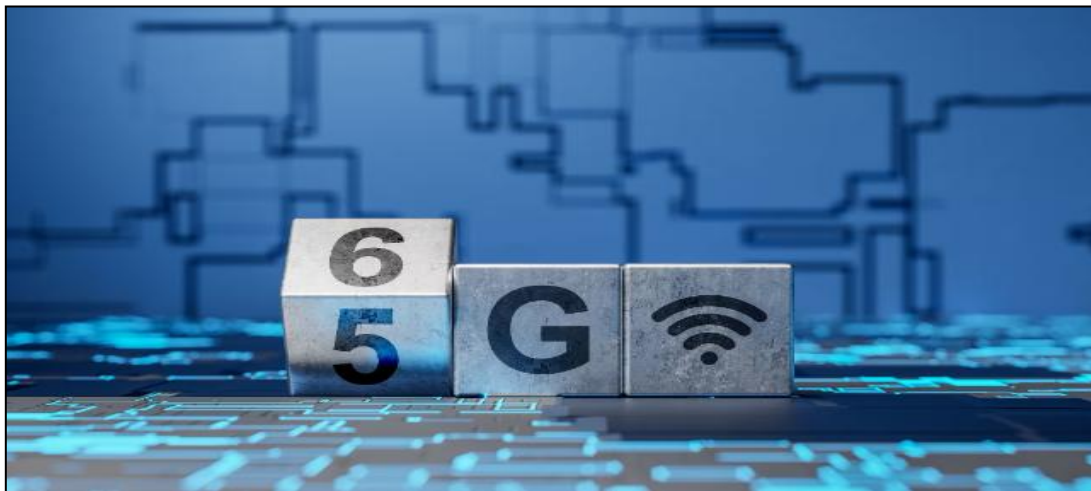




FACULTY OF ENGINEERING  
DEPARTMENT OF INFORMATION AND  
ELECTRONIC ENGINEERING

MSc Thesis

Exploring Sustainability in 5G and 6G Networks: A  
Systematic Literature Review



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Η έγκριση της διπλωματικής εργασίας από το Τμήμα Μηχανικών Πληροφορικής και Ηλεκτρονικών Συστημάτων του Διεθνούς Πανεπιστημίου της Ελλάδος, δεν υποδηλώνει απαραίτητως και αποδοχή των απόψεων του συγγραφέα, εκ μέρους του Τμήματος.

*"To my family, for their unwavering love and support."*

## Prologue

The selection of the topic of this MSc thesis, which focuses on the development of fifth-generation (5G) and sixth-generation (6G) networks, stems from my strong interest in cutting-edge technologies and the critical need to integrate the principles of sustainable development into technological evolution. The advent of 6G promises revolutionary changes, but at the same time it raises significant challenges, particularly with regard to energy consumption and environmental impacts. The connection of 6G technology with the United Nations Sustainable Goals (SDGs) was an additional strong motivation.

The preparation of the thesis was a particularly beneficial process. Through the systematic literature review, using the PRISMA methodology to analyze 120 scientific publications, I gained deeper understanding of current research trends and approached aimed at integrating sustainability principles into 5G and 6G networks. Moreover, this research offered me the opportunity to identify important research gaps and outline future directions, sharpening my analytical thinking and my ability to synthesize information.

## Abstract

Sustainability has become a central requirement for the evolution of mobile communications, as 5G deployments scale and 6G research introduces even more ambitious targets, heterogeneous architectures and AI-native operation. This thesis investigates how sustainability is addressed across 5G and 6G networks through a systematic literature review following the PRISMA methodology. A structured search was conducted across major scientific sources using title-restricted queries and predefined inclusion/exclusion criteria. From an initial pool of 447 records, a final dataset of 120 eligible studies was selected after screening and duplicate removal.

The review is guided by three research questions: (i) the current state of sustainability-focused research in 6G, (ii) the main approaches that enable sustainable development in wireless communications and (iii) the differences in sustainability goals, strategies and challenges between 5G and 6G. The findings indicate a clear shift from sustainability as an operational optimization target in 5G-primarily centered on energy efficiency-to a broader 6G agenda that includes carbon reduction, lifecycle impacts, circularity and sustainability by design. Key enabling directions include AI/ML-driven optimization and automation, virtualization and sustainable network management, edge-assisted architectures for application-aware efficiency, energy-efficient hardware and power systems and the integration of non-terrestrial platforms.

In addition, the literature increasingly distinguishes between “Sustainable 6G” (reducing the network’s own footprint) and “6G for Sustainability” (enabling sustainability benefits in other sectors). Overall, measurable progress depends on consistent sustainability metrics, comparable assessment methods and stronger alignment between research, industry practice and standardization.

**Keywords:** 5G, 6G, Sustainability, Sustainable 6G, 6G for Sustainability, Systematic Literature Review (SLR), PRISMA

# Διερεύνηση της Βιωσιμότητας στα Δίκτυα 5G και 6G: Μια Συστηματική Ανασκόπηση της Βιβλιογραφίας

Στέργιος Χατζόγλου

## Περίληψη

Η βιωσιμότητα έχει αναδειχθεί σε κεντρική απαίτηση για την εξέλιξη των κινητών επικοινωνιών, καθώς οι αναπτύξεις 5G κλιμακώνονται και η έρευνα για το 6G εισάγει ακόμη πιο φιλόδοξους στόχους, ετερογενείς αρχιτεκτονικές και λειτουργία εγγενώς βασισμένη στην τεχνητή νοημοσύνη (AI-native). Η παρούσα διπλωματική εργασία διερευνά πώς αντιμετωπίζεται η βιωσιμότητα στα δίκτυα 5G και 6G μέσω μιας συστηματικής βιβλιογραφικής ανασκόπησης, ακολουθώντας τη μεθοδολογία PRISMA. Πραγματοποιήθηκε δομημένη αναζήτηση σε βασικές επιστημονικές πηγές, με χρήση ερωτημάτων περιορισμένων στον τίτλο και προκαθορισμένων κριτηρίων ένταξης/αποκλεισμού. Από ένα αρχικό σύνολο 447 εγγραφών, μετά από έλεγχο και αφαίρεση διπλοτύπων, επιλέχθηκε ένα τελικό σύνολο δεδομένων 120 επιλέξιμων μελετών.

Η ανασκόπηση καθοδηγείται από τρία ερευνητικά ερωτήματα: (i) την τρέχουσα κατάσταση της έρευνας με επίκεντρο τη βιωσιμότητα στο 6G, (ii) τις κύριες προσεγγίσεις που επιτρέπουν τη βιώσιμη ανάπτυξη στις ασύρματες επικοινωνίες και (iii) τις διαφορές στους στόχους βιωσιμότητας, στις στρατηγικές και στις προκλήσεις μεταξύ 5G και 6G. Τα ευρήματα υποδεικνύουν μια σαφή μετατόπιση: από τη βιωσιμότητα ως στόχο λειτουργικής βελτιστοποίησης στο 5G—με κύριο επίκεντρο την ενεργειακή αποδοτικότητα—προς ένα ευρύτερο πλαίσιο στο 6G που περιλαμβάνει τη μείωση εκπομπών άνθρακα, τις επιπτώσεις σε όλο τον κύκλο ζωής, την κυκλικότητα και τη βιωσιμότητα «εξ αρχής σχεδιασμού» (sustainability by design). Βασικές κατευθύνσεις που λειτουργούν ως καταλύτες περιλαμβάνουν τη βελτιστοποίηση και τον αυτοματισμό με οδηγό την AI/ML, την εικονική υλοποίηση και τη βιώσιμη διαχείριση δικτύου, αρχιτεκτονικές με υποστήριξη από/στο άκρο (edge-assisted) για αποδοτικότητα με επίγνωση εφαρμογών, ενεργειακά αποδοτικό υλικό και συστήματα ισχύος, καθώς και την ενσωμάτωση μη-επίγειων πλατφορμών.

Επιπλέον, η βιβλιογραφία κάνει ολοένα και μεγαλύτερη την διάκριση μεταξύ του «Βιώσιμου 6G» (μείωση του ίδιου του αποτυπώματος του δικτύου) και του «6G για Βιωσιμότητα» (ενίσχυση της βιωσιμότητας σε άλλους τομείς). Συνολικά, η μετρήσιμη πρόοδος εξαρτάται από συνεπείς μετρικές βιωσιμότητας, συγκρίσιμες μεθόδους αξιολόγησης και ισχυρότερη ευθυγράμμιση μεταξύ έρευνας, πρακτικής της βιομηχανίας και τυποποίησης.

**Λέξεις-κλειδιά:** 5G, 6G, Βιωσιμότητα, Βιώσιμο 6G (Sustainable 6G), 6G για τη Βιωσιμότητα (6G for Sustainability); Συστηματική Βιβλιογραφική Ανασκόπηση (SLR), PRISMA

## Ευχαριστίες

Η παρούσα διπλωματική εργασία πραγματοποιήθηκε στα πλαίσια του Προγράμματος Μεταπτυχιακών Σπουδών «Ευφυείς Τεχνολογίες στο Διαδίκτυο» του Τμήματος Μηχανικών Πληροφορικής και Ηλεκτρονικών Συστημάτων του Διεθνούς Πανεπιστημίου της Ελλάδος.

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## Acronyms

6G-MN	6GMaritimeNetworks
A2G	Air-to-Ground
ACO	Ant-Colony Optimization
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
AR	Augmented Reality
APs	Access Points
ASICs	Applications-Specific Integrated Circuits
ASMs	Advanced Sleep Modes
AU	Access Units
AxC	Approximate Computing
BDA	Big Data Analytics
BER	Bit Error Rate
BS	Base Stations
BSOnet	Base Station Optimizer net
C-V2X	Cellular Vehicle-to-Everything
CAMD	Chanel-Aware Minimum Distance
CARS	Channel-Aware Random Selection
CCAM	Cooperative Connected and Automated Mobility
CEERP	Collaborative Energy-Efficient Routing Protocol
CMOS	Complementary Metal Oxide Semiconductor
CNNs	Convolutional Neural Networks
CRANs	Centralized Radio Access Networks
CREG	Centralized Renewable Energy Generation
CU	Central Units
C-V2X	Cellular-V2X
D2D	Device – to – Device
DAS	Distributed Antenna Systems
DQN	Deep Q-Network
DREG	Distributed Renewable Energy Generation

DRL	Deep Reinforcement Learning
DSRC	Dedicated Short Range Communications
DTNs	Digital Twin Networks
DTs	Digital Twins
E2E	End-to-End
EB	Energy Beamforming
EOA	Energy Consumption Optimization Algorithm
ECSTAR	Excellence Center of Space Technology and Research
EECV	Edge-based Efficiency Coordination for VANETs
EH	Energy Harvesting
ELAs	Experience Level Agreements
eMBB	enhanced Mobile Broadband
EMF	Electromagnetic Fields
EPR	Ext-‘ended Producer Responsibility
ESAP-NOMA	Energy Savings and Performance-aware NOMA
ESS	Energy Self-Sustainable
EVs	Electric Vehicles
FL	Federated Learning
GenAI	Generative AI
GEO	Geostationary Satellites
GNNs	Graph Neural Networks
GSC	Green Smart Cities
GSO	Glowworm Swarm Optimization
HAPS	High-Altitude Platform Stations
HetNets	Heterogeneous Networks
HEVC	High Efficiency Video Coding
HQDLM	Hybrid Quantum Deep Learning Model
IAB	Integrated Access and Backhaul
IADE	Improves Adaptive Differential Evolution algorithm
ICT	Information and Communication Technology
IIoT	Industrial Internet of Things
ILP	Integer Linear Programming
IoI	Internet of Intelligence

IoV	Internet of Vehicles
IoS	Internet of Space
IoT	Internet of Things
IRS	Intelligent Reflecting Surfaces
ISAC	Integrated Sensing and Communication
ITS	Intelligent Transport Systems
JPAPS	Joint Power Allocation and Phase Shift
KPI	Key Performance Indicator
KVIs	Key Value Indicators
LBS	Location-Based Services
LEO	Low Earth Orbit Satellites
LOS	Line-Of-Sight
LPWAN	Low-Power Wide-Area Network
MAC	Medium Access Control
MADS	Mesh Adaptive Direct Search
MARL	Multi-Agent Reinforcement Learning
MBS	Mobile Base Stations
MEC	Mobile Edge Computing
MEC	Multi-Access Edge Computing
MEET	Mobility-Enhanced Edge Intelligence
mmWave	Millimeter-Wave
mMIMO	massive Multiple-Input Multiple-Output
mMTC	massive Machine-Type Communications
ML	Machine Learning
MRL	Meta Reinforcement Learning
MOISA	Multi-Objective Improved Seagull Algorithm
MOOA	Multi-Objective Optimization Algorithm
mWET	massive Wireless Energy Transfer
MZM	Mach-Zahnder Modulator
NDT	Network Digital Twin
NFV	Network Function Virtualization
NLOS	Non-Line-Of-Sight
NOMA	Non-Orthogonal Multiple Access

NR	New Radio
NTN	Non-Terrestrial Networks
NWDAF	Network Data Analytics Function
O-RAN	Open Radio Access Networks
OTT	Over-The-Top
PBAs	Performance Boosted Areas
PDND	Power Distribution Network Design
PIFA	Planar Inverted-F Antenna
PML	Pervasive Multi-Level
PV	PhotoVoltaic
QoE	Quality of Experience
QoS	Quality of Service
RAAP-NOMA	Resource Allocation And Power-saving NOMA
RABS	Robotic Airborne Base Stations
RAN	Radio Access Network
RE	Renewable Energy
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RISC-V	Reduced Instruction Set Computer-V
RISE	Reconfigurable Intelligent and Sustainable Environments
RL	Reinforcement Learning
RoD	Resource-on-Demand
RoF	Radio-over-Fiber
ROI	Return On Investment
RNNs	Recurrent Neural Networks
RSSI	Received Signal Strength Indicator
SAE	Society of Automotive Engineers
SAT	Social Acceptance of Technology
SCBSs	Small Cell Base Stations
SDGs	Sustainable Development Goals
SDN	Software-Defined Networking
S-IoT	Sustainable IoT
SFI2	Slicing Future Internet Infrastructures

SLA	Service Level Agreement
SMBS	Super Macro Base Stations
SNM	Sustainable Network Management
SNR	Signal-to-Noise Ratio
SSO	Sustainable Service-Oriented
SWIPT	Simultaneous Wireless Information and Power Transfer
TCO	Total Cost of Ownership
THz	Terahertz
TIS	Technological Innovation System
UAPBs	Unmanned Aerial Power Beacons
UAVs	Unmanned Aerial Vehicles
UD CF	Ultra-Dense Cell-Free
UE	User Equipment
umMTC	ubiquitous massive Machine Type Communications
UN	United Nations
URLLC	Ultra-Reliable Low-Latency Communications
V2Fog	Vehicle-to-Fog
V2G	Vehicle-to-Grid
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANETs	Vehicular Ad Hoc Networks
VA-NSGA-II	Virtual Force and Annealing-Non-dominated Sorting Genetic Algorithm II
VEC	Vehicular Edge Computing
VLC	Visual Light Communication
VR	Virtual Reality
VVC	Versatile Video Coding
WEaaS	Wireless Environment as a Service
WET	Wireless Energy Transfer
WIEP	Wireless Energy Provision
WIT	Wireless Information Transfer

WPT	Wireless Power Transfer
WRSN	Wireless Rechargeable Sensor Network
XR	Extended Reality
ZTM	Zero-Touch Management



## Chapter 1: Introduction

### 1.1 Introduction to the 6G Era and Sustainable Development

Wireless communication technologies have developed rapidly and have become the backbone of our modern world. Mobile connectivity reinforces and supports economic growth, digital public services, industrial automation and helps people participate fully in society. On the other side, as mobile traffic continuously grow, the densification of network infrastructures and our heavy use of high-power digital services is bringing up some serious questions to tackle about energy use and environmental impact. For this reason, sustainability is increasingly seen as a core design requirement for the communication systems of the next generation and not a secondary consideration [1], [2].

In this context, 6G is for everyone, the next major step beyond 5G which is expected to enable not only faster connectivity to the Internet but also new types of services and create a super-connected ecosystem that brings together communication, computing and sensing all in one [3]. Many studies discuss about 6G as this really smart, adaptable platform that can handle some seriously heavy-duty applications while also increasing connectivity and automation. However, if we are not careful, all these exciting advancements could increase energy and resource demands. This is the main reason why it is crucial to weave sustainability into the whole 6G research and design process from the start point. We have to ensure that technological progress will be aligned with our long-term responsibility to the environment.

One really practical way to link technology and sustainability with a broader societal impact is through the United Nations (UN) Sustainable Development Goals (SDGs). When someone dives into the 6G literature that focuses on these goals, it becomes clear that sustainability is not just a thing, but it is actually a mix of environmental, economic and social aspects. Thus, if we build communication infrastructures the right way, they can support SDG-related outcomes [4], [5]. In this way, 6G is not only expected to reduce its own footprint but also to enable sustainability improvements across multiple areas, like smart cities, industry, health and large-scale monitoring systems. Table I shows a brief overview of the 17 SDGs [6].

Table I A brief overview of the 17 SDGs[6]

SDG Goal	Brief Overview
Goal 1 – No Poverty	End poverty in all its forms all over the world
Goal 2 – No Hunger	End hunger. Achieve food security and promote sustainable agriculture
Goal 3 – Good Health	Promote well-being for all, at all ages
Goal 4 – Quality Education	Ensure inclusive and equitable quality education for all
Goal 5 – Gender Equality	Achieve gender equality and ensure women and girls inclusion and empowerment all over the world
Goal 6 – Clean Water and Sanitation	Secure availability, sanitation and sustainable management of water to all
Goal 7 – Renewable Energy	Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 8 – Good Jobs and Economic Growth	Promote sustained and inclusive economic growth, full and productive employment and decent work for all
Goal 9 – Innovation and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
Goal 10 – Reduced Inequalities	Reduce inequalities within and among countries

SDG Goal	Brief Overview
Goal 11 – Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 12 – Responsible Consumption	Ensure sustainable consumption and production patterns
Goal 13 – Climate Action	Take urgent action to combat climate change and its impacts
Goal 14 – Life Below Water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
Goal 15 – Life On Land	Protect, restore and promote sustainable use of natural resources, sustainably manage forests, combat desertification and halt and reverse land degradation and halt biodiversity loss
Goal 16 – Peace and Justice	Foster inclusive and peaceful societies, ensure justice for all and establish effective, accountable institutions at all levels for sustainable development
Goal 17 – Partnerships for the Goals	Enhance implementation mechanisms and rejuvenate the Global Partnership for Sustainable Development

It is very important that many researches show a lot of interesting about how sustainability plays a big role in the 6G era. Thus, there are two sides, firstly the “Sustainable 6G” which focuses on reducing the environmental impact of the network itself, like energy usage, carbon footprints and all those lifecycle impacts. Secondly, there is the “6G for Sustainability” that keeps an eye on how services powered by 6G can actually help other sectors achieve their sustainability goals [7]. These two different prospective provide a clear foundation for what will analyzed in depth later in Chapter 6.

When we dive deeper into 6G, in comparison with 5G, it is clear that sustainability is not just an add-on, but it is a fundamental requirement for the whole system. This shift motivates a focused comparison of how sustainability goals, strategies and even the trade-offs evolve from 5G to 6G, which one of the main issues that it is been discussed in this thesis.

## 1.2 Policy Initiatives and Global Cooperation for Sustainable 6G

Sustainable 6G is not only a technical research agenda but it goes much more beyond. It is also influenced by policy priorities, funding programs and of course collaboration on a global scale. It is also very important to be multi-disciplinary 6G discussions around 6G and more specifically about sustainability-related decisions are influenced by the broader ecosystem, including regulations, business goals and what society expects in the long run [2]. Thus, sustainability is not just something to deal with in isolation with technical fixes, but it needs coordinated action across industry, academia and policymakers. This action is crucial if we want to make real progress as a team.

When we look at the research ecosystem, it is clear that collaborative programs and projects are really putting a spotlight on sustainability and societal impact. For instance, project-oriented deliverables highlight that future 6G technologies should be aligned with what society actually needs and keep sustainability into consideration. It is not just achieving certain technical benchmarks. It is about integrating sustainability into the research direction itself [8]. In addition, there are architecture-focused studies which argue that sustainability and security considerations should be integrated into end-to-end process. This really drives into the point that sustainability is not just a checkbox but it requires a coordinated approach to design and governance across the board. It is a big issue and if we are going to address it, it is required to have everyone on the same side [3].

At a broader level, several studies highlight that sustainability goals require common objectives and comparable assessment methods to support meaningful collaboration between regions and stakeholders. Without alignment on sustainability objectives, metrics and methods of reports, there is a

real risk that sustainability is difficult to be real and put into practice [1], [2]. Therefore, this global cooperation is crucial and the key, not just for driving innovation forward but also for setting clear, measurable expectations for sustainability as step into the 6G era.

### 1.3 The Role of Standardization Organizations

Standardization organizations are also crucial for turning research ideas into technologies that we can actually use. These organizations incorporate all those sustainability requirements into standards, so all suppliers and operators must follow them when making design decisions. In this way, sustainability is treated as a fundamental parameter and not an optional add-on. There are many studies about roadmaps for achieving sustainable 6G which highlight that standardization is crucial for transforming sustainability goals into technical specifications, evaluation criteria and implementation baselines [9].

One of the huge challenges that we have to overcome is that sustainability is really complex. It is not only just about being energy efficient or being aware of carbon footprints. It also involves looking at lifecycle impacts and also system-level issues like how management works and how different vendors can work together. Thus, standardization is a consistent way to measure our sustainability goals and create methods that we can all compare fairly. Otherwise, without these harmonized frameworks, sustainability targets may end up being pretty vague and difficult to verify across implementations [9], [2].

As we move from 5G to 6G, we are not just upgrading, we are opening the door to a whole new world of capabilities. Smarter systems and more complex designs are introduced, which sounds very interesting, but if we do not manage this transition carefully, we might end up with higher computing and energy demands. Standardization can support sustainable innovation by promoting energy-conscious design and establishing guidelines for balancing system performance and energy use. Furthermore, it allows for better coordination between the different parts of the network. Thus, it is like a delicate balance between progress and resources, but with the right approach we can achieve it [1].

### 1.4 Main Purpose of Thesis

This thesis aims to study how sustainability has been determined and implemented in the transition from 5G to 6G. Through a systematic literature review of existing published literature on the topic, this research seeks to provide an organized overview of the current state of 6G research with a focus on sustainability. Additionally, the results will give a comprehensive comparison of the different sustainability paradigms of both 5G and 6G technologies, highlighting the nature of trade-offs and new challenges that comes up by ambitious 6G goals [10].

