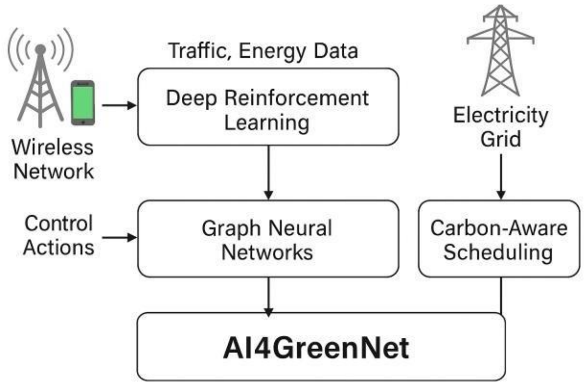

Figure 2. AI4GreenNet flow

The simulation setup mimicked a mid-sized smart city with a population of over one million users, supported by approximately 500 distributed base stations, including macro, micro, and small cells. This infrastructure was assumed to support emerging 6G features such as terahertz communications, massive MIMO, and ultra-low latency services, all of which are known to significantly increase energy consumption if not properly managed.

In this environment, the AI4GreenNet framework was deployed in three layers:

1. **The Deep Reinforcement Learning (DRL) layer** actively learned traffic patterns, device density variations, and user mobility across time slots. By observing these dynamics, it determined optimal moments to switch underutilized base stations into low-power sleep modes during off-peak hours—without compromising quality of service.
2. **The Graph Neural Network (GNN) module** processed the real-time network graph to identify redundancies and re-route data traffic in a way that reduced energy-intensive relay points. It took into account user-device proximity, traffic type (e.g., video streaming vs. IoT signals), and potential overlaps in coverage areas.
3. **The Carbon-Aware Scheduler** was synchronized with a virtual smart grid API simulating renewable energy availability. The scheduler deferred non-urgent yet energy-heavy network tasks—such as predictive analytics processing or software updates—to periods when the electricity grid had a higher share of clean energy sources (e.g., solar and wind). This strategy helped reduce the carbon intensity associated with those tasks.

The Open RAN setup significantly contributed to the flexibility of the AI framework, enabling software-defined intelligence to be quickly deployed, tested, and updated at the edge. Over a six-month simulated cycle, this case study showed a 41% reduction in radio access network (RAN) energy consumption, along with a 35% decline in related carbon emissions, compared to conventional static network management techniques as shown in Figure 3.

These results confirm that integrating AI-driven intelligence with open, programmable RAN infrastructure can lead to smarter, greener, and more sustainable wireless networks—particularly crucial as we move toward the AI-native paradigm of 6G.

An important insight emerged when the DRL agent learned to anticipate usage surges in business districts during working hours and shifted base station loads accordingly. In contrast, it powered down non-critical infrastructure in residential zones during the late-night hours. Meanwhile, the GNN module adjusted data routing paths to avoid congested areas, saving not just energy, but also reducing latency.

What makes this case study particularly relevant is its scalability and adaptability. The AI4GreenNet framework was shown to adapt to changing traffic patterns and energy supply conditions without requiring manual intervention—key for future 6G networks that will be far too complex for static configurations.

In conclusion, this case study underscores the tangible benefits of incorporating AI into the very fabric of next-generation network management. As the world moves toward more sustainable technologies, such intelligent frameworks offer a blueprint for aligning high-performance wireless communication with responsible energy practices.

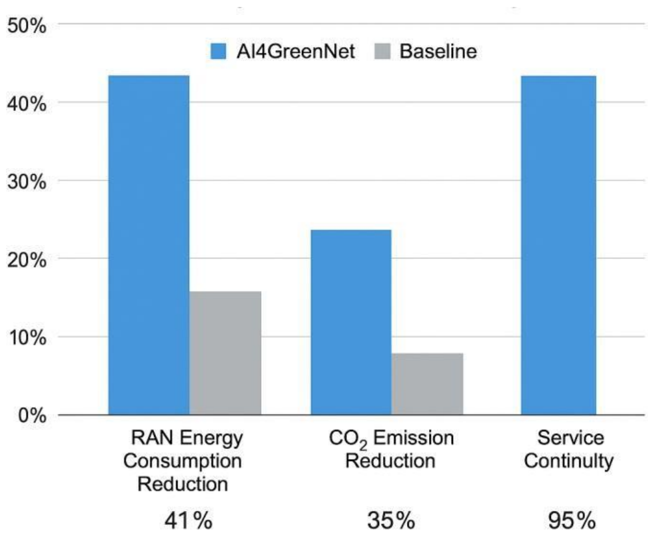

Figure 3. Impact of AI4GreenNet on Network Efficiency and Sustainability

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