The rest of this thesis is structured as follows. Chapter 2 discusses enabling technologies that have been described as fundamental to creating sustainable 5G/6G technology, including green AI/ML, Sustainable Network Management (SNM), smart mobility and Vehicle-to-Everything (V2X) systems, smart-city communication technologies, energy-efficient hardware - power transfer and in the end non-terrestrial platforms. After that the research protocol, search strategy analysis and study eligibility criteria are defined in Chapter 3, as well as the research questions which guide this study. Chapter 4 is a comparative literature review of the sustainability of 5G and 6G describes how different objectives and challenges of each generation evolve. Chapter 5 describes mapping of enabling technology to sustainability mechanisms, discusses how each technology area contributes toward reducing energy/carbon footprints and identifies potential concepts for future sustainability-aware services.

## Chapter 1

Moreover, the two approaches of “Sustainable 6G” and “6G for Sustainability” are discussed in Chapter 6. Finally, Chapter 7 summarizes the conclusions and findings of the previous chapters identifying future research gaps and future strategic direction.

## Chapter 2: Enabling Technologies

### 2.1 AI/ML for Green Communications

#### 2.1.1 Introduction

As we move towards the 6G era, it is becoming clear that the integration of Artificial Intelligence (AI) and Machine Learning (ML) is not just an option, but one of the key technologies that will take networks in the next level. Nowadays, networks are characterized as “AI-native”, which indicates that intelligence is a fundamental part of the system’s design and operation. The growing demand for broadband services with extremely high data transmission speeds and huge capacity, combined with the need to reduce energy consumption and environment footprint, are some of the reasons why AI is a central pillar for the design of future networks. The rise of the Internet of Things (IoT) and the integration of new demanding applications like augmented and virtual reality are creating a dynamic ecosystem with higher needs for computational resources. AI and ML are going to play a centric role in managing these challenges.

ML is also being included in new architectures like Service-Oriented RAN Slicing. This advanced setup takes one physical RAN and splits it into several virtual sections, the “slices” and operates independently. This approach allows every each of these sections, to be adapted to the specific requirements of a particular service or application. For example, the network can create a dedicated slice for a low latency application such as tele-surgery, another slice for high - throughput video streaming and so on.

#### 2.1.2 Historical Evolution

The use of AI and ML in communication networks signifies a big shift from the rule-based systems to something much smarter. The first time that ML appeared was in the 4G years, when the amount of data increased massively and the main task of ML appearance was the anomaly detection and spectrum management. In the fifth - generation of wireless communications, new AI techniques were integrated especially at the RAN and network slicing levels. In the near future, 6G is on the horizon and it takes AI to the next level, where AI-native architectures can make decisions based on real - time data. In the 6G era, network metrics will be monitored continuously, AI algorithms can predict changes and take automatically important decisions about a considerable amount of parameters, improving themselves and learn constantly, making the manual interventions needless.

#### 2.1.3 Basic AI/ML Techniques and Methods

AI and ML are making their marks in every part of today’s wireless networks. At the physical (PHY) layer for example, ML algorithms are busy analyzing the radio channel conditions, improve signal quality and automatically adjust parameters such as modulation schemes and beamforming directions. This means that the network can quickly adapt to any changes in the radio environment, keeping communication reliable [11], [12].

At the Medium Access Control (MAC) and Radio Access Network (RAN) layers, Reinforcement Learning (RL) and Deep Reinforcement Learning (DRL) techniques are applied to optimize the use of the available resources[10]. These techniques help with things like packet scheduling, ensuring that

they need to go most efficiently and improve how we manage interference and make transitions smoother for users moving between different cells. Now if we focus on the core network, the function Network Data Analytics Function (NWDAF), which is designed by 3GPP, integrates AI/ML to predict traffic patterns and support automatic policy decisions. Thus, the network can react automatically, without manual configuration. Finally, at the service layer, AI/ML is used to predict technical failures, detect anomalies in an early stage and provide personalized services. Furthermore, these technologies support continuous monitoring and improve the Quality of Experience (QoE) for end users [13].

Techniques like RL, Unsupervised Learning and DRL help networks adjust automatically to changing conditions. This feature is very important, especially as we move into 6G era, where, there are so many different applications that need more autonomy and flexibility than ever before. Another crucial part for AI/ML is Federated Learning (FL), which is a technique that lets ML models get trained on various devices without having to centralize all the data. This method reduces the need for extra data transfer, protects privacy and support flexibility.

Figure 1 shows how this FL-based architecture makes a difference, allowing for collaborative model training across various devices and edge servers, while keeping data decentralized. This setup not only reduces energy use across the network, but also boosts sustainability.

Furthermore, another ML technique with a huge advancement is the DRL, which is a very interesting technique that helps networks get better at things like figuring out where to place base station, routing performance and QoS, taking into account multiple and often competing factors. In addition to traditional techniques, there are exciting progress in techniques like Graph Neural Networks (GNNs), which analyze the intricate relationships and topology among network nodes, providing more accurate solutions for handover and interference management. Another notable technique that will help in coordination of multiple nodes and transform devices to smart agents is the Multi-Agent Reinforcement Learning (MARL). This development model of RL use multiple smart agents, that are acting together cooperative or competitive for a common purpose, such as the spectrum management.

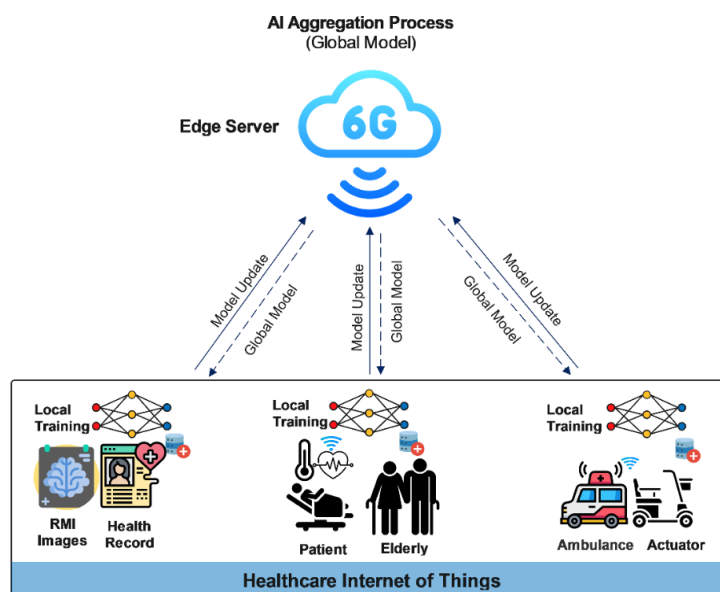


Figure 1 FL architectures in 6G IIoT systems showing distributed AI training at edge devices supporting green communications [10]

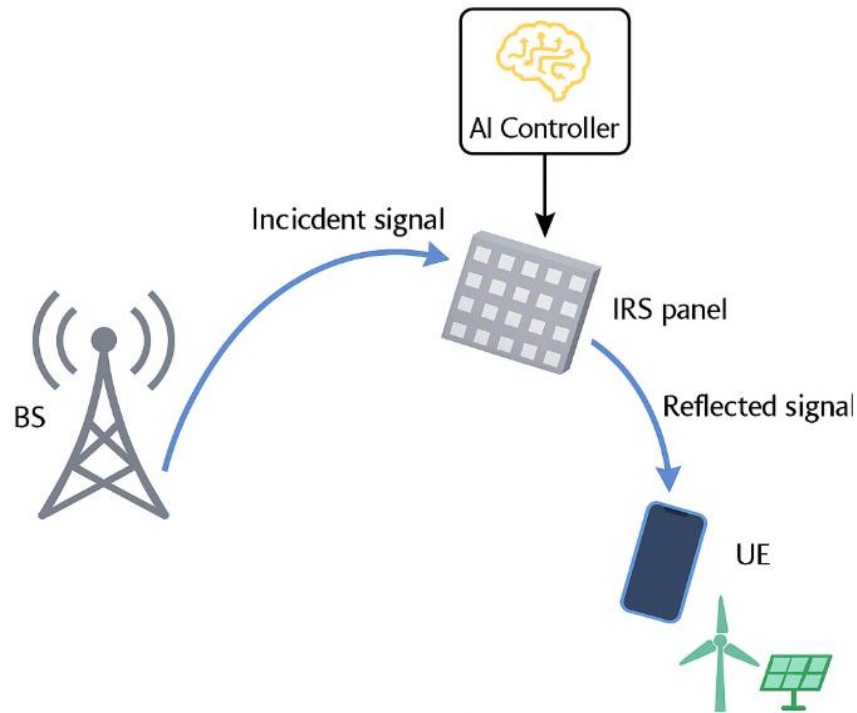


Figure 2 Application of IRS in sustainable 6G systems

The combination of AI and ML with other modern technologies is expected to change the game in 5G and especially 6G networks. AI and ML are already playing a crucial role in some of the network's basic functions. However, their full potential will be unlocked when we will start mixing in new strategies that completely rethink how we design wireless communication. One really exciting development to watch is the use of the Intelligent Reflecting Surfaces (IRS). These surfaces are made from metamaterials and, in conjunction with AI algorithms, can actually adjust the wireless channel on the fly. The dynamic reconfiguration helps to make better use of the channels and boost the whole system. Figure 2 depicts how we can actually position IRS panels in 6G networks in a way to improve coverage while also reducing transmission power. This is possible because of some AI-assisted beam optimization techniques. Moreover, it can be more eco-friendly if it is combined with renewable sources of energy.

#### 2.1.4 Challenges

Although there are many opportunities, the integration of AI/ML into networks is followed by many challenges as well. DL algorithms need massive amounts of data that is crucial to develop efficient methods for data collection, storage and processing. Moreover, training the ML models requires high data transfer speeds, a fact that makes necessary the appropriate hardware like GPUs and NPUs. Additionally, understanding the decisions made by AI algorithms is very important for “winning” the trust of providers and users in autonomous networks.

Therefore, AI/ML is not just another supporting technology that will help in the practical application of a technology, but a key enabler which will become central pillar to 6G network operations. Using predictions, automation and distributed intelligent, the main goal is to create faster, more reliable and more responsible networks, in dynamic environments.

## 2.2 Sustainable Network Management

### 2.2.1 Introduction

SNM is very important as we make the transition from 5G to 6G. It faces the obstacle of managing these really complex wireless networks while simultaneously trying to reduce energy use and keep things eco-friendly. The demand for data is increased rapidly, as there are incredible applications, like Augmented and Virtual Reality (AR/VR), and automation in industry and IoT. To overcome these obstacles, networks need to be able to adjust their resources, monitor their energy consumption and stay stable even if the things get a bit chaotic.

### 2.2.2 Foundational Principles and Functions

When we talk about SNM, we mainly mean the combination of automation, optimizing resources and being mindful of energy use to manage communication systems. Unlike traditional ways of management in networks, that they depend on static setups and manual work, SNM is stepping into the future with the use of AI and ML to manage the network orchestration. It helps networks to predict traffic flows better, adjust resources with flexibility and boost the performance while operational costs are reducing. In the case of 5G, SNM is reducing energy use in BSs and balancing the load more effectively. Looking towards into 6G, SNM is about making a real commitment to sustainability and connecting the world in a more holistic way [14].

### 2.2.3 Network Slicing and Virtualization

One of the hottest topics and most widely discussed approaches to sustainable management is Network Slicing. This approach allows us to create multiple logical networks on top of a shared physical infrastructure. Each of these networks can be tailored to meet specific needs. For instance, as lice designed for massive IoT devices has the ability to keep energy use low and also make sure that it can scale up efficiently. From the other side, there is a slice that it is meant for Ultra-Reliable Low Latency Communication (URLLC), focusing on reliability and speed. The best part of Network Slicing is how it can smartly allocate resources, helping to improve energy efficiency and promote more sustainable operations. Furthermore, virtualization technologies like Network Function Virtualization (NFV) and Software-Defined Networking (SDN) are key players in this whole setup, because they allow us to separate services from the physical hardware and enable scales things up or down as needed. The work in [15] proposed that the SFI<sup>2</sup> reference architecture aimed at energy-efficient slicing, showing the integration of ML modules designed to fine-tune resource allocation during various slicing phases. The AI-driven orchestration framework continuously monitors traffic and adapts slice configurations in real time. This approach helps make network operations more sustainable.

### 2.2.4 Open RAN and Collaborative Management

A key piece in the puzzle of SNM is the rise of Open Radio Access Networks (O-RAN). One of the most important things in O-RAN is that embraces openness and modularity. It lets operators mix and match hardware and software from various suppliers. This approach increases vendors' flexibility while it enables the development of energy efficient solutions. AI and ML are often combined with O-RAN to improve traffic management and balance energy loads more effectively. Several recent studies focus on how O-RAN can really help with sustainability goals by enabling intelligent load balancing, energy control that adapts to needs and better resource allocation. These approaches can tweak their operations based on what users actually need at any moment and manage the energy use while keep

service in same high quality. Through this combination of openness and intelligence, O-RAN finds a way to connect technological performance and environmental responsibility.

### **2.2.5 Energy-Efficient Resource Management**

Managing network resources efficiently is a big obstacle that we have to overcome when it comes to making wireless systems more sustainable. As mobile networks expand and get more complicated, energy consumption is increased making researchers searching for various strategies mixing advanced optimization techniques, AI-driven prediction models and Renewable Energy (RE) sources. Some recent studies have proposed energy management systems that have the ability to predict changes in traffic patterns fine-tune power usage and coordinate renewable sources like solar and wind to keep BSs operating. Furthermore, there are a lot of methods, like adaptive power control and dynamic sleep modes that have come in the game to help reducing energy waste. Although here are various approaches, all they seem to have the same goal: to make network operations more efficient, flexible and eco-friendly, which is crucial step for shaping the future of 6G infrastructures.

### **2.2.6 End-to-End Performance and QoE Management**

However, SNM is not just reducing power usage, but it is also keeping performance and QoE high for users. End-to-End (E2E) performance management combines energy efficiency with user satisfaction, making sure that improvements in sustainability do not sacrifice the Quality of Service (QoS).

There are a lot of studies in 5G and 6G days that explores AI and ML frameworks that can monitor network conditions in real-time. They can even predict when performance might suffer, before it actually bothers users. These smart systems help networks adjust their resources and power levels in real time, which means that they can operate smoothly while also being energy-efficient. AI/ML techniques are widely applied to improve E2E performance and QoE management. For example, video streaming applications need constant monitoring of data rates and control over bit rate. ML models are able to predict traffic demand and adjust resources in advance to prevent a decrease in quality. Similarly, applications such as VR and AR are highly sensitive to latency. ML algorithms can predict network congestion and changing routing paths in real time to keep steady an uninterrupted user experience.

Moreover, there are also AI-powered QoE prediction frameworks that play a key role in detecting faults and anomalies. ML models analyze patterns in network and user behavior, so they can change corrective actions before users realize the service disruption. Thus, SNM requires combination of QoE monitoring with energy efficient operations. For example, BSs can switch to low-power modes during times of low demand, with the help of algorithms that confirm that this change will not harm the user experience.

Thus, in this way, E2E management integrates sustainability into the network operation, finding the sweet spot between technical performances and being eco-friendly, promoting networks that are not only faster and smarter but also greener and more responsible.

### **2.2.7 Challenges and Limitations**

Despite SNM has its benefits, presents also a few of challenges. First of all, the complexity of the network architecture makes management and orchestration difficult topics. Another trouble issue is the interoperability, which comes into the surface because of the co-existence of components of different

generations like 4G, 5G and 6G elements. Last but not least, the most important obstacle that we have to overcome is to find a way to make things more efficient without compromising the QoS.

In conclusion, SNM combines technology with environment responsibility. SNM uses advances technologies such as AI, ML, network slicing, virtualization, O-RAN and smart resource allocation to reduce energy use while still keeping service quality high. Thus if we want to find ways to address the challenges above, we have to understand how 6G can help us build a more sustainable and intelligent communication system.

## **2.3 Smart Mobility – V2X**

### **2.3.1 Introduction**

Smart Mobility has become a huge focus in the world of wireless communications these days, especially with the rise of 5G and the upcoming 6G technology that powers V2X systems. V2X is covers a bunch of different communication types, like Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N) and Vehicle-to-Pedestrian (V2P). All of these play a crucial role in shaping Intelligent Transport Systems (ITS), driving autonomous vehicles, connecting electric cars and enhancing smart urban mobility.

The ability of vehicles to communicate and make real-time decisions depends on the technical foundation built by 5G and 6G networks. This is mostly achieved because of technologies like URLLC, enhanced Mobile Broadband (eMBB) and massive Machine-Type Communications (mMTC) [16].

### **2.3.2 Foundational Principles of V2X Communication**

The basic idea of V2X is built on the principles of Vehicular Ad Hoc Networks (VANETs) and it goes further by connecting vehicles not only to each other but also to infrastructure, pedestrians and various networks. This kind of connection allows vehicles to exchange real-time information about traffic, potential hazards and road conditions. This leads to a safer and more efficient travel.

Technologies like Cellular-V2X (C-V2X) and IEEE 802.11p, which relies on Dedicated Short Range Communications (DSRC), play a crucial role in making V2X real. Furthermore, a newer concept has been introduced as a bigger ecosystem, the Internet of Vehicles (IoV), which brings together connectivity, data management and control among vehicles, infrastructures and users. It is exciting the fact how all these elements work together [17].

V2X systems are typically categorized by their main function. One important category is safety applications which include collision avoidance, cooperative adaptive cruise control and vehicle platooning. These features allow vehicles to travel in close proximity to each other safely. All the above with the help of some efficiency services, like traffic flow optimization, smart parking and eco-routing can manage to reduce energy use that is crucial for the future networks. Furthermore, there are many applications that provide in users real-time streaming of traffic flow and make the driving experience smoother and more enjoyable. In addition to this, V2X communication can provide some benefits to electric vehicles, like smart charging systems and Vehicle-to-Grid (V2G) integration [18].

### 2.3.3 Basic Techniques and Methods

When we talk about Smart Mobility, there is a variety of techniques that support it. One of the most important methods is Network Slicing and QoS management. Thanks to 5G and the crucial features of Network Slicing that allow the divide of network's physical resources into virtual slices, makes possible to allocate resources for critical services like remote driving, collision avoidance, get the resources they need when they really need them. This capability is a game changer and make sure that everything will run smoothly and efficiently [16].

Another important piece of the Smart Mobility puzzle is the Multi-Access Edge Computing (MEC), which allows real-time analysis of data by bringing computation closer to where it is needed, in user. This is essential for applications that need quick responses (low-latency), like optimizing traffic signals and remote driving [19]. With the above setup, the system can easily handle the huge amount of data that generated by all those connected vehicles in the road. Furthermore, AI and ML are playing central role in Smart Mobility because they help create predictive models to predict traffic flow, improve routing and manage resources dynamically. Moreover, DRL and FL improve decision-making in autonomous vehicles and also protect data privacy in the same time [20].

One more important approach that we have to explore in Smart Mobility is how V2X technology works in combination with electric vehicles, because it opens exciting possibilities for managing energy thanks to smart charging and V2G services. This capability makes vehicles behaves mobile energy storage units connecting mobility with smart grid systems [18]. In addition to the above, the lots of sensors, like radars can cooperative with V2X making driving experience safer and more reliable.

As we explore the 6Gera, new techniques have been appeared, like Terahertz (THz) frequencies that offer ultra high capacity connections, Reconfigurable Intelligent Surface (RIS) that improve propagation and Integrated Sensing and Communication (ISAC) that combine communication and radar. All these innovations, along with many others are crucial for making sure smart mobility is efficient and also safer, especially in ever-changing environments [21].

### 2.3.4 Challenges

Despite the significant progress, Smart Mobility has also many obstacles that we have to overcome. The most pressing issue is the fact that there are huge demand for low latency and high reliability. Safety-critical applications, like collision avoidance and remote driving demand end-to-end latency lower than 1ms, which is very hard to be achieved, especially in urban areas [22]. In addition to the above, interoperability and standardization are still issues that we have not solved, as different technologies like DSRC, C-V2X and many other 6G upcoming technologies co-existed.

Furthermore, there are two other critical issues that we have overcome yet. These are security and privacy. The huge amount of data that shared between vehicles, infrastructures and networks makes us exposed to cyberattacks, including denial-of-service attacks and spoofing a critical risk. Moreover, as we step into the 6G era, we are going to see some new use cases like smart intersections without traffic lights, large vehicles working together in platoons and green driving assistance will become routine in the near future [23]. Beyond the above, there is still a lot of worry among people when we talk about autonomous driving and connected vehicles. All these concerns are critical for the future of transportation.

### 2.3.5 Future Trends

As previously mentioned, the emergence of 6G is expected to change Smart Mobility and take sustainability to a new level. 6G technology aims to achieve climate-neutral mobility while simultaneously support the UN SDGs and the European Green Deal targets [23]. Furthermore, Smart Mobility is going to rely on intelligence at the network edge, as AI-driven digital twins and distributed learning methods like FL which will help us predict and adapt how we manage mobility, making things safer and more efficient. It is really we have a personal assistant for our transport needs [20].

In conclusion, Smart Mobility is really changing the game of how we think about transportation, about the connecting vehicles, infrastructures, networks and users into a single system. With 5G technologies like eMBB and Network Slicing, we are looking at real-time communication and many use cases are possible, like autonomous and remote driving, vehicle platooning and smart parking. The 6<sup>th</sup> generation of wireless communication will bring new technologies like THz communication and RIS, which will drive the development of Smart Mobility forward. Figure 3 shows the use case of smart parking where two vehicles are notified about the availability of parking spots in a parking area [23].

## 2.4 Green Communication Technologies for Smart Cities

### 2.4.1 Introduction

The rapid way of cities growing and populations skyrocketing combined with the urgent need for sustainability are some of the main reason that led to smart cities. These urban areas face some pretty serious challenges, like traffic jams that never seem to end, pollution that hangs in the air, wasted energy and limited resources. We try to solve these problems with entering in 5G and soon the development of 6G will not only bring faster internet but also creating sustainable urban space by blending upcoming technologies with eco-friendly methods [24].

Moreover, Green Communication in smart cities is not just reducing the carbon footprint of telecommunication system, but also enabling connected services to boost energy efficiency, support RE use and help manage resources better. Thus, in fact, it is more than a technical challenge, it is critical piece of the puzzle in making our cities not only smarter, but more sustainable too. Figure 4 shows some of the applications served by future communication networks, like the smart city units.



Figure 3 The use case of Smart Parking [23]

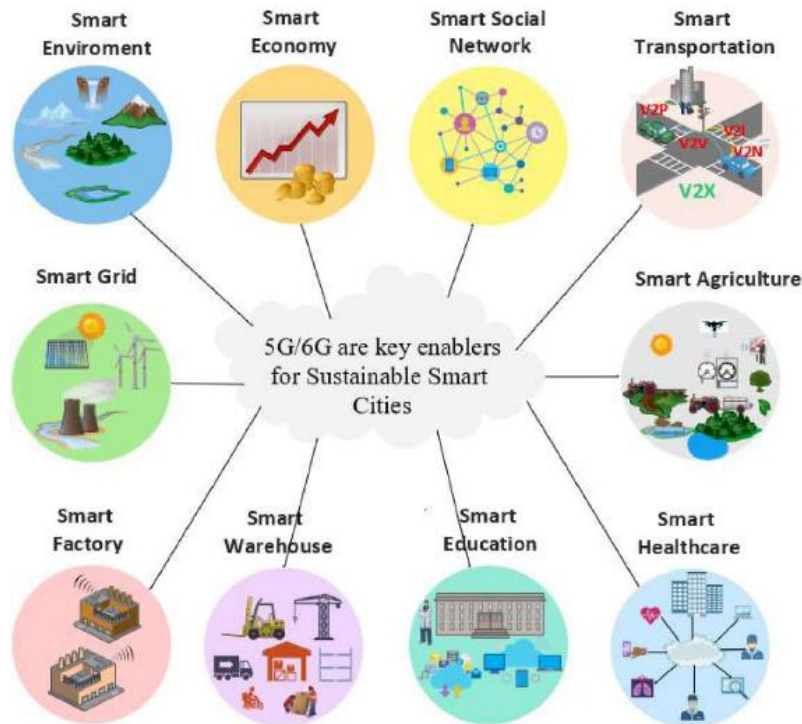


Figure 4 Applications served by 5G/6G [24]

### 2.4.2 Fundamental Principles

When we refer to Green communication technologies in smart cities, we talk about the strategies and solutions that aimed in reducing the environmental impacts while still keeping connectivity strong. These technologies focus on energy efficiency by improving RAN, backhaul connections and core infrastructures to use less energy but still performing high. Another key point is spectrum optimization, which is achieved through dynamic spectrum sharing and modulation techniques that make more efficient use of available frequency resources [25].

Moreover, RE sources, like solar and wind, are integrating into BS operations and are crucial if we want to reduce our reliance on fossil fuels. Additionally, the explosion of the IoT brings in our smart infrastructures the ability to monitor and manage resources like water and electricity in real time. Last but not least, urban digital twins that are basically virtual replicas of our cities allow us to simulate different scenarios and predict outcomes, which can help us manage communication flows and energy usage in urban settings.

### 2.4.3 Basic Techniques and Methods

Using green communication in smart cities is like using some technical methods that mainly focus on energy efficiency and sustainability. One of the standout methods here is network densification, which basically means using small cells and heterogeneous networks. This technique helps shorten the distance data has to travel, which in turn improves spectral efficiency and reduce energy use.

AI and ML are also game changers and help with to predict traffic flow, adaptive beamforming and dynamic power allocation. These methods allow networks to react in real-life demands, reducing unnecessary energy use [26]. This approach is enhanced by edge computing, which brings data

processing closer to the source. This reduces backhaul traffic and supports decisions that lead to energy savings for applications such as autonomous transport and smart energy grids.

Another key player in the game of sustainability is the use of renewable-powered Base Stations (BS), which often use hybrid systems to combine solar or wind with battery storage to maintain reliability while simultaneously carbon footprints are reduced [27]. Last but not least, non-terrestrial platforms such as satellites and aerial communication systems are becoming pretty essential. These kind of systems offer a sustainable way to link urban areas with their surrounding peri-urban zones, finding a smarter and more efficient way to keep everyone connected [28].

### 2.4.4 Challenges

Despite the fact that green communication technologies offer some pretty amazing benefits, there are also a few hurdles that we need to address before their use in smart cities. One huge issue is the rising energy demand that comes from the explosion of IoT devices and the intricate wireless setups we are seeing everywhere nowadays. Another big obstacle that we have to overcome is the interoperability issue. Smart cities are operation areas of a huge amount of devices and platforms from different manufacturers. The co-operation of all these devices is made more difficult if there are no common standards and policies. This can lead to a drop in system's performance.

Furthermore, cybersecurity and privacy are always critical concerns that can lead to unexpected conditions. Many applications in smart cities depend on real-time data sharing, which makes them pretty vulnerable to hacks, threatening citizen trust. Additionally, the cost of setting up BS which powered by RE sources or upgrading the already existed infrastructures is huge and seems out of reach especially for developing countries [27].

### 2.4.5 Future Trends

The growth of green communication technologies is going to transform smart cities into fully connected and autonomous areas. One big step to this direction is embracing circular economy models which encourage the use of recyclable materials and sustainable manufacturing practices when designing communication hardware. Another direction that plays key role is the AI-driven optimization, where smart algorithms are set to manage energy consumption and tweak networks based on changing demands [26].

At a policy level, there is strong support for the UN SDGs. This support is crucial because it will help guide future projects, ensuring that new communication networks align with important objectives like clean energy, sustainable urban growth and building resilience against climate change [25]. Finally the shift towards 6G networks, which promise ultra-low latency, use of THz spectrum and widespread intelligence, is expected to boost sustainability in smart cities. The 6G technology will lead to innovative applications, including energy-efficient autonomous systems.

In summary, it is clear that green communication technologies play a critical role in promoting sustainable smart cities. They help create energy-efficient networks, using of RE sources and support real-time smart services. The upcoming 6G technology will bring sustainability-focused innovation and set up international policies, transform cities into greener, smarter and fully connected places.

## 2.5 Energy-efficient Hardware & Power Transfer Technologies

### 2.5.1 Introduction

As we move from 5G to the next generation networks, energy efficiency has become a key requirement in the development of wireless communication systems. With the phenomenon of the huge increase in connected devices, thanks to IoT environments getting bigger and the rising use of AI and ML in how networks operate, there is a growing demand for sustainable solutions.

Furthermore, energy-efficient hardware and power transfer technologies are essential because not only help in achieving high data rates but also work towards minimizing out impact on the environment. One of the most serious concerns is the reducing of power consumption in base station, end User Equipment (UE) and network infrastructures. There is also big try to find new ways of energy harvesting and Wireless Power Transfer (WPT).

### 2.5.2 Fundamental Principles

With the term “Energy-efficient hardware and power transfer technologies” we refer to exciting innovations in creating physical components and smart energy management strategies that help reduce energy use without sacrificing performance. Basically, the key areas that we are focusing on are the energy-efficient hardware design, the power transfer technologies, which is about how the energy is moved efficiently, the adaptive power management, that includes technologies that adjust energy use based on what is needed at every moment and we also explore hot to integrate RE sources into the whole setup.

The term of energy-efficient hardware design is referred to optimizing baseband processors, Radio Frequency (RF) front-ends, antennas and memory subsystems to reduce energy use while simultaneously keeping performance at normal levels. Power transfer technologies though, include WPT, Simultaneous Wireless Information and Power Transfer (SWIPT) and energy harvesting systems that absorb energy from the environment, like solar, RF or kinetic energy.

Moreover, adaptive power management involves some clever tricks like sleep and wake models and resource allocation techniques that determine how much energy gets used based on the current traffic of the network. Lastly, as we have already mentioned, the integration of the RE sources is crucial. Using energy sources like solar, wind and other green systems helps power BSs and edge computing infrastructures, making a holistic approach in a more efficient and sustainable communication system.

### 2.5.3 Basic Techniques and Methods

Lately, there has been quite a bit of focus on creating energy-efficient hardware components to get ultra-low latency and high throughput, while simultaneously using less power. For instance, the massive multiple-input multiple-output (mMIMO) systems are based on low-power circuits and energy-saving power amplifiers which help boost spectral efficiency and keeps heat generation under control[29].

Another energy-efficient hardware component is RIS that acts as passive or semi-passive metasurfaces that have the ability to bounce signals around which helps improve coverage without using a huge amount of energy. These surfaces are crucial for the future communications, especially when they combined with RE sources [30]. Another technique that may have the ability to slash energy

consumption is the heterogeneous integration, such as combining photonic elements with silicon circuitry that offers a promising way, especially in high-frequency 6G systems.

WPT and SWIPT techniques represent another important and crucial area for sustainable communications. We have the ability to harvest RF energy from everyday sources like signals from cellular, Wi-Fi and TV broadcasts and turn those signals into usable power. SWIPT technique also allow the simultaneously delivery of data and energy, making devices to operate with less need for batteries [29]. Other promising technique, like resonant inductive coupling and far-field WPT offer ways to power devices without physical connections, at close or long distances.

Furthermore, renewable powered infrastructure is becoming crucial as energy demands have been increasing in 5G and 6G networks. For instance, hybrid energy supply models use solar, wind and fuel cells at BSs to help decrease the energy footprint [31]. Figure 5 shows a typical distributed RE enabled BSs.

Additional, energy storage systems, such as efficient batteries and supercapacitors, are also key players in this game. They ensure that the network stays powered up and running smoothly without any hiccups. Finally, energy-efficient network management techniques are crucial for reducing energy use. For example, BSs can actually be turned off when traffic is low, which is a great way to save energy. These technologies in co-ordination with AI and ML techniques help with predictive traffic routing and resource allocation, which means we can reduce energy waste in RAN.

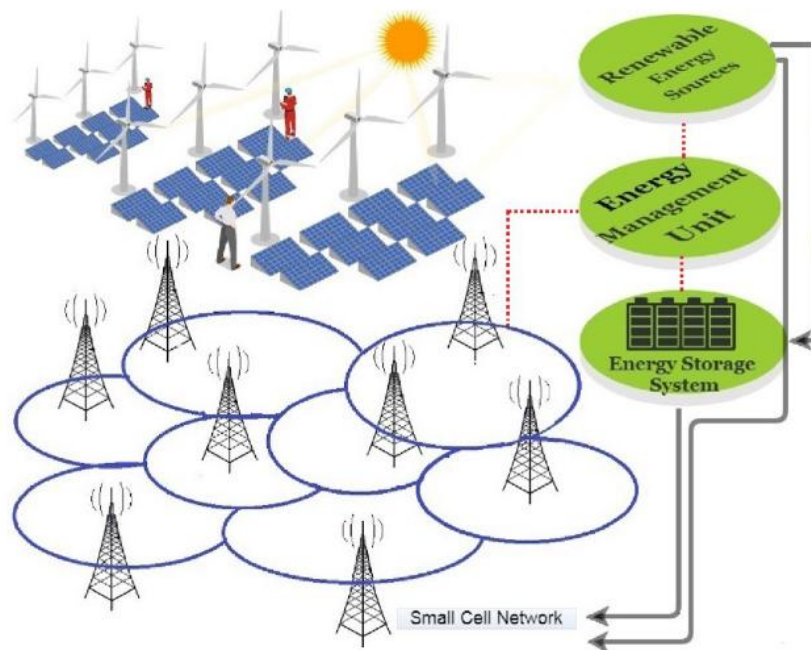


Figure 5 Distributed renewable energy enabled BSs [31]

#### 2.5.4 Challenges

Even though there have been made some strides, there are still quite a few obstacles that we have to overcome for moving forward to adopting the technologies from above. First of all, the cost of energy-efficient hardware, like RF chains and RIS panels, can be pretty high. This is a significant barrier that we have to pass. Another big challenge is the balance between efficiency and performance, because if

we try to reduce energy use, we might end up with lower throughput or increased latency. This is not going to happen especially with the high standards of reliability and low latency that 6G demands.

Another issue that we have to solve is the complexity. Coordinating RE systems, WPT and all those network functions that we have already mentioned is calling for some advanced control systems and standards for interoperability. The smart devices which are deployed across a smart city come from a wide variety of technologies and vendors, using different communication protocols, power requirements and data formats. Because of this mix getting everything to work together smoothly is not easy. It needs smart orchestration frameworks to help these diverse systems collaborate effectively.

Another issue that nowadays all the networks face is the security and safety. There are a lot of new risks coming out, like issues with electromagnetic radiation, interference and keeping our data confidential. Last but not least, scalability and standardization are challenges we need to address. It is a complex landscape, but these issues are crucial for moving forward.

### **2.5.5 Future Trends**

When we talk about the future of energy, it is important not to ignore how AI-driven energy optimization is really going to take center stage. ML is set to play a huge role in things like adaptive power allocation, predictive maintenance and spotting faults in hardware and energy systems [32].

Another big trend is the exciting world of electronics. New advancements like nanoelectronics and graphene-based transistors are going to play a big part in cutting down energy use, especially in THz communications. It is like we find a whole new technological era. On top of that, we can improve the efficiency of WPT through some innovative techniques, like energy beam steering and securely multiplexing developments [33].

Furthermore, circular economy is an approach that focuses on recyclability and reducing carbon footprints, so it needs to be established solid international standards and frameworks to make sure that power transfer in 6G networks is safe and efficient. Thus, as it comes to developing sustainable 5G and 6G technologies it is very important to find ultra-low latency, massive connectivity, energy efficiency and sustainable power solutions.

## **2.6 Non-Terrestrial Platforms for Sustainable Communications**

### **2.6.1 Introduction**

The rapid process in wireless communication technologies as we move toward 6G really highlights the growing need for sustainability and global connectivity. One major game-changer is the rise of Non-Terrestrial Networks (NTN) that includes Low Earth Orbit Satellites (LEO), Geostationary Satellites (GEO), High-Altitude Platform Stations (HAPS) and even Unmanned Aerial Vehicles (UAVs).

In contrast to the traditional terrestrial ways, NTNs not only can extend networks coverage to isolated areas but also offer a more eco-friendly way to communicate, in reducing energy consumption by using RE sources and support new services that align with the SDGs. Thus, NTNs are opening new pathways to create a more sustainable 6G system [34], [35].

### 2.6.2 Fundamental Principles

In the beginning, NTN is designed to fill the gaps in terrestrial networks, offering wide-area coverage and being super flexible when it comes to deployment options. First of all, there are satellites in LEO and GEO orbits, which are crucial for global connectivity, especially for the communities in remote locations where a solid connection is hard to come by [36].

After that, there are HAPS, which are established in the stratosphere and offer vital link between terrestrial networks and the satellites. They provide massive coverage and they are often powered by RE sources, like solar panels [37]. Moreover, there are UAVs, which add a whole new layer of flexibility, acting as aerial BS or relays. Their aim is to support data transfer and power sharing, which is very useful [38].

All of the above aerial platforms help in reducing the need for ground stations so as lowering the carbon footprint. In addition to this fact, NTN can leverage RE sources and AI/ML algorithms to make communication even greener, contributing to sustainability [39].

### 2.6.3 Basic Techniques and Methods

One of the several techniques that support the use of NTN is UAV-assisted WPT. This is significant because it makes less our dependence on batteries by enabling energy harvesting right from drones/UAVs. This fact is especially useful for monitoring agriculture and environment in generally, since batteries can be not only costly but also a bit harmful to the environment [38].

Furthermore, another useful technique is HAPS, which are very useful because they have the ability to run with RE sources like solar energy, cutting down lifecycle emissions. They can also cover huge geographical areas, especially when ground infrastructure is destroyed by a natural disaster or something like that [37].

Moreover, satellites are crucial in NTN networks. For instance, LEO systems provide low-latency coverage worldwide, which is especially beneficial for remote areas. These really improve applications like smart agriculture, maritime communications and others. Finally, the combination of NTN with terrestrial networks allows managing communication resources flexibly. With the help of AI in the resource management, it can be achieved a more efficient balance between ground stations, UAVs and satellites. This fact is really helping networks operating smoothly and sustainably [40].

### 2.6.4 Challenges

Even though NTN come with some significant benefits, they also have several challenges that it must be overcome. A major challenge is the high energy demands resulting from launching and maintaining satellite constellations and also the energy that consuming during the operation of UAVs while they are flying smoothly on long missions. Despite the fact that RE sources can help with these energy issues, the continuously changing weather conditions and the limited energy storage capacity in many types of platforms like HAPS, make the solution tougher to achieve [37].

Another big obstacle that we face is spectrum management because of the difficulty in simultaneously management of all frequencies in NTN and terrestrial networks, especially nowadays that the huge number of LEO satellites has been increased [35]. Furthermore, there are still lots of safety concerns that are unsolved. UAVs, satellites and HAPS have to follow international standards and guidelines regarding things like electromagnetic exposure, avoiding collisions and protecting the environment [41].

Moreover, the cost of the NTN platforms is huge and it consists a major issue, especially for the developing countries which need NTN the most and they do not have the funds to begin the deployment. Last but not least, there are technical obstacles that we have to overcome. Researchers are still trying to determine the exact way of signals travelling between NTN platforms and devices on the ground. The solution of this issue will be promising for reducing the energy consumption of future networks [39].

### **2.6.5 Future Trends**

The future of NTN seems really bright, with some key-enablers making this vision a reality by extending coverage and connectivity. AI and ML techniques, RE sources and international teamwork in different approaches are expected to play a key role in helping reducing energy consuming, giving the ability in UAVs to operate autonomously and coordinate with satellites in multi level networks. Furthermore, a hybrid energy system seems that is the new trend that will help networks reduce their energy consumption. Solar power, wind energy and even wireless energy transfer are poised to enhance how NTN platforms operate.

In concerning with satellites, LEO constellations are seemed to take the lead in deploying NTN. However, there are some obstacles to overcome first, like the chaotic orbital congestion and the challenge of standardization. HAPS are also expected to develop hybrid energy systems which they will give them the ability to operate for years, even when there are tough conditions [37].

Furthermore, it is really important to establish international standards and frameworks. In order to achieve the safe and sustainable development of NTN, the collaboration among all governments, industries and organizations is vital.

In conclusion, NTN are going to change the communications forever. UAVs, HAPS and satellites will transform the way we look communications providing connectivity to remote areas and reducing the environmental footprint of our current wireless networks. NTN perfectly align with the UN SDGs will lead our networks in a more sustainable future.

## Chapter 3: Methodological Approach

### 3.1 Research Protocol

The goal of this thesis is to investigate sustainability in 5G and 6G communications through a structured and reproducible literature review process. To ensure a transparent study selection, we follow the methodology of PRISMA approach (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). PRISMA is a widely adopted solid framework to explain how studies were found, checked and decided on for final inclusion. The PRISMA 2020 update provides an improved checklist and revised flow diagram that reflect the latest practices for identifying, selecting and synthesizing evidence [42].

More specifically, in this thesis, PRISMA is used as a kind of framework to organize the literature search and selection into three main stages: Identification, Screening and Eligibility. During Identification, we define our search strategy, identify our sources and then we start collect files. Next comes Screening, in which step we carefully review the titles and abstracts, using some predefined criteria to remove anything that is irrelevant. Finally, during Eligibility, we dive into the full texts to make sure each study really aligns with the scope and the research questions of this work. In Figure 6 is shown the PRISMA-style flow diagram, which clearly separates these three stages and documents the number of records retained and excluded at each step. To ensure that we did not miss any new publications, we ran the search twice, the first on January 30, 2025 and then repeated on May 27, 2025. After collecting all sources, we used Zotero reference manager to remove duplicates before final consolidation of the dataset.

#### 3.1.1 Objectives and Research Questions

The first task of this methodological approach is to clearly lay out the goals of our literature review. The objective is to map and analyze how sustainability is currently addressed in 6G research, to organize the main sustainability-enabling approaches in wireless communications and finally to compare sustainability goals and challenges between 5G and 6G. To keep these goals formalized we have posed some specific research questions.

##### **(RQ1) What is the current state of research on sustainability in 6G technology?**

The aim of this research question is to map the current situation of academic and industrial research on sustainability in 6G wireless networks. We are trying to identify the key themes, figure out what the priorities are and suggest directions. In this way we try to clarify how sustainability is positioned in the emerging 6G era and which topics receive the strongest attention in the literature.

##### **(RQ2) What are the main approaches to ensuring sustainable development in wireless communications?**

The aim of this question is to identify and categorize the key approaches that have been proposed to improve sustainability in wireless communications. We have already mentioned enabling technologies in Chapter 2, like AI/ML for green communications, SNM, smart mobility, green communication technologies for smart cities, energy-efficient hardware and power transfer technologies and Non-terrestrial platforms for sustainable communications.

**(RQ3) What are the main differences in sustainability goals, strategies and challenges between 5G and 6G technologies?**

The aim of this research question is to dive into a comparative analysis in how 5G and 6G approach sustainability. The comparison focuses on differences in sustainability goals, how their design philosophies differ, the role of enabling technologies and the various obstacles that we have to overcome as networks become more intelligent.

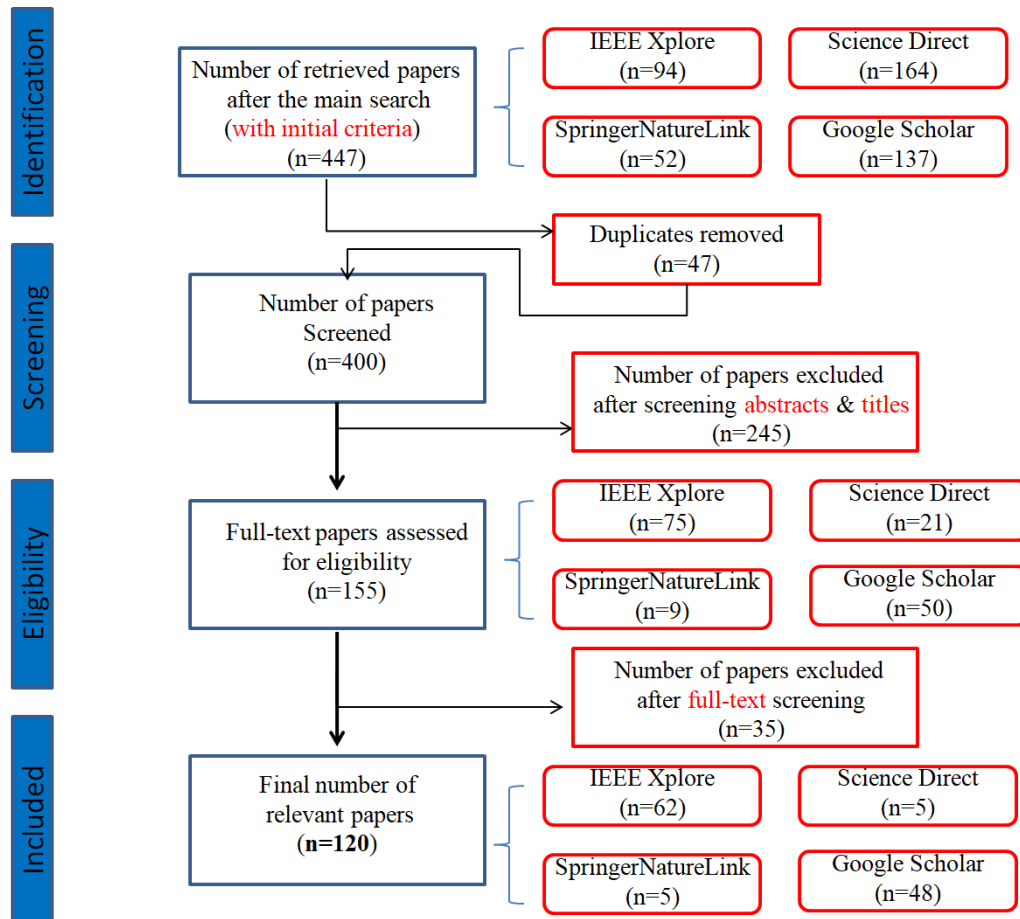


Figure 6 PRISMA-based study selection workflow used in this thesis

### 3.2 Search Strategy

The foundation of this methodology is the identification of relevant scientific studies through a solid search strategy. In order to keep the retrieval focused and reduce irrelevant results, we focused our research with title-restricted queries. Basically, that means that we made sure the key terms had to appear in the publication title. This approach helps us get more precise results, because it emphasizes studies where sustainability and 5G/6G are central topics and not peripheral keywords.

The search was conducted across four sources: IEEE Xplore, ScienceDirect, SpringerNatureLink and Google Scholar. From the beginning of the search, we applied filters to restrict results. Firstly, we search only English-language publications so to exclude publications in other languages and secondly we set a specific time window, from January 2021 up to the execution date of each search, January 30, 2025 in the first search and May 27, 2025 in the second.

More specifically, in IEEEExplore, we executed the query in the “Document Title” field using “5G AND Sustainability “OR” 5G AND Sustainable “OR” 6G AND Sustainability “OR” 6G AND Sustainable”. The execution of this query returned **94** records.

In ScienceDirect and SpringerNatureLink, we organized a two-step logic search because these platforms do not provide a dedicated “Document Title” field as IEEEExplore does. Thus firstly, in A-search approach we try to use four separate title queries: TITLE(“6G”AND “SUSTAINABILITY”), TITLE(“6G” AND “SUSTAINABLE”), TITLE (“5G”AND “SUSTAINABILITY”) and TITLE(“5G” AND “SUSTAINABLE”). This broad search returned **1.042** results in ScienceDirect and **629** results in SpringerNatureLink, a fact that is very wide for efficient screening at thesis scale. For this reason we applied a more focused search (B-search) in both platforms using the combined title query: TITLE(“6G” AND “SUSTAINABILITY” AND “5G” AND “SUSTAINABLE”). This query returned **164** results in ScienceDirect and **52** results in SpringerNatureLink. In the present thesis, we continued the final screening and selection process using the results from B-search.

This approach helped us narrow things down to a more focused and manageable set of records and also it ensured that everything remained relevant to our comparison of 5G and 6G sustainability. Finally, we used Google Scholar and tried out a title-restricted method with the “allintitle” operator and four different queries: “6G AND Sustainable”, “6G AND Sustainability”, “5G AND Sustainable” and “5G AND Sustainability”. These four queries produced a total of **137** records.

Thus, crossing through all sources, the initial stage of Identification produced 447 records (IEEEExplore:94, ScienceDirect:164, SpringerNatureLink:52 and Google Scholar:137).

### **3.3 Study Eligibility**

This section describes the criteria that we used to decide which studies to include or exclude and it goes over the steps we took to get to our final dataset. Eligibility was applied through two main checking steps. First, we examined the titles and abstracts, and then we moved on to the full texts. Furthermore, we used “Zotero” to clean up any duplicates records.

The inclusion criteria were defined to ensure that all the studies that we select are directly relevant to sustainability in 5G and/or 6G. Specifically, only studies that were written in English and published within the previously mentioned timeframe were retained. Moreover, we have to choose from the studies above only these that address sustainability issues related to mobile networks, like energy-efficiency, carbon footprint, lifecycle impacts, sustainable network architectures and others. On the other hand, we excluded studies that lacked a solid connection to sustainability in 5G and/or 6G or did not seem to fit based on the title or abstract. Last but not least, we thorough read the full text of studies that were remained from the exclusion criteria and kept those that aligned with our research questions.

After the application of the exclusion criteria, the initial results were minimized. In IEEEExplore we firstly had 94 records, after title and abstract screening 81 records were retained and after full-text screening results were reduced to 71 relevant studies. Finally using Zotero we removed 6 duplicated entries, resulting in **62** final eligible IEEE studies. In ScienceDirect, the initial 164 records were reduced to 23 studies after title and abstract screening and to 7 studies after full-text screening. In the end we remove 2 duplicates studies, so the final number of eligible ScienceDirect studies was **5**.

Similarly, in SpringerNatureLink, the initial pool of 52 records was reduced to 9 studies after title and abstract screening and to final **5** eligible studies after full-text screening. Furthermore, out of 137 initial records retrieved from Google Scholar, 39 were identified as duplicates. Following the

screening of titles and abstracts and full-text, in which filtered out 50 irrelevant studies, **48** records were deemed eligible.

In conclusion, the final dataset used in this thesis includes of 120 studies that are considered eligible, across all sources (IEEEExplore:62, ScienceDirect:5, SpringerNatureLink:5, Google Scholar:48). Table II shows the summary of retrieved records and final included studies per source. This collection serves as the backbone for many important parts of the thesis, like the comparative sustainability review in Chapter 4, the enabling-technology mapping in Chapter 5 and the discussion of sustainability in the dual perspective in Chapter 6.

Table II: Summary of retrieved records and final included studies per source

Source	Number of papers	Number of papers with title/abstract screening	Number of papers with full-text screening	Number of removed duplicates papers	Final number of relevant papers
IEEEExplore	94	81	68	6	62
ScienceDirect	164	23	7	2	5
SpringerNature Link	52	9	5	0	5
Google Scholar	137	89	87	39	48
<b>TOTAL</b>	447	202	167	47	<b>120</b>

## **Chapter 4: From 5G to 6G: A Comparative Literature Review on Sustainability Implications**

This chapter dives into some interesting findings from the literature on the sustainability with regard to 5G and 6G, providing a clear comparison between these two generations. Specifically, the chapter reviews how well 5G networks are performing right now in terms of sustainability and explores the new sustainability principles and capabilities envisioned for 6G.

Furthermore, the chapter highlights both the progress that it has been done and the limitations that have popped up in recent research. It aims to shed light on how each generation contributes to environmental and social sustainability and also discusses the challenges and technological factors driving to their development. Thus, this chapter offers a straightforward comparison highlighting some common trends, unique features and areas where requiring further research.

### **4.1 Introduction**

Sustainability is becoming a central issue when we talk about how wireless communication systems are changing, due to the rapid growing of the digital infrastructures and the environmental costs of global connectivity that is continuously increased. As cities start to become more like smart ones using all these platforms and deploy all these IoT devices, along with data-heavy applications, mobile networks have to meet demanding performance goals while simultaneously reducing their energy footprint and environmental impact. This dual need has made the research to focus on greener designs, ways to manage resources more efficiently and communication technologies that align with the UN SDGs making our societies more sustainable.

When we talk about 5G, it is interesting to note that it is the first mobile generation where sustainability started to take center stage in the design process. Many studies explore how improvements in 5G's architecture, like network firmware design, massive support by IoT devices and better spectral efficiency, can actually reduce energy use, especially when we manage things smartly[43], [44]. Simultaneously, while these advancements are promising, there are also some significant sustainability obstacles that we have to overcome. The network is becoming denser on and on, massive MIMO is getting rise and in addition to the boom of edge computing nodes make things more complicated. To make it operational we have to rely on optimized control systems, smart AI-driven orchestration and adaptive power management strategies [12], [45]. As a result, sustainability in 5G networks is complex and depends on various factors like how it is deployed and how effective the management algorithms are.

In a parallel way, as 6G research is coming into play, it really changes the boundaries of what we think about sustainability. It is not only a performance metric but it is a core part of how these systems are designed. When someone looks at recent studies, he will see the portray of 6G as a AI-based, context aware communication system that is all about being smarter, operate with higher autonomy and better resource management, while also align strongly with environmental goals, including carbon neutrality and embracing circular economy practices [13], [46].

However, the most interesting fact in 6G technology is that it is not about making the network greener but also is a tool that can help drive larger sustainability efforts, like supporting the climate

monitoring, eco-friendly industrial automation, smart transportation and even the large-scale environmental sensing [47], [48]. This whole idea of “two-dimensional” sustainability is very revolutionary, because it separates the sustainable 6G on the one side and “6G for sustainability” on the other. We will explore this further in chapter 6. This is a big significant step compared to previous generations.

With research in this era moving so quickly, it is really important to take a good look at how 5G and 6G relate to each other. Furthermore, we need to understand how sustainability goals change as technology advances and how these developments impact the environment. So in this section, we are going to lay out the basic ideas for evaluating sustainability in mobile networks. This will set the stage for the detailed analyses that follow in section 4.2, 4.3 and 4.4.

By reviewing the main topic emerging in the literature, like energy efficiency network management, green AI/ML, hardware optimization and non-terrestrial communication platforms. By approaching these key topics, we are building a solid foundation for a deeper look at what sustainability really means as we transition from 5G to 6G.

## **4.2 Current State of Sustainability in 5G Technology**

5G has brought several architectural updates aimed at making networks operate more smoothly and efficiency. However, its sustainability performance is a bit of mixed. While this technology provide higher data rates, flexible network management and support by huge amount of IoT devices, it also brings new energy demands, adding layers of complexity to operations with their environmental footprint.

This section explores the current sustainability state of 5G, highlighting the main challenges that are observed in real-world applications and the ways that 5G is contributing to achieve greener digital infrastructures. In this way, it will be more understandable how 5G fits into the bigger picture of moving to a more sustainable generation of networks, 6G.

### **4.2.1 Challenges and Limitations**

Despite the fact that 5G was designed to be more efficient and with more flexible network architectures, it faces significant sustainability issues that impact its environmental performance. One of the main problems that have been made a source of controversy is the amount of energy that 5G consumes. The introduction of dense small-cell networks, massive MIMO arrays and the wideband millimeter-wave carriers raises the power demands by RAN. Several studies have shown that while each individual transmission link might be more energy-efficient, the whole picture shows that 5G actually demands more power than earlier generations due to the large number of active hardware components and the computational complexity [43], [45].

Another important obstacle that we have to overcome is the operational challenges that come with managing huge IoT ecosystems. While 5G was built to handle the heterogeneous IoT traffic, the real-life operation is completely different. Lots of connected devices give constant signaling that give a huge amount of processing at BS. This fact affects how energy-saving features can do their job, leading to higher energy consumption, especially in busy urban areas [44]. In reality, many IoT setups do not take advantage of the sleep-mode features that we thought that will help, giving a less sustainable approach than we initially hoped.

Furthermore, 5G has to overcome obstacles related to the complexity of network orchestration. More specifically it mixes SDN, network slicing, edge computing and other techniques that create highly complex architectures and the fact how energy efficiency these setups are, depends on how well everything is coordinated at different levels. Research shows that setups lacking a unified approach to green management, particularly those involving equipment from various vendors, often end up in mismanaged resources and this leads to a lot of wasted energy [46], [47]. This is especially challenging in environments where multiple tenants or slices are operating at the same time.

Another challenge that we meet as a sustainability concern in 5G setups is the security and privacy requirements. In 5G setups there are lots of edge nodes and virtual network functions making potential attacks more accessible. This means that we need to increase our safety with methods like authentication, encryption and intrusion detection. These processes are highly demanding on the computational side and subsequently these are energy demanding, highlighting that advanced security measures can actually boost processing demands on edge servers and BS[10].

Moreover, another obstacle concerning the sustainability issues of 5G is that the continuous building of dense infrastructure and the constant hardware upgrades lead to a boost of electronic waste that exacerbating the carbon footprint. A lot of research highlights how costly is to produce high-performance RF components, massive MIMO modules and specialized chipsets. This cost must be considered also alongside operational energy consumption [12], [48]. This phenomenon will be increased without adopting some circular-economy practices like reusing components, recycling and designing things to be modular.

### 4.2.2 Contributions of 5G to Sustainability

Although 5G introduces several sustainability challenges, like these that we have already mentioned, there is quite a bit of interesting things in which 5G can actually help with both environmental and socio-economic sustainability. The most of these 5G contributions are not going to happen on its own, automatically, but they will depend on the way 5G is designed, powered and operated in practice. A lot of studies highlights that 5G brings in or boosts many green-friendly strategies, like energy-aware network operation, strategies that are based on using RE sources and of course the applications that opens up for smart cities, improved mobility and overall economic growth. Thus, there is definitely potential but it all depends on how we implement it [49], [31].

Diving into the first contribution, we can see the energy-aware operational features of 5G that can actually help reduce energy use, especially when traffic and deployment conditions are appropriate. When we look at 5G and its energy implications, there are some remarkable technical issues. For example, there are strategies like putting base station elements into sleep mode when they are not needed, focusing on cells and using different types of configurations that deploy lower-power small cells to cover high-demand areas. Furthermore, there are also techniques, like device-to-device (D2D) communication that have the ability to help reduce the distance that data has to travel, which is an advantage in terms of energy savings.

Moreover, there are some researches that focusing on renewable-powered infrastructure. They integrate these energy-saving techniques into a bigger picture which is called “green networking toolbox”. This toolbox is not just about technology, but also includes energy harvesting, adaptive operations and cross-layer optimization. All these elements can really help improve sustainability, especially as networks get denser on and on [31].

Another major contribution of 5G is growing focus on RE integration and reducing grid energy in 5G deployments, especially with those high-density small-cell setups. So an interesting way to address this is to power these busy small cell BS with centralized microgeneration of RE. They also use traffic-aware load offloading and advanced sleep-mode operations with the main aim to lower energy use of network while still have the QoS that required, like controlling outage probability and reactivation delays.

Additionally there are researches that looking into emission-aware energy provisioning that compares centralized with distributed RE supply systems for 5 and beyond, with a goal of cutting down carbon emissions through smart low-carbon energy management strategies [50].

Furthermore, if we focus on the site level, there are some techno-economic analyses that reveal that hybrid power systems for nowadays cellular sites, can lead to significant cuts in operational costs and emissions. For instance, [51] highlights that combining grid, wind, solar and hydrogen fuel cells in an optimized setup could lead to huge reductions in CO<sub>2</sub> emissions.

However, when we talk about 5G, it is easy to focus on how it improves network speed and reliability. But there is so much more to this, because it plays a vital role in promoting sustainability, especially in smart cities and through IoT. The detailed review in [52] dives into how 5G's impressive features, like high data rates, low latency, high reliability and massive connectivity, connect with smart city initiatives. It is much more than the fastest connectivity, it is about making urban services smarter and more sustainable, talking about IoT-based monitoring and city management that actually focuses on sustainability.

Furthermore, there is also a lot of research that presents 5G and beyond as a critical factor in energy efficiency, touching a more environmental, economic and social approach, bringing into the surface green techniques likes energy harvesting [24].

In the sector of energy, 5G supports IoT connectivity that enhances "smart environment" scenarios, where huge amount of sensors and mechanisms support more effective energy distribution and management decisions with one and only goal, to reduce energy waste maintaining or even improving efficiency [48].

Another great contribution of 5G is in the sector of mobility and transportation, through V2X and vertical-oriented network slicing that is about running vehicular applications, trying to improving sustainable vehicular services using the 5G capabilities through one single physical infrastructure [16]. This fact helps support various types of transport services. By aligning what these services need with some clear, measurable KPIs, we can make the design of those slices and the planning of capacity a lot more precise. This means that we will not waste resources and this will improve efficiency across the board. This will make smarter choices for a greener future.

Last but not least, the studies show that 5G opens up some exciting pathways for social and economic sustainability. More specific, the systematic review in [53] zooms in on SDG8, which is all about decent work and economic growth. It makes a strong case for how 5G can really push the boundaries of innovation, making operations more efficient and even creating jobs. It shows the significant impacts in various sectors like manufacturing, healthcare and transportation, highlighting that IoT and AI are important players in the technology landscape.

On the other side, there is also the focus on designing low-power 5G communication specifically for remote areas, that is driven by the energy shortages and limited infrastructure. Thus the main goal is to

improve energy efficiency while simultaneously ensuring that these underserved communities remain still connected [54].

### **4.3 Future state of Sustainability in 6G**

While the previous section explored how 5G can actually help with sustainability through energy-aware operations and supporting sustainable applications, this section will dive into the 6G era. Moving from 5G to 6G is not just an upgrade of performance, but it is also a whole new way of thinking about design. The 6G vision takes the classical usual goals that we have already focused on like capacity, latency and reliability and widen them. The 6G vision is a more holistic view that embraces things like smart networking, exploring new spectrum capabilities, trying to integrate them more closely with the physical world. Sustainability is not just an add-on anymore, but a core requirement that it will lead us in a way of thinking about environmental impacts, resource efficiency from the start of designing. It is a big change of thinking that we cannot ignore and we have to make it real as we move forward.

#### **4.3.1 Key Characteristics of 6G**

In many studies 6G presented as a “beyond connectivity” platform that is aiming for impressive performance while also opening the door to many new services. It is expected to be a game changer in a lot of ways, not only for making communications fast with ultra low latency, but mainly because it is incredible dependable for mission critical services [55].

One of the exciting areas that 6G provides is the exploration of new spectrum ranges, including THz communications, which could really widen the bandwidths and bring much higher capacity. This shift comes with some significant challenges, especially in terms of how signals are propagated and the hardware we need, but it is also a key enabler for future high-data-rate services and applications based on dense sensing [56]. Another key feature of 6G is its focus on being AI-native. AI/ML is not an optional add-on but 6G is a network where intelligence is a basic characteristic, supporting decision-making at various levels including resource allocation, orchestration and even adaptive configuration. This approach connected to applications like digital twin-assisted control and data-driven optimization for complex and changing environments [11].

Furthermore, 6G, in contrast with 5G, is a whole new system that brings in some really advanced techniques like RIS to shape how signals travel, improving coverage and efficiency, especially in demanding environments. These technologies could easily boost performance while also taking into account energy consumption [55]. Finally, 6G will be able to extend connectivity into a three-dimensional and ubiquitous coverage model where terrestrial networks work together with non-terrestrial platforms (like LEO satellites) to increase coverage, resilience and availability of service. This is interesting especially for remote areas and also for services in all over the world, bringing this architectural feature among of the most important in the future networks [55].

#### **4.3.2 6G Sustainability Priorities**

Exploring the 6G sustainability literature, the key takeaway is the idea that sustainability needs to be integrated from the start, “by design”. This means that 6G is expected to make things faster and more efficient while simultaneously prioritize the reducing of energy consumption and the environmental impacts as its main goal. Sustainability should not be treating like an add-on in the networks but in contrary networks have to be designed aiming sustainability. Furthermore, there is a big issue in trying

not only reducing energy use during operation but also on considering the wider environmental impact across the entire technology lifecycle. Everything in technology, from the materials that we use to how devices are disposed of, needs to be considered [1].

One also important priority of 6G is the need to focus on embracing lifecycle and circular-economy thinking. Researches like the one in [57], suggest that when we explore the sustainability in 6G, we cannot only estimate the energy which is used when networks are running but also we must consider the entire process from how the technology is developed and rolled out all the way through to upgrades and what happens when it is time to end up with devices that are included in the operational chain, including issues like electronic waste and material reuse. All this amount of energy which is used in the whole lifecycle is far from the power consumption during operation. This also means that we need clear measures and standardized ways to assess all those impacts and estimate the advantages and disadvantages of 6G.

Another key focus of 6G is how it aligns with larger sustainability goals, especially SDGs by UN. As we have already mentioned sustainability is beyond just creating greener networks but is also about how 6G can actually help achieve sustainable development generally. Many researches, like these in [1] and [4] explore the link between 6G and the SDGs. They highlight that sustainability should be seen as not an engineering challenge but also a social goal. This perspective really influences what gets prioritized in research, how we evaluate success and even how governance is approached. Thus we can understand that 6G is more than just a technology because it will have a real impact on society and the environment.

In addition to the above, sustainability in 6G has also priorities that includes more practical goals like energy-aware management, operating with low carbon emissions and smart system optimization. In all these practical goals, AI and ML are usually the main key players, helping in better adaption and matching resources to what it really needed. Of course, this comes with the parallel requirement in energy use, so it is very important the balance between the complexity of the intelligent management tools and the efficiency gained in network operation [11].

### **4.3.3 Emerging Requirements and Challenges**

While 6G introduces strong sustainability ambitions, it also brings a whole bunch of new requirements and challenges that we need to tackle to make these goals realistic. First of all, an important obstacle that arises is new physical-layer and hardware demands that we are dealing with, especially for THz communications and advanced radio technologies. These demands complicate things because they increase device complexity, higher power use and challenges in thermal design. There is also issue of how feasible is for these technologies to be deployed. It is a real tricky balance between achieving high-performance goals and simultaneously energy and resource limits [56], [58].

Another major challenge is the sustainability impact of AI-native networking. Although AI/ML can help us optimize energy use and automate processes, but the training and operation of AI model may introduce additional computational cost. This brings us the need to consider “green intelligence” requirements, including designing models that are efficient, using data responsible and careful placemen of intelligence across edge and cloud infrastructures [10].

Simultaneously, 6G sustainability requires new metrics, ways to monitor operations and standardized evaluation methods. Several studies, such as these in [57] and [2], suggest that sustainability goals must be measurable and comparable no matter who is architecture of the technology. This means that we have to create harmonized KPIs and reporting methods about energy consumption, carbon

emissions and the overall lifecycle impact. These methods must be in shared measurement frameworks so as sustainability goals risk remains qualitative and deployed in the real world.

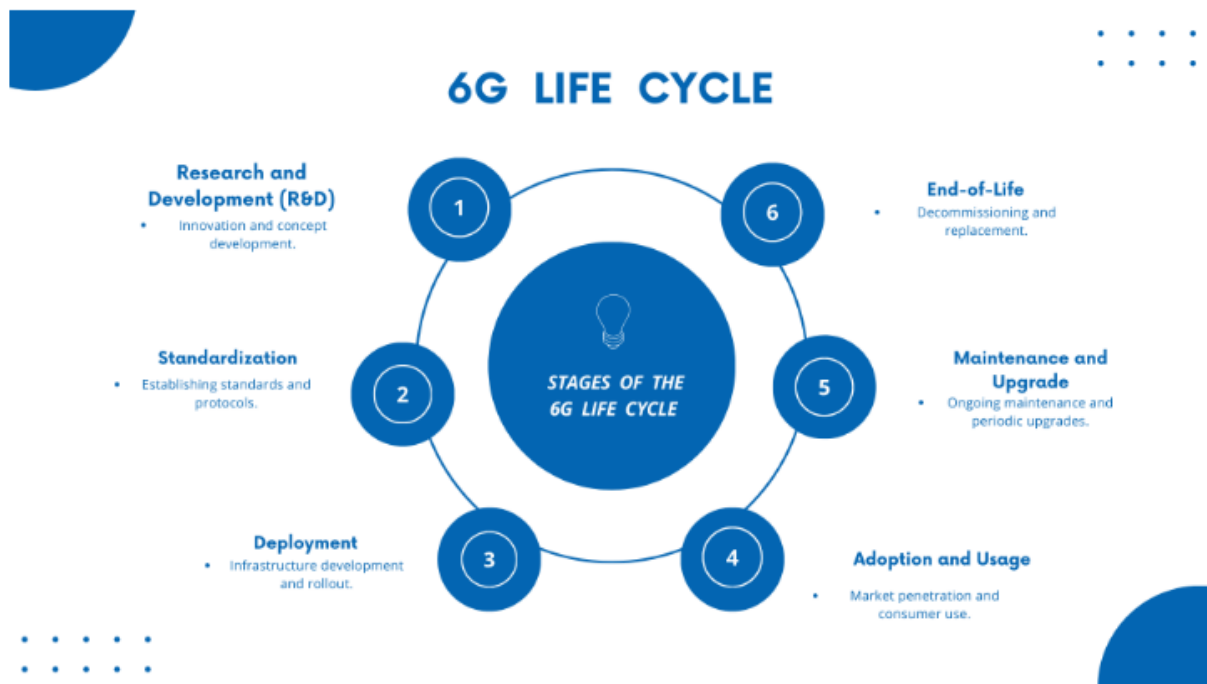


Figure 7 A Lifecycle Analysis of 6G [57]

Last but not least, 6G faces also socio-technical challenges that are connected to sustainability, including security, privacy, ethical dilemmas and the whole governance and regulation landscape. As networks become smarter and start been integrated into essential services and data-driven automation, the energy demands and the complexity of keeping everything secure may increase. At the same time, we have to make sure that we align policies and regulations to support innovation that is not only effective but also sustainable [1], [59].

In conclusion, the most articles highlight that achieving sustainability in 6G is not just about strike high performance goals but balancing that ambition with a keen awareness of the entire lifecycle of the technology and more specific being mindful of energy use and carbon emissions. These requirements ensure the view that sustainability in 6G is a complex issue that it touched on various aspects like how we operate and the broader impact it has on society. It is a multi-faceted goal that requires a lot of collaboration and consideration. Figure 7 shows a lifecycle analysis of 6G [57].

#### 4.4 Comparative Analysis of 5G an 6G in Terms of Sustainability

In this section we dive into a comparison of 5G with 6G from a sustainability perspective, focusing on how the initial objectives evolve across generations and how the main challenges shift as the technology becomes smarter, more heterogeneous and more connected to societal services. First of all we have to mention that the goals of these two generations of technology are quite different and so are their priorities. While the focus of 5G was on efficiency within the network itself, 6G is not just about making the network faster and more efficient but it is also considering the entire lifecycle of technology, as we have already mentioned. Its goal is about how it impacts the environment over time, being mindful of carbon footprints and thinking about the societal objectives [1].

#### 4.4.1 Comparison of Initial Objectives

A good starting point is to compare the basic goals and priorities of 5G and 6G. It is undeniable that 5G is often seen as a big leap forward which really boosts mobile broadband performance, connects massively different kind of devices (especially for IoT) and introduces more flexible and software-based operation, like virtualization and slicing). In addition to this, as it concerns sustainability, 5G's main goal is to improve efficiency for every bit of data sent and making better use of resources. Sustainability is often framed as an optimization goal that depends on how we deploy it and the practices we use to run it [49], [31]. On the other side, 6G is usually described as a generation that pushes the limit of performance and simultaneously weaving the intelligence and sustainability into the whole vision. Table III shows a comparison of main features in 5G and 6G.

Table IIIA comparison of main features in 5G and 6G [10]

Features	5G	6G
Peak Data Rates	10 Gbps	1 Tbps
End-to-End Latency	10 ms	1 ms
Reliability	About 99.9%	99.999%
Spectral Efficiency	30 (bps)/Hz	100 (bps)/Hz
User Experience Data Rates	1 Gbps	10 Gbps
Mobility	500 Km/h	1000 Km/h
Connection Density	1 million/Km <sup>2</sup>	10 million/Km <sup>2</sup>
Support IIoT Systems	Partial	Fully
Space-Air-Ground-Under Sea	Partial	Fully
Support AI	Optional	Endogenous AI
Reconfigurable Intelligent Surfaces	Optional	Fully
THz & VLC Communications	Initial	Widely
Energy Efficiency	Low	Ultra-low

For instance, Table III reports a shift from 10 Gbps to 1 Tbps peak data rates, from around 10 ms to 1 ms end-to-end latency and from 1million/km<sup>2</sup>to 10 million/km<sup>2</sup>connection density. Lastly, it also highlights that the support of AI is “Optional” in 5G but in contrary the AI is endogenous in 6G while technologies like RIS and THz/VLC communications are taking center stage. All these targets matter, especially when we talk about sustainability because they will increase computational power, denser infrastructure and broader range of devices, matters that we have to keep in mind [10].

It is very interesting to explore how sustainability evolves over time. Many articles, such as the one in[57] highlight that sustainability should be integrated “by design”. It is not just about being efficient anymore, but it must look at the whole lifecycle of the technology and consider its wider impact on the environment. It has already mentioned that nowadays the circular economy thinking has been added that it was not in trend back to 5G era. Thus it is clear that as we advance, our understanding of what being sustainable means, is getting deeper and more comprehensive. Furthermore, one big difference

between 5G and 6G is how they connect with bigger societal goals like the UN SDGs. Nowadays, 6G is not only a technology about making the network greener. It is about using it as a platform that will drive sustainability across various sectors [4]. To sum up, in 5G-era, the focus is mainly on boosting efficiency and enabling certain applications. In contrary, 6G takes a step further aiming for a more comprehensive approach to sustainability, lifecycle responsibility and clear alignment with societal needs.

#### 4.4.2 Comparison of Challenges

The sustainability challenges of 5G and 6G are also different in both scope and nature. Many researches, like these presented in [49] and [31], highlight that the system in 5G uses a lot of energy because of the need for densification (to build many more BS), use more powerful hardware and process a lot more data. Thus, 5G characterized as “green” only if we design the network carefully and use smart ways to save power while it is operating. There are also difficult technical challenges, like managing various parts of the network simultaneously. Another worry that we have is about the “trash”. As we have to keep 5G networks alive, we have to update our equipment very often and this fact creates electronic waste. So, we must find ways to reuse or recycle these parts of the equipment so as to keep environment safe [49].

On the other hand, regarding 6G it is clear that the area of challenges is expanding. First of all, there are new spectrum and device requirements, like THz-related hardware constraints, that can really complicate things. Things become more complex in RF design, thermal management and energy usage. Thus, we can see that it is a balance between hitting the high-performance goals and staying within sustainability limits [56], [58]. Furthermore, the shift to AI-native networking can help use resources more efficiently but the training and inference processes can increase computational and energy demands, motivating the idea of “green AI”, pushing us towards smarter and more efficient edge intelligence [11], [10].

Moreover, the raise of 6G brings up some strong socio-technical requirements that are connected to sustainability. Many issues like digital inclusion, trust, privacy and security are becoming central to sustainability framing, because 6G is expected to be crucial for societal services all over the place, especially in underserved areas [2]. At the same time, security and privacy make the system more complex and demand in computing power. It is necessary to balance strong protection with energy-aware use in order to overcome this obstacle.

Finally, many studies, like these presented in [57] and [2], argue that measurement and governance will play a huge role in the sustainability in 6G. Shared metrics, solid lifecycle accounting practices and standardized evaluation methods are very important for the deployment of 6G. These tools are necessary to accurately measure the true environmental impact of the network and ensure that all companies are following the same rules. In conclusion, while 5G sustainability challenges are often around energy use and how complicated it is to deploy, 6G sustainability challenges changes quite a bit. They broaden to include responsibility for the entire lifecycle, managing AI overhead, digital inclusion and stronger governance needs. This comparative analysis between 5G and 6G in terms of sustainability shows that sustainability progresses from a mainly efficiency-oriented goal in 5G to a broader frame “by-design” and lifecycle-aware requirement in 6G [1].

## Chapter 5: Mapping Enabling Technologies towards Sustainable 5G/6G Communications

### 5.1 AI/ML for Green Communications

AI and ML play a key role in creating greener and more sustainable wireless communications. As 5G networks are widely deployed and research into 6G progresses, the focus has changed. It is not about meeting technical performance goals, but we also need to resolve key environmental and energy issues. AI/ML offers the appropriate methods to improve the design, deployment and management of networks. This leads to lower energy use, better resource allocation and smarter cooperation between different infrastructures. These methods are crucial for balancing the demand for connectivity with the need for sustainable development [13]. In this section presented the four main pillars that make AI/ML the most appropriate technology for a more sustainable 6G era.

#### 5.1.1 Energy Efficiency and Resource Allocation

Energy efficiency is still a key challenge in today's wireless communication systems. AI and ML are essential for ensuring that BS, network nodes and user devices use power wisely without sacrificing service quality. Several studies address how AI and ML methods can improve resources allocation and help in decision making.

Millimeter-Wave (mmWave) frequencies are crucial for 5G and beyond, because they provide a large amount of bandwidth for transmitting data at very high speeds. However, they suffer from significant path loss and are vulnerable to blockages in crowded city areas. This is a huge challenge that makes the decision of base station placement a crucial task for infrastructure design because it is essential for meeting coverage need and for supporting localization. To solve this complex multi-objective optimization problem, the systematic review in [43] proposes a DRL algorithm to optimize base station placement. The approach uses a Deep Q-Network (DQN) with a three-layer grid representation of the city layout and a well-designed reward function to balance coverage and localization accuracy. The findings show that this model achieves results similar to exhaustive search methods, with less computational costs and greater adaptability. Thus, the study concludes that multi-objective optimization through DRL is a promising method that can find the trade-off between coverage and accuracy.

Furthermore, the authors in [60] try to solve the same challenge of using mmWave frequencies with another algorithm. Addressing this problem requires deploying many small cells in ultra-dense networks but this introduces a new challenge, finding the right balance between received signal strength, coverage, deployment cost and energy consumption. Thus, it formulates a 3D cellular deployment as a multi-objective optimization problem and presents the VA-NSGA-II algorithm. This algorithm is an enhanced update of the classical Non-dominated Sorting Genetic Algorithm II. This one optimizes Received Signal Strength Indicator(RSSI), coverage and deployment cost but simultaneously considers the impact of building interference. This article provide analysis and recommendations for different environment, such as rural areas (low population density), suburban areas (penetration loss is high), smart cities (high concentration of connected devices) and mountainous observatory areas. In the Table IV lists the prioritized objectives for each scenario. For instance, in rural areas with low population density, the base station's coverage is sufficient. However if RSSI is prioritized, deployment costs could become too high for operators. Thus, this is a way to

showing how AI-inspired metaheuristics are being used to improve resource allocation, which can lead to greater energy efficiency and sustainability in 6G networks.

Table IV. Prioritized Objectives for each scenario [60]

Scenes	Rural Area	Suburban Area	Smart City	Mountain Observatory
Coverage	X	X	X	X
RSSI	-	-	X	X
Deployment Cost	X	X	-	-

Both works that introduced in [10] and [12] discuss how AI and ML can support more sustainable 6G systems by improving energy efficiency and resources use. The work in [10] explores the way that FL can optimize computation and communicate resources in Industrial IoT environments. By keeping data locally while sharing only models updates, FL reduces communication overhead, protects privacy and lowers the energy consumption of large-scale training. This makes it greater fit scenarios, where efficiency and sustainability matter.

Building upon this concept, the authors in [12] investigate how surplus RE from sources like wind or solar power can help meet the high computing needs of distributed and FL in 6G. The study points out the issue of changing RE supply and suggests using predictive AI models, such as ARIMA, so as to handle server failures and improve task scheduling. In this way, the article connects resource use to sustainability, showing how distributed AI training can be more environmentally friendly by using RE more effectively

Thus, these two works provide strong evidence that AI and ML based approaches, through FL and RE resources are key enablers for creating a sustainable 6G.

### 5.1.2 Orchestration and Automation

Beyond direct energy savings, AI/ML plays an important role in managing network resources and automating operations. As networks become more and more complex, including both terrestrial and non-terrestrial nodes and various service requirements, smart orchestration is necessary to maintain sustainability while also achieving good performance.

An article that gives a characteristic example for smart orchestration is suggested in [47]. A big obstacle that mankind must overcome is the challenge of balancing energy efficiency with QoS in the 6G era. In next generation wireless systems the RAN uses most of the energy. This makes service-oriented slicing both a necessary solution and challenge. It improves resource use through virtualization but can also lead to high energy costs. The authors present a Sustainable Service-Oriented (SSO) scheduler that manages both the distribution of tasks and the allocation of resources. The proposed solution uses Meta Reinforcement Learning (MRL), which treat each service type as a distinct RL problem. Workload distribution is solved by convex optimization resource allocation is handled by Q-learning policy. The paper's simulation findings show that this method greatly reduces long-term energy use compared to other approaches while still maintaining good performance. This proves that AI and ML are crucial for making AI-based 6G networks more environmentally friendly and sustainable.

As 6G networks will need many BS and edge servers, which results in high energy costs, Edge intelligence is another emerging area in orchestration. Q. Wang and K. Yang J. Hu in[46] introduce a new structure that combines AI, edge computing and mobility management to support sustainable 6G systems. The Mobility-Enhanced Edge inTelligence (MEET) framework shows how AI-supported orchestration at the network edge can manage highly mobile situations in 6G, like autonomous vehicles and drones. By using AI methods such us Recurrent Neural Networks (RNNs), GNNs and fuzzy logic, MEET allows for better mobility prediction and real time management of edge resources.

Thus, the study shows how AI-driven methods can lower energy consumption, improve traffic routing and ensure dependable QoS in fast changing settings like intelligent transport. Simulation results show that MEET reduces how orchestration with AI and ML directly leads to more energy efficient and sustainable 6G networks.

Another article that can be categorized in “Orchestration and Automation” for AI/ML technologies suggested in[61]. It presents the EcoEdgeTwin framework, which combines Mobile Edge Computing (MEC) and Digital Twins (DTs) to manage network resources in 6G more effectively. MEC offers quick local computing power, while DTs serve as virtual replicas that forecast network conditions and assist with decision-making. This integration allows the system to automatically respond to user movement, service demand and network changes, aiming to lower energy use, reduce latency and enhance user experience.

A main feature of EcoEdgeTwin is its use of DRL, especially the Advantage Astor-Critic algorithm, to manage resource allocation, transferring tasks and service migration in real time. This method is different from traditional static approaches, because it is predictive and more flexible, making the orchestration process smarter and more energy efficient. Simulation results show clearly, improvements in energy savings and latency reduction in comparison with existing methods. Overall, the work underscores how AI-driven orchestration and DT-based automation can play a key role in sustainable 6G networks.

While AI/ML methods can become key enablers for the orchestration of 6G networks, there are still many challenges to be overcome. The reliance on large AI models for orchestration increases computational complexity, which can prevent sustainability goals if not managed well.

### **5.1.3 QoE, Reliability and Anomaly Detection**

Sustainability in wireless networks is not only about reducing energy use, but also about maintaining high reliability and user satisfaction. AI and ML provide powerful tools to monitor and predict QoE and detect anomalies.

The authors in [45] present a new optimization method called Improves Adaptive Differential Evolution algorithm (IADE). IADE is based on the traditional Differential Evolution algorithm, which is a commonly used optimization technique. It introduces dynamic adjustments to key parameters like the mutation factor, crossover rate and selection strategy. This adaptive approach helps IADE avoid frequent issues such as slow convergence and getting stuck in local optima. It also makes resource allocation more efficient in large-scale 6G systems.

Thus, the article shows that IADE makes three essential contributions. First, by better managing how tasks are distributed and how resources are allocated, it reduces latency and provides more stable services, ultimately improving the user experience. Second, its adaptive design increases reliability, ensuring steady performance even with highly variable 6G traffic conditions. Third, the self adjusting

feature of IADE helps prevent anomalies like resource bottlenecks and excessive energy use. This article shows how an AI-driven optimization algorithm like IADE can enhance sustainability while maintaining service quality in future 6G networks.

Another paper contributing to this category is Shaman Bhat’s work in[44]. This article shows how Big Data Analytics (BDA) can help 5G enabled IoT and Industrial IoT systems create sustainable smart cities. It highlights the huge and diverse data generated to billions of connected devices needs to be processed to ensure reliable performance and secure data handling. By using methods like classification, clustering and prediction, BDA can detect anomalies in data streams, predict system failures and improve service quality for critical applications such as healthcare, smart grid and intelligent transport.

Figure 8 shows the connection between IoT systems and big data management. In the first step, IoT data sources like sensors work with various applications to generate complex data. This data has the typical features of big data, including high volume, speed and variability and is stored in distributed storage solutions. Analytical systems then process these large datasets through four layers of analytics: reporting, querying, analytical tools and training data. This helps to extract valuable insights. By following this process BDA supports better decision-making in IoT systems and enhances sustainable services in areas like smart grids, transportation, healthcare and inventory systems.

Overall, Shaman Bhat in [44] shows that combining BDA with 5G-enabled IoT not only improves QoE and reliability, but also ensures that anomalies are detected early. This makes smart cities services more sustainable and resilient. Thus, the above research shows that AI, ML and BDA can make 6G and IoT systems stronger and better for the environment, keeping simultaneously high the experience of users.

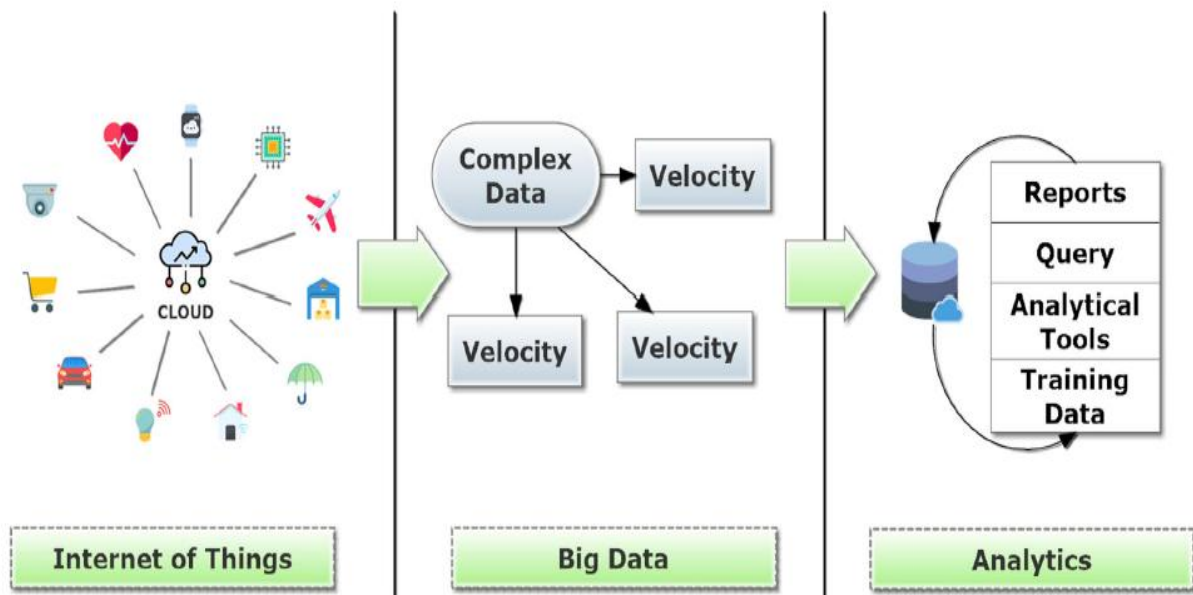


Figure 8 BD Analytics and IoT relationship [44]

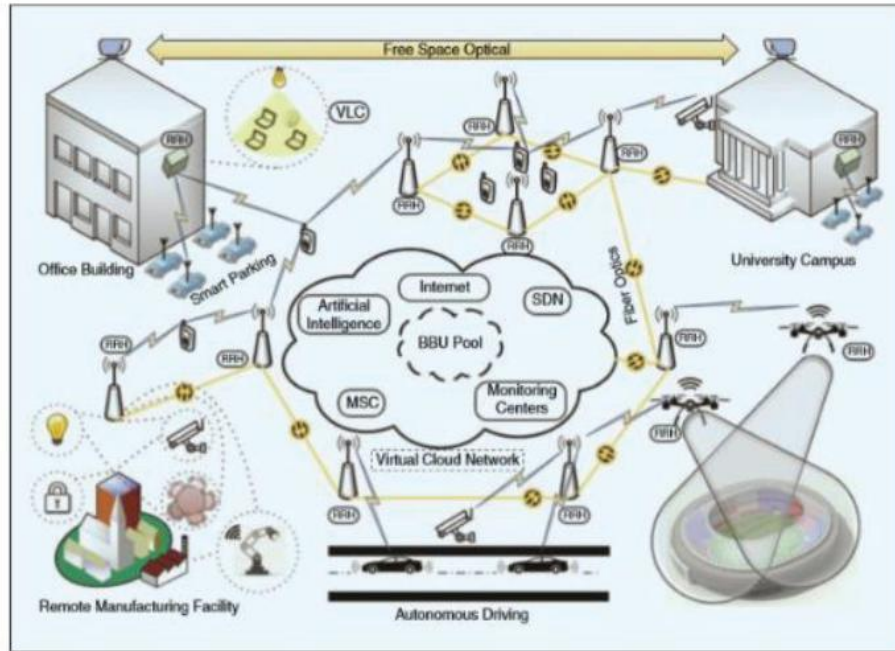


Figure 9 6G setup displaying all requirements [13]

#### 5.1.4 Emerging Technologies

The most promising area of AI/ML technologies for green communications is perhaps its connection with new technologies that change how networks are designed and managed. These innovations go beyond traditional resource allocation and management and characterized by new ways of thinking.

The work in [13] highlights how 6G networks will use advanced AI to achieve ultra-fast connectivity, very low latency and massive connectivity while staying sustainable. By putting AI at the center of network design, 6G can support new applications like autonomous driving, remote manufacturing and smart cities. It will also enable greener methods, such as energy efficient communication protocols and proactive fault detection. This makes 6G not just a technological upgrade but also a foundation for sustainable development.

Figure 9 shows a complete 6G setup that demonstrates how different technologies and applications fit together in one system. It connects various environments, including office buildings, university campuses, smart parking systems and remote manufacturing, through advanced communication methods like free-space optics, Visual Light Communication (VLC) and AI-powered control. Centralized functions like cloud networks, monitoring centers and AI-based orchestration ensure effective resource management across applications such as autonomous driving and large scale industrial systems. Figure9 shows the vision of 6G as an ecosystem where new technologies and AI work together to support green, reliable and sustainable communications.

Furthermore, the works in[10] and [12] were already discussed under 5.1.1 as both of them focus on reducing energy use and managing resources better in future 6G systems. However, both articles also fit into current category because they not only propose ways to improve efficiency but also offer new concepts that could change how 6G networks are designed and run. This dual relevance shows that some technological innovations can impact multiple aspects of sustainable communications.

The authors in[10] highlight the role of FL as more than an energy-saving method but it also presents FL as a groundbreaking technology that moves intelligence closer to the network edge. Rather than centralizing large amounts of raw data, FL allows for collaborative training across different devices while maintaining privacy and cutting down communication costs. This distributed intelligence approach marks a new design direction for 6G, making large-scale IIoT systems more autonomous, secure and sustainable.

Moreover, the authors in[12] introduce a different but connected idea by examining how surplus RE can be used to power distributed AI clusters in 6G networks. By employing predictive AI models to assess RE availability and adaptively scheduling computational tasks. It creates a model that integrates energy systems with communication networks. This presents a forward-thinking vision where AI does not just function within networks but also connects them with outside infrastructures to promote sustainability at a broad level.

Building upon this concept, works in [10] and [12] show that new technologies in AI/ML go beyond simple improvements. They reshape the architecture and sustainability framework of future 6G networks. Furthermore they show how FL and renewable-energy-powered AI clusters can serve as foundational elements for a new generation of networks, where intelligence and sustainability are tightly linked.

Similarly, the work in[61] was already mentioned in 5.1.2 because it focused on AI-driven resource allocation but it also belongs to current category because it presents a new integration of MEC and DT to create predictive, adaptive and energy-aware 6G systems. DTs create virtual copies of physical systems, allowing for continuous monitoring and simulation. From the other side, MEC makes sure that computation and decision-making happen close to the user. With the help of AI tools, such as DRL, the framework can manage task offloading, service migration and resource allocation effectively. Thus, it balances latency, energy use and QoE making EcoEdgeTwin something more than just a tool for better management. EcoEdgeTwin is not just a way to improve efficiency but it is a new design idea that demonstrates how the merging of physical and digital elements can change the way sustainable next-generation networks are built.

M. Georgiades and M. S. Poullas in[11] present the Pervasive Multi-Level AI (PML-AI) framework as a response to three main issues of AI in 6G networks: high energy use, the need for real-time decision-making and the difficulty in controlling AI models. The framework combines Knowledge Graphs, lightweight AI models and DTs to improve both efficiency and safety in next-generation smart networks. This method reduces computational complexity and helps the sustainability of the future networks.

Figure 10 shows a simplified version of the PML-AI framework, in which included two interdependent cycles: the outer cycle, which gathers and organizes large-scale wireless data using Knowledge Graphs and creates a precise DT of the network. The inner cycle works with real-time data and lightweight AI models to make quick decisions. Before these decisions are put in action, they are verified in the same DT to ensure reliability and stability. This design shows how new AI technologies can support the green and sustainable 6G networks.

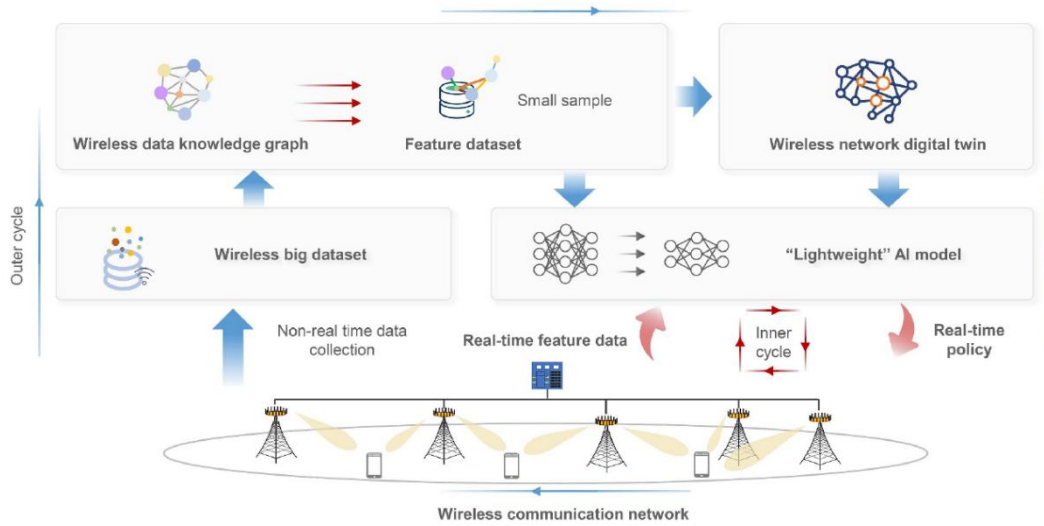


Figure 10 Pervasive Multi-Level (PML) – AI framework [11]

In summary, AI and ML are central to developing sustainable 6G networks. Various approaches, such as resource allocation, energy efficiency, reliability and new frameworks like FL and DTs show that intelligence can make future communications both greener and reliable. Table V presents a detailed list of the papers that have been categorized, including the most important issues that they address.

TableV List of Papers in AI/ML for Green Communications category and coverage issues

Article	AI/ML for Green Communications				Focus and Coverage (Key Findings)	Type of Study	Year
	Energy Efficiency and Resource Allocation	Orchestration & Automation	QoE, Reliability and Anomaly Detection	Emerging Technologies			
[13]				X	Highlights how the use of AI will achieve ultra-fast connectivity, very low latency and sustainable networks in 6G	Conceptual / Theoretical Paper	2024
[43]	X				Multi-objective DRL to optimize base station placement. DQN to balance coverage and localization accuracy	Experimental / Simulation Study	2024
[60]	X				Formulate 3D cell deployment with multi-objective AI models. Prioritize objectives for different area scenarios	Methodological Paper	2025
[10]	X			X	Focus on federated learning for IIoT, reducing energy cost and preserving data privacy.	Survey / Review Paper	2024
[12]	X			X	Distributed learning clusters powered by surplus renewable energy, shows potential of AI/ML for green training	Experimental / Simulation Study	2023
[47]		X			Proposes AI-native service-oriented RAN slicing to optimize energy and resource usage.	Methodological Paper	2023
[46]		X			Introduces MEET framework, mobility-enhanced edge intelligence for efficient orchestration and reduced energy.	Experimental / Simulation Study	2024
[61]		X		X	EcoEdgeTwin framework using digital twins for sustainable orchestration and predictive management.	Methodological Paper	2025

Article	AI/ML for Green Communications				Focus and Coverage (Key Findings)	Type of Study	Year
	Energy Efficiency and Resource Allocation	Orchestration & Automation	QoE, Reliability and Anomaly Detection	Emerging Technologies			
[45]			X		Proposes improved differential evolution algorithms (IADE) to ensure sustainable network operations, with focus on fault prediction and anomaly detection.	Methodological Paper	2021
[44]			X		Uses big data analytics and AI/ML for QoE prediction, anomaly detection, and proactive network management	Survey / Review Paper	2022
[11]				X	Discusses future paradigms: neuromorphic computing, quantum ML, lightweight AI models for sustainability.	Survey / Review Paper	2025

## 5.2 Sustainable Networks Management

As 5G networks expand in the whole world and the 6G research grows up, there is a big conversation about the environmental impact of telecom infrastructure. SNM is a way of redesign networks operation, combining performance optimization and ecological responsibility. The literature highlights key points, such as energy-aware network slicing, flexible orchestration through O-RAN, end-to-end QoE management and carbon-aware resource allocation. Putting all these elements together, it is clear that the 6G networks are moving away from focusing only on performance but also prioritize sustainability too, trying to balancing between service quality and environmental impact.

### 5.2.1 Network Slicing for Sustainability

Network slicing is essential for 5G and 6G technologies. It helps support flexible and personalized services over shared infrastructures. It is not only improving performance but also it promotes sustainability by allowing for dynamic resource allocation. This minimizes energy waste and lowers the carbon footprint of network operations. By integrating AI and ML in orchestration, slicing architectures can include energy awareness throughout their lifecycle. This makes network slicing a technical approach but simultaneously a sustainability-focused strategy for future networks.

The work in[15] discusses how to incorporate energy-saving methods into 6G networks slicing architectures to reduce the carbon footprint of telecommunication systems. By using the SFI2 reference architecture, the authors suggest deploying ML-native agents that adjust resources based on user needs. A key contribution of the work is applying contrastive learning to spot anomalies in energy use and improve resource allocation efficiency.

Figure 11 shows the SFI2 Network Slicing Reference Architecture. It provides a clear view of how network slices are created, deployed and managed. The Slice Builder module selects and organizes resources from the available infrastructure. The Slice Instantiator deploys the configured slice and ensures resource efficiency. Once it is running, the Slice Supervisor monitors the slice's performance and reconfigures it when needed to respond to changes in traffic, user behavior or Service Level Agreement (SLA) adjustments. ML-based optimizations are included at each stage, allowing for proactive energy management and resource organization. The architecture also emphasizes energy-efficient slicing and integrated security features as essential components.

By combining these elements, the figure shows how sustainability is part of the slicing lifecycle. The paper concludes that ML-based optimization, especially through contrastive learning, allows for more flexible and energy-efficient 6G network management, supporting directly to global sustainability goals.

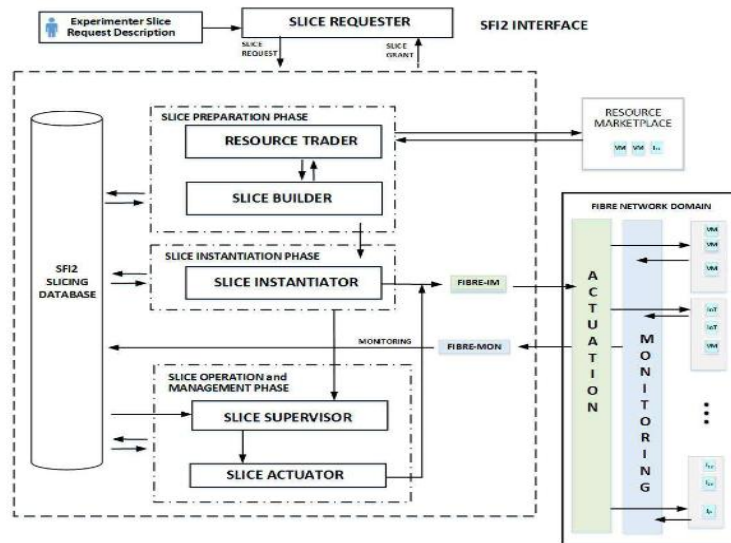


Figure 11 The Slicing Future Internet Infrastructures (SFIZ) Network Slicing Reference Architecture [15]

### 5.2.2 O-RAN and Open Architectures for Sustainable Management

O-RAN and open architectures go beyond traditional proprietary, closed RAN models. They break apart hardware and software, enable virtualization and use standardized open interfaces. This change allows for flexible integration with multiple vendors and promotes more cost-effective innovation. At the same time, O-RAN supports sustainability by incorporating AI-driven and energy-efficient resource management. This positions it as both a performance booster for 5G/6G and a way to develop greener, more adaptable networks.

A detailed overview of O-RAN as a game-changing model for future mobile communications is given in [62]. It shows how disaggregation, virtualization and open interfaces create flexible, cost-effective and compatible infrastructures. This approach reduces vendor lock-in and encourages innovation. The paper points out how intelligent controllers (RICs) and cloud-native O-cloud platforms help with dynamic resource allocation, optimization driven by AI and energy-saving operations, making O-RAN a reliable platform for SNM.

The study reviews over 800 papers to discover key contributors, main research areas and trials led by industry, highlighting O-RAN global importance. It concludes that O-RAN not only improves performance and scalability in 5G and 6G systems but also include sustainability in network design. By blending openness with AI-driven management, O-RAN stands out as both a technological and management framework to build green and more adaptable mobile networks.

### 5.2.3 End-to-End QoE and Performance Management

Managing QoE and performance from start to finish has become a key challenge in creating sustainable 5G and 6G networks. Unlike traditional QoS metrics that focus mainly on network

parameters. QoE considers the user's point of view. It connects technical performance with how users perceive service quality. By using AI-driven monitoring, predictive analytics and adaptive resource management, operators can enhance both user satisfactions energy efficiency. This makes QoE-focused strategies vital for running sustainable networks while meeting that demanding needs of future digital services.

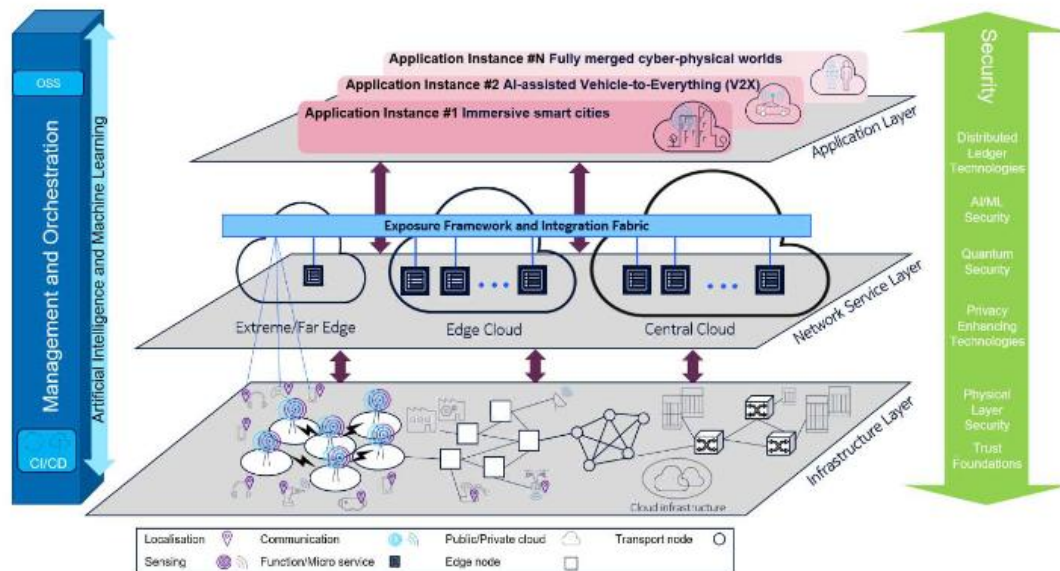


Figure 12 Hexa-X end-to-end 6G architecture integrating AI/ML-driven management, orchestration, and sustainability principles[3]

The work in[3] proposes a clear end-to-end architecture for future 6G networks. This framework comes from the European Hexa-X project. It focuses on integrating cloud-based, virtual functions along with AI and ML for management and orchestration. This approach aims for flexibility, improved automation and proactive optimization. A major innovation is linking the architecture with Key Value Indicators (KVI). These indicators measure aspects like sustainability, trust and digital inclusion, in addition to standard performance metrics. This way, the architecture meets the challenge of improving technical performance while also lowering energy consumption and supporting the UNSDGs.

Figure 12 presents the proposed Hexa-X end-to-end architecture. It shows the different functional layers, including the radio and core domains, as well as management, orchestration and security components. The diagram shows how these parts connect to form a complete system. It emphasizes the role of AI and ML as vital tools, the integration of land-based and satellite networks and the smooth coordination between edge, core and extreme-edge resources. By including this figure, readers can more easily understand how sustainability principles, like energy efficiency and resource adaptation, are built into the architecture. This visual aid makes the complex design more accessible, even for those who are less familiar with the technical details.

A new End-to-End Quality of Experience (E2E – QoE) framework is presented in[63], as a basis for sustainable 6G design. It argues that traditional Key Performance Indicator (KPI) or KQI-based optimization often leads to unnecessary energy use without significant improvements in the quality perceived by users. To undertake this issue, the authors suggest an E2E – QoE collaborative optimization model that brings together services, terminals and network components under a shared optimization goal. Figure 13 shows this model, breaking it down into three parts: E2E model, which predicts performance in technical transmission, the APP model, which turns impairments into service-

level quality and the QoE model, which reflects how users perceive the delivered service. This layered approach makes it clear how network parameters, application mechanisms and user experience connect within a single optimization framework.

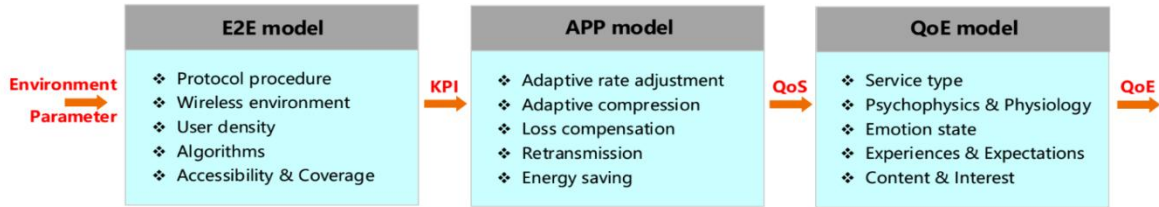


Figure13 Decoupling of the proposed E2E-QoE model into three pillars—E2E model, APP model, and QoE model [63]

Furthermore, this article also shows use cases such as offline planning, online decision-making using RL and the development of digital twins for QoE – focused testing. Experimental results with real 5G terminal data confirm the model’s feasibility, achieving over 97% accuracy in detecting anomalies and finding chances for energy savings in uplink transmission. The study concludes that E2E – QoE-based optimization offer a promising way to balance energy efficiency and user satisfaction, making it essential for sustainable 6G networks. The authors in [64] present a complete 5G slicing prototype that combines inter- and intra-slice management with ML to improve performance and sustainability. The framework uses SDN, which separates the control plane from the data plane to allow for programmable and flexible network control, and NFV, which substitutes dedicated hardware with virtualized, software-based functions. This combination creates a foundation for scalable and cost-effective network slicing.

Figure 14 shows the system framework. It highlights how user requests flow through the SDN/NFV infrastructure, are assigned to inter- and intra-slices, and are then managed by ML-based modules that handle classification, prediction, and optimization. The evaluation shows that decision tree-based classifiers reach over 97% accuracy in slice prediction while keeping low computational overhead. This result stands out from the anomaly detection accuracy found in other studies. By ensuring correct slice allocation with minimal resource use, the proposed system shows how end-to-end slicing enhanced by ML can improve QoS and QoE while also promoting energy efficiency and greener 5G networks.

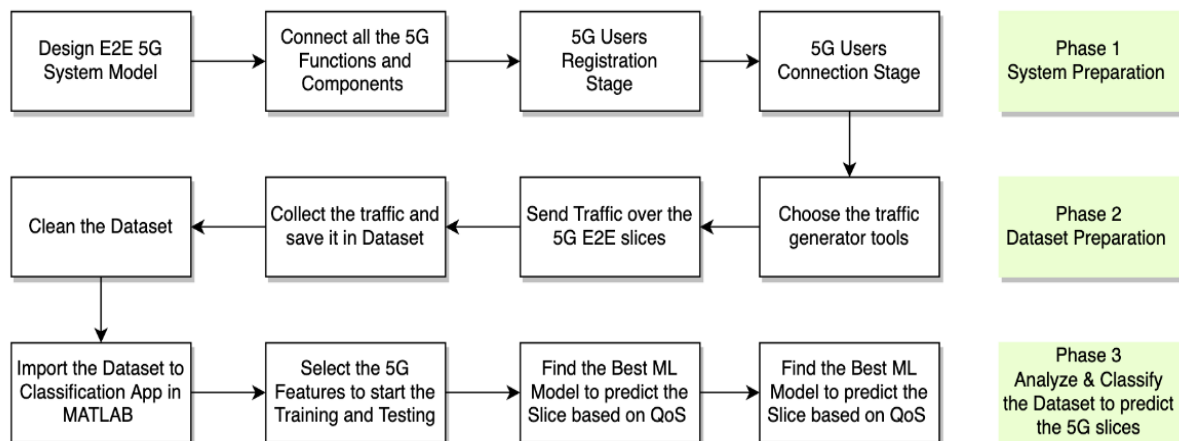


Figure 14 System framework of the proposed end-to-end 5G slicing architecture integrating SDN, NFV, and ML-based optimization [64]

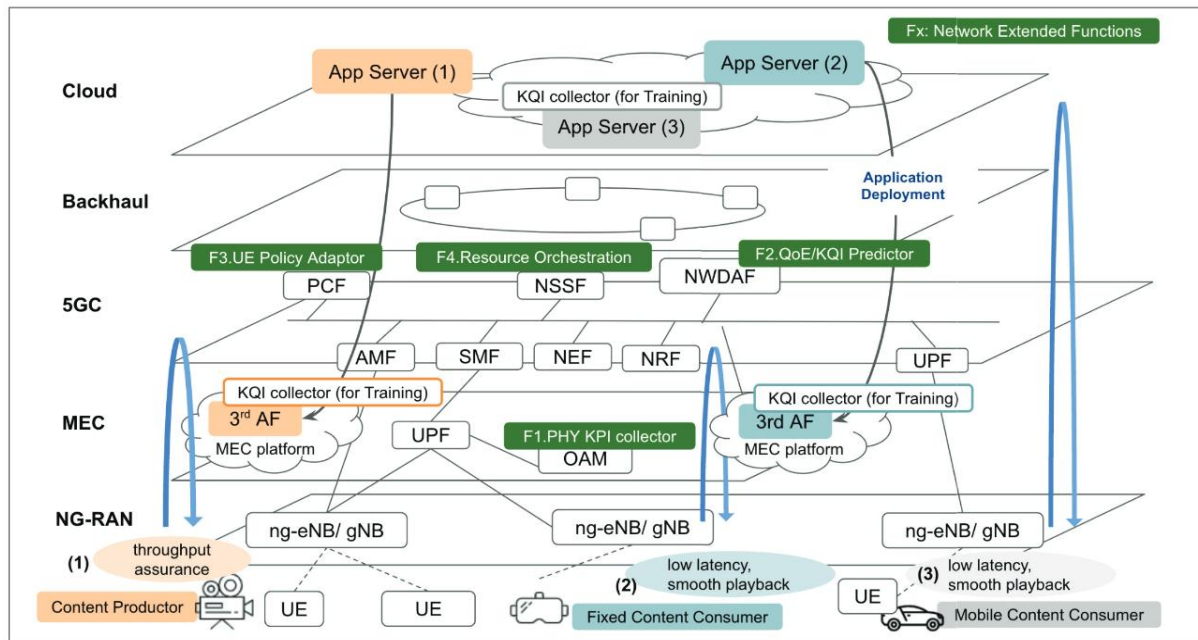


Figure 15 Proposed QoE sustainability architecture that includes KPI monitoring, QoE prediction, policy adaptation, and resource orchestration with NWDAF [65]

Furthermore, another article that belongs to this category, the one in [65] suggests a QoE sustainability framework for 5G and future 5G networks. It focuses on combining AI and ML prediction models with network functions like NWDAF, MEC, and network slicing. The framework defines QoE sustainability as the ability to maintain user-perceived quality while cutting down on energy use. This connects performance improvement with green communication goals. Figure 15 shows the suggested architecture. It includes extended functions such as a KPI collector to monitor QoS metrics, a QoE predictor that translates these metrics into user-focused quality levels, a UE policy adaptor that changes device behavior automatically, and a resource orchestrator that manages network resources efficiently. Together, these components work with NWDAF to allow real-time analysis and sustainability-focused management across the network.

Moreover, the paper highlights its ideas with examples like cloud VR gaming, where ML-based QoE prediction reached about 90% accuracy in spotting major stalling events during driving scenarios. It also argues that QoE-driven management can support new business models, such as Experience Level Agreements (ELAs), while improving energy efficiency. The study concludes that integrating QoE prediction and sustainability strategies into the core of 5G and future 5G networks is essential for delivering a reliable user experience and promoting environmentally friendly operations.

In conclusion, it is essential that all the studies above highlight the key role of end-to-end QoE management in building sustainable 5G and 6G networks. The focus is shifting from traditional and only using QoS or KPIs for optimization to connecting network performance with actual user experiences, changing also the aims to reduce energy use and costs. The works discussed propose different frameworks, like ML-driven QoE prediction, and end-to-end slicing. These ideas show that putting users first can lead to higher satisfaction and a smaller environmental impact. However,

significant challenges still exist. Measuring QoE in real time is difficult. There are not enough suitable datasets for ML training, and balancing user experience with energy efficiency can be complex. Overall, the literature suggests that QoE should be a main principle in designing future networks, but more research is needed to transition from experimental models to large-scale, real-world use.

#### 5.2.4 Energy- & Carbon-Aware Orchestration

As networks move towards 5G and 6G, the energy use and related carbon emissions from telecom infrastructures have become a major concern. Energy and carbon-aware orchestration means carefully managing resources, functions and workloads while keeping energy efficiency and sustainability in mind. With the help of AI, ML, virtualization, and real-time monitoring, orchestration frameworks aim to improve performance while also reducing energy waste and emissions. This new approach puts network management at the crossroads of digital advancement and environmental awareness, making it crucial for creating greener and more sustainable communication systems.

D. Chauhan et al. in [48] examine how smart environments can use IoT and 5G to manage energy in a more sustainable way. IoT sensors track both energy production and demand. 5G provides quick and reliable communication between devices and the controller. The centerpiece of the system is the Glowworm Swarm Optimization (GSO) algorithm. It serves as an energy-aware coordinator, matching supply and demand in real time. Tests indicate that this method cuts energy loss, prevents over- or under-allocation, and promotes better use of RE sources.

Figure 16 shows the proposed architecture. It depicts how IoT devices gather energy demand data and send it through the 5G network to a central controller. There, the GSO algorithm allocates energy resources effectively. The diagram outlines the flow from renewable sources to connected devices. It illustrates how sensing, communication, and optimization work together to support greener and more reliable energy use.

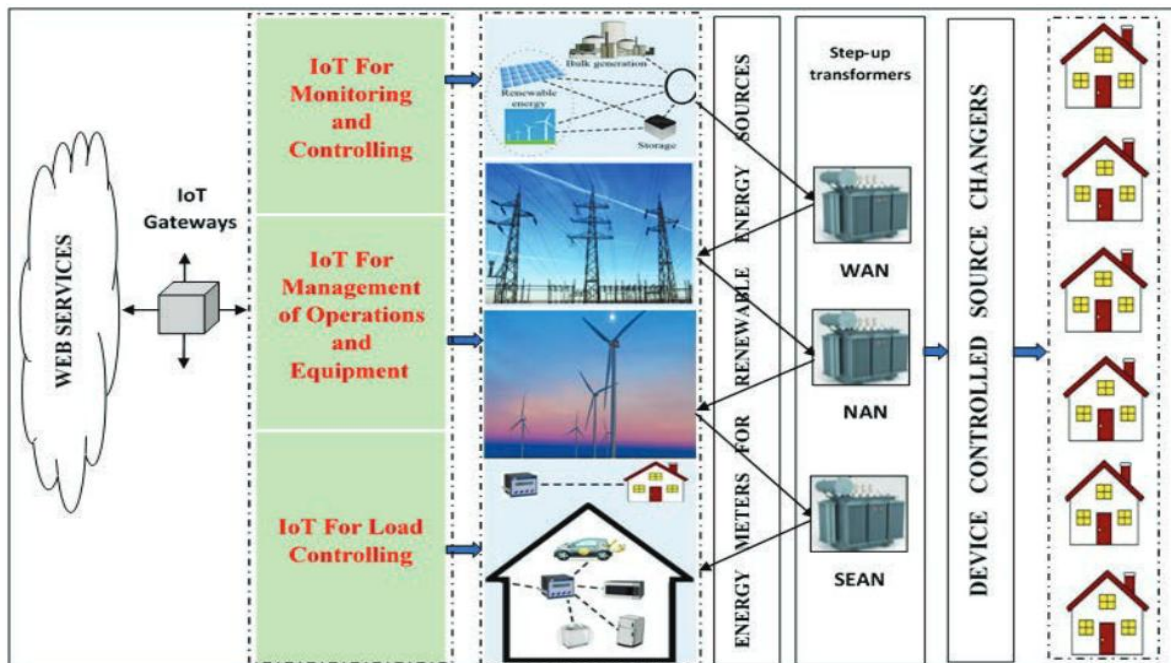


Figure 16 IoT and 5G setup for sustainable energy management using GSO [48]

Furthermore, the work in [66] proposes a sustainable business model for ultra-dense host. Instead of each operator setting up overlapping infrastructures, a neutral entity manages a shared network. This

approach lowers the Total Cost of Ownership (TCO) and reduces energy use. Among the architectural options considered, which include Digital DAS, small cells, and integrated C-RAN, the latter is noted as the most sustainable due to resource pooling and multi-tenancy. This method supports dynamic resource allocation and energy-aware operation by using virtualized RAN and Radio over Ethernet. However, challenges still exist in ensuring interoperability, fair agreements among operators, and sufficient regulatory support. In conclusion, the study finds that neutral host-based architectures can speed up UDN deployment while reducing carbon emissions, making them a promising step toward sustainable network development.

In [67], Q. Yang and A. Israr A. Israr examine how to use energy efficiently in 5G networks. This is necessary for sustainable development and connectivity in Industry 4.0. It reviews important techniques like RE harvesting, energy storage, and cooperation among BS. It also covers device-level approaches such as sleep modes, Device – to – Device (D2D) communication, and cyber-foraging. These methods aim to lower the high energy demand of ultra-dense deployments while supporting reliable industrial applications. A key finding is that combining RE with AI-based management can cut energy consumption by up to 78%. Despite these improvements, the paper points out challenges like managing interference, ensuring IoT security, and the lack of strong energy trading frameworks. Overall, it argues that being aware of energy and carbon use is crucial for making 5G sustainable and suitable for Industry 4.0.

While the previous article focused on energy efficiency in 5G to support Industry 4.0, the one in [68] shifts to another key cause of network energy use: the Over-The-Top (OTT) video distribution. It discusses the sustainability issues related to OTT video distribution, which makes up over 80% of global internet traffic and is one of the most energy-intensive applications. The authors propose a hybrid delivery framework that combines 5G multicast and unicast transmission with the new Versatile Video Coding (VVC) standard. VVC achieves up to 50% bitrate savings compared to High Efficiency Video Coding (HEVC) at the same quality level. Additionally, the framework includes Green-MPEG metadata that lets video players know about energy and quality trade-offs. This allows for adaptive playback choices that cut energy use without greatly affecting user experience.

The work in [68] shows the effectiveness of this method through quantitative evaluations. The results show potential savings of up to 75 kWh from better compression, 15 to 20% in display-related energy through HDR optimization, and extra radio resource savings when multicast is used for popular content. By coordinating video coding, adaptive playback, and delivery methods in a way that considers energy and carbon use, the paper outlines a path toward greener OTT streaming that benefits both operators and end-users in the 5G era and beyond.

Beyond application-level challenges, like video delivery, Elina et al. [49] adopt a network perspective, analyzing the complete energy footprint of 5G, including the power it uses to run, the energy it takes to build the equipment and the energy consumed by its users. This article examines the energy use implications of 5G technology from a comprehensive network perspective, rather than just focusing on the typical RAN considerations. The authors distinguish between three types of energy: operational energy, which refers to the power consumed during network operation, embodied energy, which is the energy required for manufacturing and deploying equipment and indirect effects, which include changes in user behavior and broader economic impacts. They believe that much of the current literature tends to concentrate exclusively on improvements at the RAN level, often neglecting the embodied and systemic dimensions that could counteract the anticipated efficiency gains.

Furthermore, the study highlights the risk of rebound effects, where improvements in efficiency may lead to increased overall consumption, such as more streaming or the use of data-intensive services. It concludes that achieving truly sustainable 5G requires not only technological innovations, like energy-efficient RAN, virtualization, and AI-driven optimization, but also coordinated policy interventions to ensure that these efficiency gains result in real reductions in energy use and carbon emissions. In this

context, the paper emphasizes the importance of energy- and carbon-aware orchestration at both technical and systemic levels.

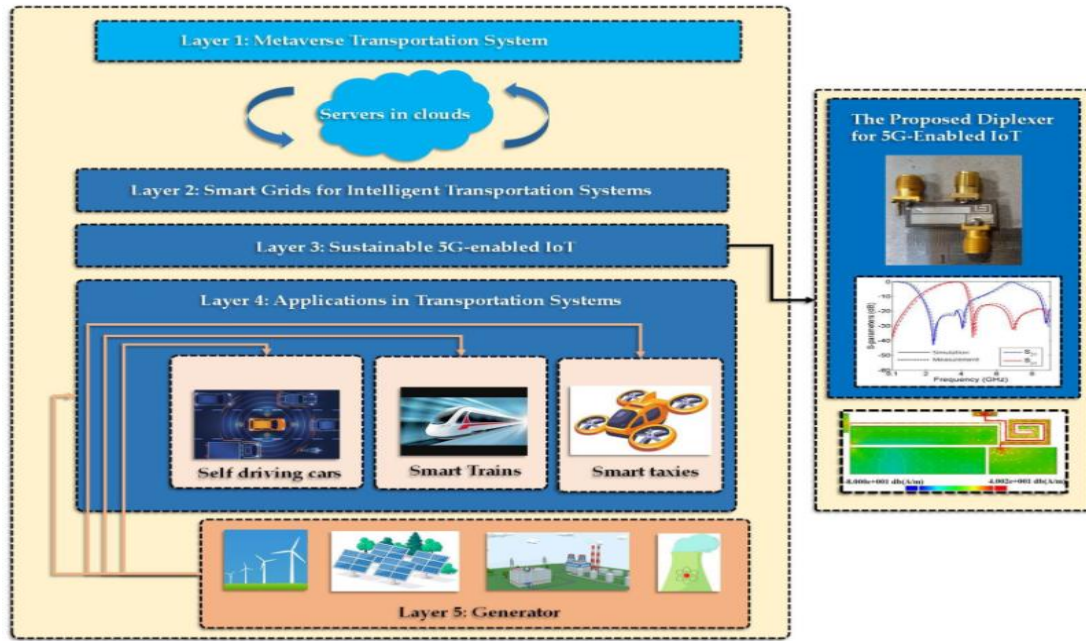


Figure 17 Five-layer architecture linking metaverse transportation, smart grids, and 5G-enabled IoT for sustainable operation [69]

Extending the discussion from whole-network impacts, the work in [69] highlights how efficient hardware design can contribute to energy- and carbon-aware orchestration. The article presents a compact and highly efficient microstrip diplexer designed to support sustainable 5G-enabled IoT applications in metaverse-based transportation systems and smart grids. By decreasing insertion losses and optimizing frequency separation, the diplexer improves energy efficiency at the device level, which is crucial for large-scale IoT deployments where power constraints are a significant challenge. The study highlights how advancements in hardware design can help lower the overall energy footprint of emerging 5G ecosystems while ensuring reliable connectivity for demanding applications, such as autonomous vehicles and intelligent power networks.

Figure 17 illustrates a five-layer architecture that positions the proposed diplexer within a broader sustainable ecosystem. These layers connect metaverse transportation systems and smart grids with 5G-enabled IoT infrastructure, transportation applications (including autonomous systems), and power generation sources. This layered approach emphasizes that energy-efficient hardware components, when integrated into system-level orchestration, can facilitate carbon-aware operations across various domains. By linking hardware innovation with system design, the study demonstrates that achieving sustainability in next-generation networks requires a coordinated effort between device-level efficiency and large-scale orchestration.

Moreover, Iqra Javid et al. [70] discuss device-level innovations for sustainable 5G-enabled IoT, specifically presenting the design and evaluation of an ultra-efficient GSM triplexer. This triplexer is designed to support smart grid edge computing and metaverse applications. It is remarkably compact and achieves very low insertion losses, ranging from 0.12 to 0.42 dB. This demonstrates how enhancing hardware efficiency can contribute directly to sustainable IoT deployments. By reducing energy consumption at the component level, this study connects device innovation with broader efforts for energy- and carbon-aware orchestration in next-generation networks.

Figure 18 shows a proposed multi-layer framework that integrates the triplexer into a sustainable 5G ecosystem. This architecture links cloud servers, edge computing layers, and 5G-enabled IoT devices with smart grids and metaverse platforms. Within this framework, the triplexer facilitates efficient frequency management and low-loss signal routing, reducing power demands across the system. The figure highlights how energy-efficient hardware, when incorporated into a layered orchestration of cloud, edge, and IoT resources, can support greener operations in complex domains like intelligent energy systems and immersive virtual environments. Together, the architecture illustrates that sustainable 5G networks require coordination between component-level efficiency and system-level orchestration.

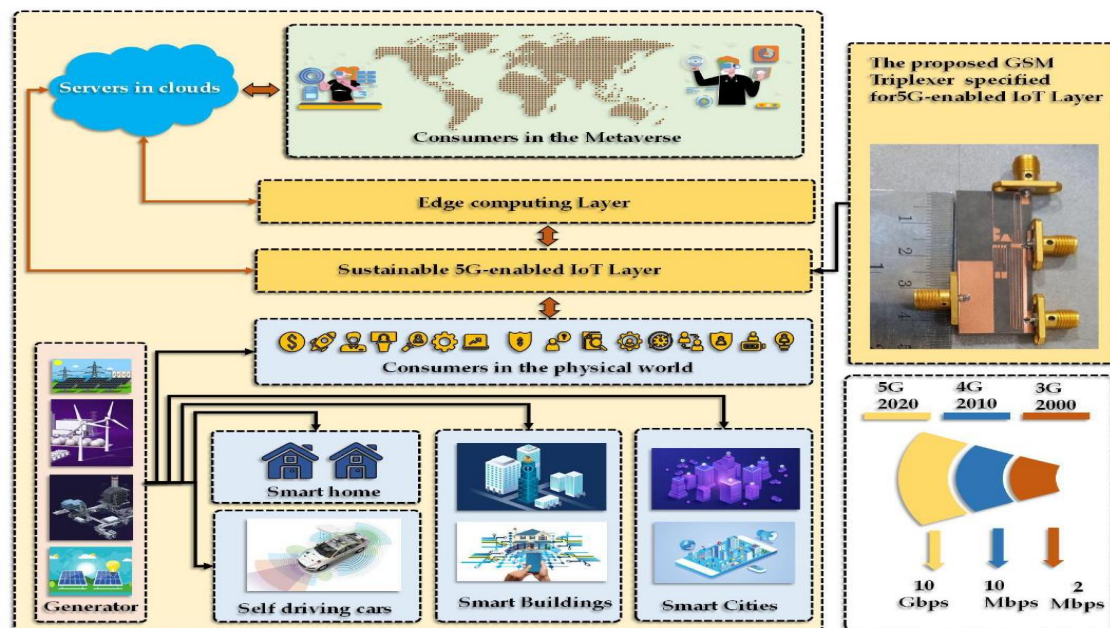


Figure 18 Multi-layer framework integrating the proposed triplexer into 5G-enabled IoT, smart grids, and metaverse systems for sustainable operation [70]

Another article that highlights the challenges of energy- and carbon-aware orchestration is the work in [71]. This article examines the environmental implications of China's extensive rollout of 5G technology, which has already established over 2.1 million BS. While 5G significantly boosts network capacity, the study reveals the existence of a "carbon efficiency trap," where energy consumption and CO<sub>2</sub> emissions rise more rapidly than traffic demand. Using real-world datasets and nationwide simulations, the authors estimate that the introduction of 5G could lead to an additional  $23.82 \pm 1.07$  megatons of CO<sub>2</sub> emissions per year.

To solve this problem, the work in [71] propose DeepEnergy, an AI-driven framework that employs collaborative RL and GNNs to optimize the operations of BS. The findings indicate potential emission reductions of up to 21 megatons annually, with even greater benefits when combined with photovoltaic energy. However, the framework is still largely in the modeling phase, and its scalability and compatibility with different types of infrastructure remain open questions. The study underscores the urgent need for energy- and carbon-aware orchestration in 5G while also highlighting the challenges in ensuring that proposed solutions provide measurable sustainability improvements in practice.

While earlier works emphasized systemic and infrastructural energy costs, the approach introduced in [72] explores how intelligent routing can enhance sustainability in wireless sensor deployments. This article discusses the challenges poses by limited energy resources in 5G/6G-enabled wireless sensor

networks. To enhance sustainability, the authors propose the Collaborative Energy-Efficient Routing Protocol (CEERP). This protocol integrates RL-based clustering with residual energy-driven selection of cluster heads and utilizes optimization through the Multi-Objective Improved Seagull Algorithm (MOISA).

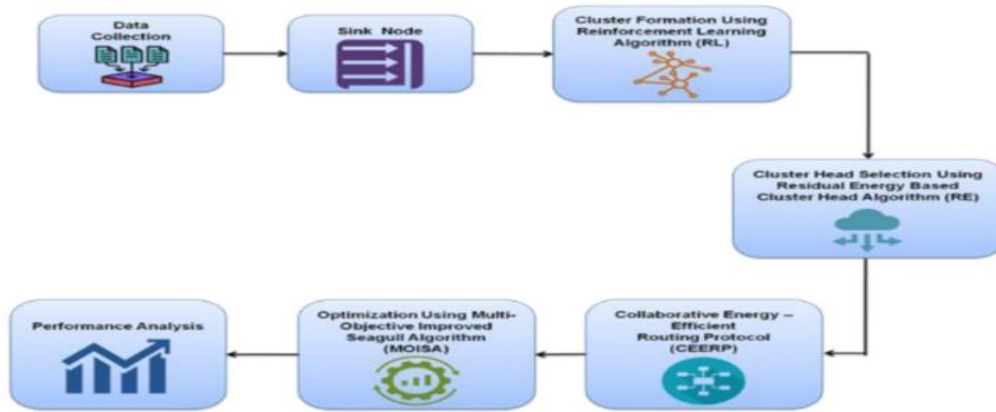


Figure 19 Workflow of the proposed CEERP protocol, from clustering to optimized routing for energy-efficient communication [72]

Figure 19 shows the workflow of CEERP, detailing how data from nodes is used for clustering, the selection of energy-aware cluster heads, optimization via MOISA, and ultimately, efficient routing toward the sink. This systematic approach showcases how collaborative and AI-driven management can effectively balance energy consumption and prolong network lifespan. Results show that CEERP reduces energy consumption by 50% while also improving throughput, packet delivery, and scalability. These findings make CEERP a promising option for achieving sustainable 5G/6G sensor deployments.

The survey in [50] builds on previous studies that emphasized the challenges of carbon efficiency in large-scale 5G deployments by exploring practical frameworks for emission-aware energy provision in ultra-dense 5G and B5G networks. The authors focus on the significant increase in energy demand and emissions caused by the growing number of Small Cell Base Stations (SCBSs), especially if they rely only on grid power. To solve this issue, two RE models are proposed: Centralized Renewable Energy Generation (CREG) and Distributed Renewable Energy Generation (DREG). Both models include a Resource-on-Demand (RoD) strategy, which allows SCBSs to enter sleep mode during periods of low traffic.

Figure 20 shows these two proposed RE models. In the CREG model, a central solar farm equipped with storage system supplies energy to a cluster of SCBSs. In contrast, the DREG model involves each SCBS having its own localized renewable generation and storage. This visual comparison highlights how the centralized approach can reduce redundancy and improve efficiency, while the distributed model offers flexibility but at the cost of higher infrastructure duplication. Simulation results show that CREG, when combined with the RoD strategy, provides better cost savings, enhances RE utilization, and reduces carbon emissions compared to DREG. The study emphasizes the importance of integrating RE systems with carbon-aware orchestration strategies to achieve both sustainability and performance goals in 5G and B5G networks.

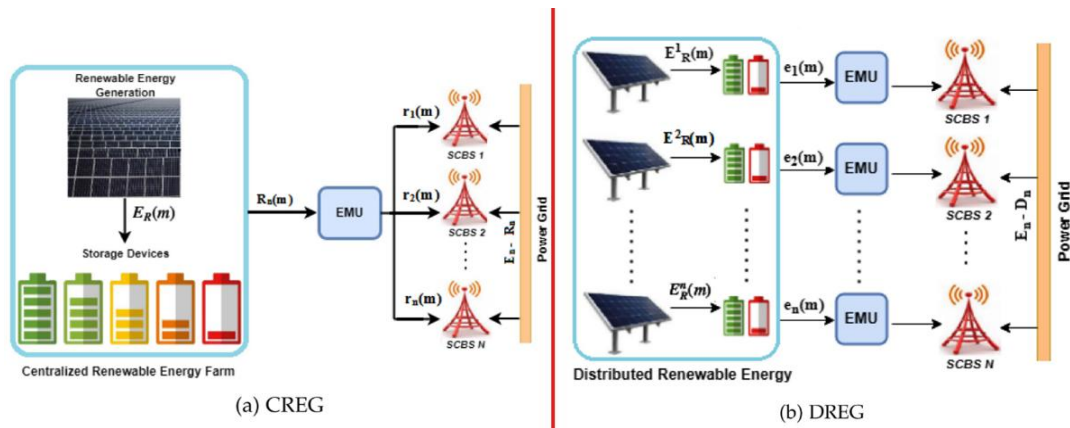


Figure 20 Centralized (CREG) and distributed (DREG) renewable energy configurations for powering small cell BS in 5G/B5G networks [50]

Continuing the discussion on energy-aware orchestration, the work in [73] proposes a comprehensive framework that merges RE microgeneration, traffic-aware offloading, and Advanced Sleep Modes (ASMs) to enhance the sustainability of 5G Heterogeneous Networks (HetNets). The authors emphasize that while renewable sources like solar power can decrease reliance on the power grid, their inherent variability make necessary careful integration with intelligent operational management techniques to maintain service quality.

Figure 21 presents the system architecture, where a centralized solar microgeneration farm with battery storage supplies power to both macro and small cell BS. The macro base station supervises the user offloading process to small cells and manages their transition into sleep states during periods of low traffic, thereby reducing energy waste. This integration enables the network to maximize the use of RE, minimize carbon emissions, and lower operational costs. In the end, the results show significant energy savings—up to 90% in optimal solar conditions—while still ensuring service quality. This highlights the potential of combining energy provision and operational strategies for creating sustainable 5G infrastructures.

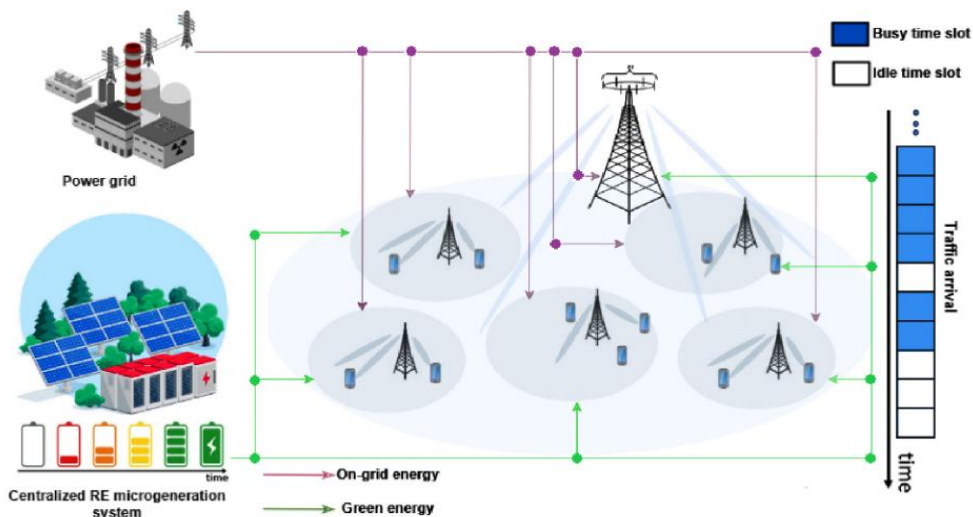


Figure 21 The architecture of a 5G HetNet [73]

Based on previous research into sustainable management of 5G infrastructures, G. Fontani et al. [74] highlight the substantial energy footprint of BS, which are responsible for most of the network's power consumption. The authors introduce the Energy Consumption Optimization Algorithm (ECO), a low-complexity solution that dynamically assigns users to either macro or pico BS based on traffic load and energy efficiency considerations. This approach centers around two key concepts: the energy break-even point, which indicates when a pico cell becomes more energy-efficient than a macro cell, and the load index, which ensures that the QoS for users is maintained.

As the work in [74] shows, ECO achieves performance levels close to the theoretical optimum, with an energy consumption overhead of less than 3%, even under high traffic conditions. Furthermore, this article highlights that intelligent orchestration strategies can significantly reduce the carbon footprint of 5G networks while preserving service quality. This emphasizes the importance of energy-aware decision-making in SNM.

Moving from cell-level energy optimization to a broader architectural viewpoint, authors in [75] investigate scalable and sustainable management strategies for 6G networks. The authors highlight the limitations of centralized orchestration and recommend for decentralized, hierarchical, and AI/ML-driven frameworks that can support zero-touch automation. The paper refers to the MonB5G project, showing how incorporating ML techniques, such as FL, can significantly reduce monitoring overhead and enhance energy efficiency, achieving over a tenfold improvement compared to traditional centralized models.

To verify this approach, the study presents a case study on VR video streaming, showing how distributed intelligence can maintain service quality while lowering energy costs. The research also recognizes challenges related to scalability, privacy, and user experience, emphasizing that achieving sustainable 6G requires not only technical innovations but also careful management of trade-offs between performance, efficiency, and trust.

In contrast to previous papers, the approach in [5] shifts its attention to how 6G networks can directly support the UN' SDGs. The authors claim that 6G will include advanced capabilities, such as pervasive sensing, ultra-low power IoT, satellite-terrestrial integration, and distributed AI, that can be orchestrated to advance objectives like clean energy, sustainable agriculture, healthcare, education, and resilient cities. By introducing the concept of SDG enablers, the paper highlights that sustainability should be a core design principle, rather than an afterthought, in future networks.

Figure 22 shows the fundamental approach to implementing 6G-enabled SDGs. It shows how inherent 6G features contribute to large-scale sensing and real-time data collection, which are after that processed through AI and ML at the edge, ensuring low latency and energy efficiency. These insights are then orchestrated into services that align with the SDGs, such as smart healthcare, carbon-aware transportation, and RE management. The figure emphasizes that 6G orchestration is not just a technical challenge, but also a socio-technical one, where coordination of energy-efficient technologies directly accelerates global sustainability efforts.

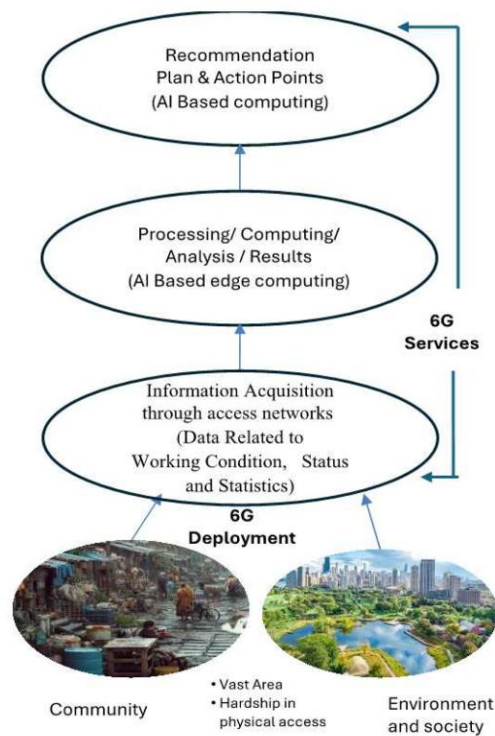


Figure 22 Basic framework showing how 6G native capabilities can be orchestrated to support the UN SDGs [5]

In addition to all above, the work in [76] presents a comprehensive architectural blueprint focused on sustainability. The authors highlight that sustainability should be integrated from the earliest design stages rather than being treated as an afterthought. The proposed architecture consists of several layers, encompassing applications, network functions, supporting functionalities, and hardware, leveraging technologies, such as explainable AI, semantic communications, digital twins, and blockchain. This approach aims to balance technical performance with environmental, societal, and economic considerations.

Figure 23, illustrates this sustainability-oriented 6G architecture, showing how the various layers interact with enabling technologies to deliver advanced use cases, including immersive Extended Reality (XR), collaborative robotics, and precision healthcare. Importantly, the diagram emphasizes that these technological advancements are interconnected with broader sustainability outcomes, such as energy efficiency, reduced carbon emissions, and improved social inclusion. Eventually, the study demonstrates that end-to-end orchestration in 6G must align technical innovation with the UN SDGs, making sustainability a crucial factor for success.

Moreover, the chapter in [77] explores a game-theoretic approach to managing congestion in ultra-dense 5G and 6G networks, especially within the context of integrating RE and emission-aware resource allocation. The authors use the Stackelberg model to design an incentive-based data offloading mechanism, where in Mobile Base Stations (MBS) act as leaders and Access Points (APs) serve as followers. The MBS offers rewards to APs that agree to manage part of the traffic load, while the APs compete to provide this service efficiently.

This redistribution of traffic reduces the burden on the MBS, which no longer needs to operate at high power levels continuously. As a result, the system achieves higher throughput, reduced delay, and improved spectrum utilization, all while lowering overall energy consumption. The study shows that

aligning economic motivations with technical optimization can improve both performance and sustainability in future dense network deployments.

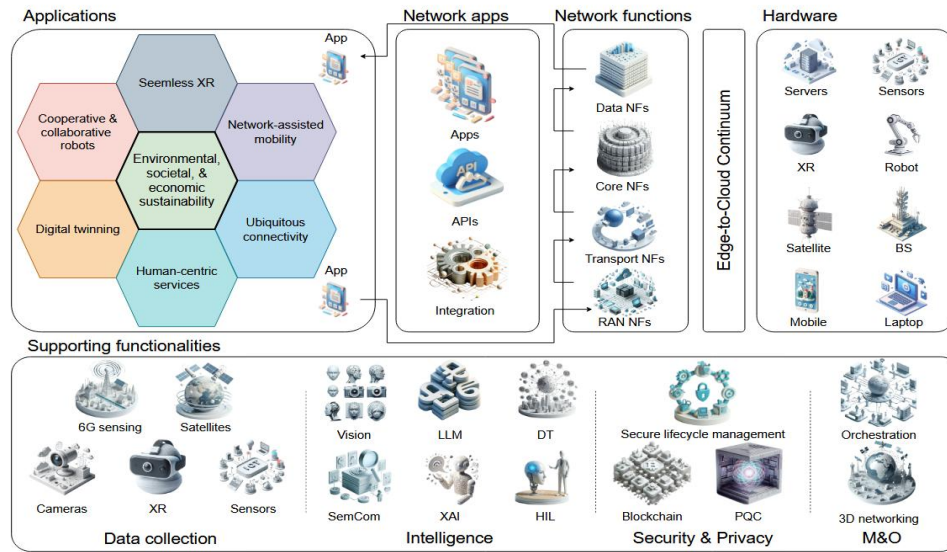


Figure 23 Sustainability-oriented architectural blueprint for 6G[76]

After examining a detailed model of energy use in 5G RANs, authors in[78] shift their focus to new approaches for orchestrating resources across the entire network. Continuing the emphasis on energy- and carbon-aware orchestration, this study presents a flexible energy modeling framework specifically for 5G RANs. The proposed model separates the physical layer into multiple computational blocks, enabling the estimation of energy consumption at each stage of signal processing. By tracking the number of operations and CPU cycles required, the model provides a detailed view of energy usage at both UE and BS. Validation against MATLAB simulations reveal a close alignment with real measurements, suggesting that this modeling can serve as a practical tool for identifying energy bottlenecks and guiding sustainable network design. In the end, this framework supports the development of more efficient orchestration strategies that reduce both operational costs and the carbon footprint of next-generation networks.

In addition to the above studies that talk explore about orchestration for sustainability, the work in[79] introduces Digital Twin Networks (DTNs) as a transformative tool for the future of 6G systems. The proposed reference architecture combines DNTs with in-network computing, the SDN and NFV paradigms to enable flexible management. In contrast with traditional KPIs monitoring, this framework emphasizes KVIs, such as energy efficiency and ethical considerations, merging network operations with broader sustainability goals.

The sustainability-oriented reference architecture is shown in Figure 24, where the physical 6G network is represented by a corresponding digital twin layer. The DTNs collect real-time data from the underlying infrastructure and input it into AI and ML-driven analytics engines. These analytics modules assess both performance metrics and KVIs, including energy consumption and environmental impact. The results, after, are sent to the orchestration layer, which uses SDN/NFV and intent-based management to dynamically allocate resources and improve service placement. The figure also emphasizes the integration of computing inside network, which allows processing tasks closer to the data source, thereby reducing latency and energy consumption. This design allows the network to prioritize green nodes and modify services, minimizing the reliance on non-renewable energy.

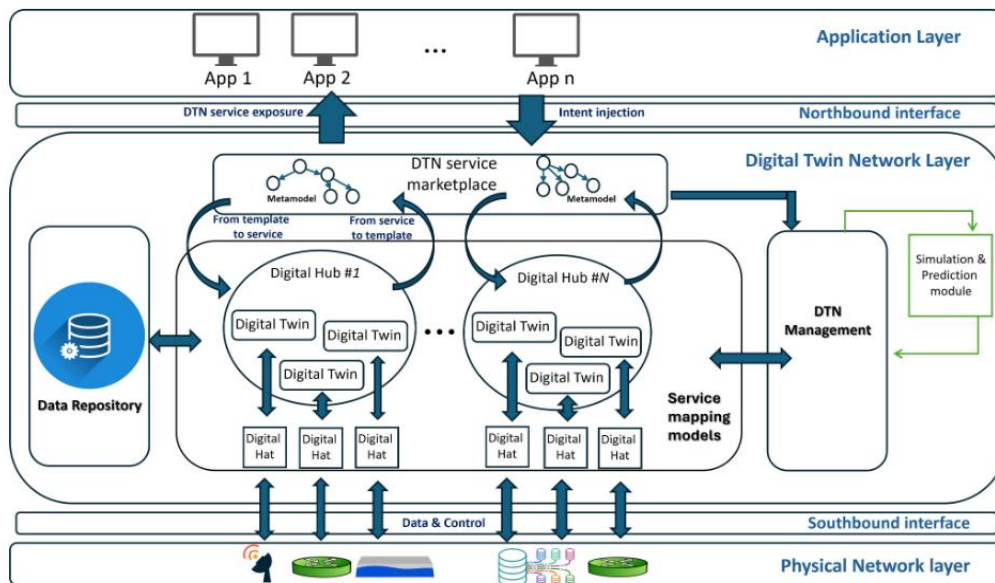


Figure 24 Reference architecture of Digital Twin Networks combining AI/ML, SDN/NFV, and in-network computing for sustainable 6G management[79]

While the last article focused on the utilization of DTNs with 6G for sustainable orchestration, authors in[80] turn their focus to the 5G capabilities to be leveraged to increase energy efficiency and decrease carbon footprint. It states that massive MIMO, dynamic spectrum sharing and network slicing effectively improve resource allocation and decrease power utilization, while SDN/NFV, MEC and energy harvesting help decrease CO<sub>2</sub> emissions. The technical advancements are placed within the context of application within smart cities, smart grids, transport and healthcare, positioning them as promoters of the UN SDGs. Thus, this article promotes that collaboration between industries and regulators is critical for future networks to ensure that new network architectures are both energy efficient and sustainable.

While prior literature showed how 5G technologies and orchestration can help virtualizes resources for 6G future and sustainability efforts, the approach introduced in[81] contributes by focusing on network sharing as an available facilitator for energy- and carbon-aware resource management. Network sharing of BS and spectrum frequencies enables multiple mobile operators to reduce capital and operational spending while simultaneously reducing energy usage. Data-driven resource offloading allows for traffic routing through fewer BS, facilitating the turn off nodes that are not fully utilized.

Thus, as shown by simulations in urban, suburban and rural environments, the approach can reduce energy consumption by as much as 40% while providing appropriate QoS. Additionally, it improves network flexibility during disruptions caused by natural disasters or storms and it can rely on green energy sources to further reduce carbon footprints. So, findings show that network sharing is the most productive and realistic way to achieve sustainable 5G infrastructure while easing the transition to 6G.

In the same category, the study in[82] introduces advanced AI-driven models for resource allocation and base station optimization in 6G networks. As depicts in Figure 25, the Hybrid Quantum Deep Learning Model (HQDLM) proposed relies on Convolutional Neural Networks (CNNs) for resource distribution and changing of networks while RNNs are used for load balancing and managing errors. The design of the system is layered in such a way that it predicts the slice allocation precisely. Furthermore, it also limits the energy-intensive misconfiguration.

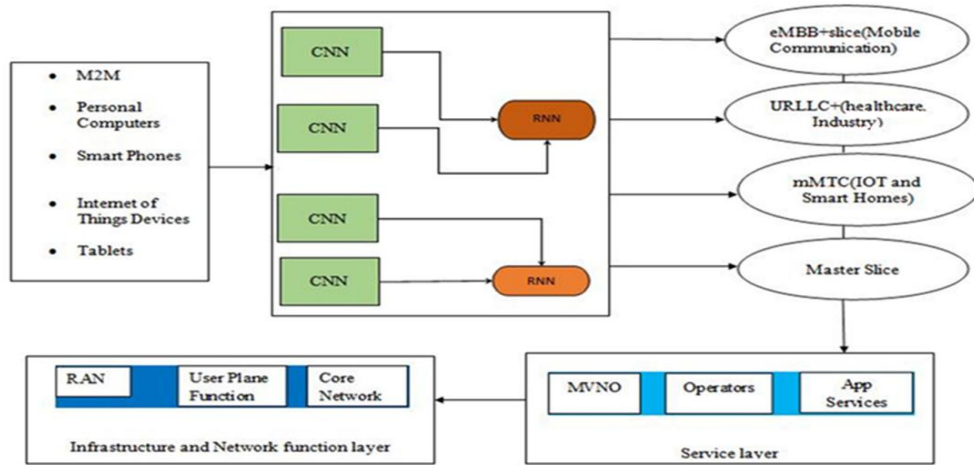


Figure 25 Architecture of the Hybrid Quantum Deep Learning Model (HQDLM) combining CNN-based resource allocation with RNN-driven load and error management [82]

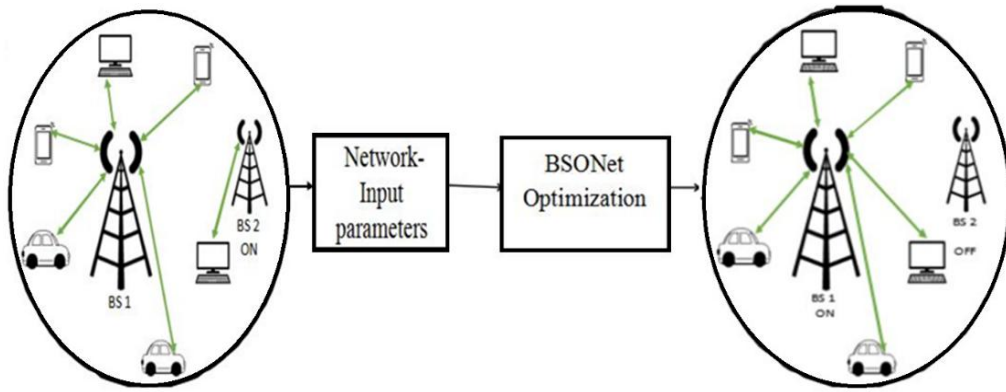


Figure 26 Base Station Optimizer net (BSO-net) architecture for dynamic on/off management of BS to reduce energy consumption[82]

Also, as shown in Figure 26, the Base Station Optimizer net (BSO-net) estimate traffic condition and accordingly, decides which BS should be active and which ones sleep. Without degrading service performing, the mechanism reduces power by about 2 dB. In cooperation, the two architectures present predictions of slice behavior and resource optimization of up to 98% representing how deep learning hybrid techniques can directly enable energy- and carbon-aware orchestration in 6G.

Unlike the earlier studies in this section that are more research-based, the work in[1]is an open letter from several EU projects, appealing for sustainability to be the main guiding principle of 6G. The “Towards Sustainable 6G” workshop invited seven EU funded projects to share the strategies they have devised to moderate the ecological footprint of future telecommunications networks. The projects include BeGREEN, 6G-TWIN, GGreen and more.

According to the open letter, energy- and carbon-aware orchestration relies on AI-driven optimization, integrating RE and collaboration across disciplines. It also includes the adoption of Key Value and Sustainability Indicators to align technical performance with environmental and social target. In the eyes of the authors, sustainability in 6G is not a choice but a necessity. Researchers, policymakers and industry members, all must ensure environmental sustainability is always forefront in mind while planning for future telecommunications.

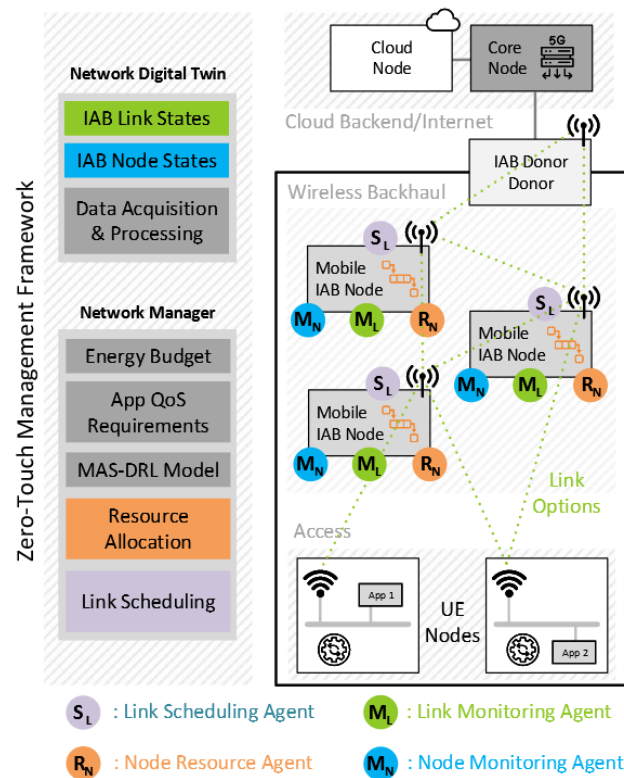


Figure 27 ZTM framework with a NDT and multi-agent DRL optimizing energy use in 5G+ IAB networks [83]

Another article that belongs to this category is the approach introduced in [83] talks about how Integrated Access and Backhaul (IAB) networks can contribute to sustainable 5G+ deployments. Presently, most IAB nodes are wired, the study highlights that battery-powered IABs may be a solution for nomadic scenarios, such as disaster relief and construction. However, these scenarios raise new questions regarding QoS versus energy efficiency.

As depicted in Figure 27, a Network Digital Twin (NDT) enables the Zero-Touch Management (ZTM) of the physical IAB network. The NDT uses several agents within the same block to optimize routing, scheduling and energy use. It puts less-utilized nodes in sleep mode and uses links efficiently. The system saves energy without loss of reliability via an autonomous loop between the physical network and its twin. According to the authors, AI-based ZTM can lead to greener and more flexible 5G+ deployments however, there is a need for more research to optimize Battery IABs.

I. Ahmad et al[84] explore how 5G networks can connect with DT technology to build energy systems that are both intelligent and efficient. DT act like a virtual copy of physical infrastructures, improving control and prediction, while simultaneously, 5G connectivity ensures real-time monitoring and improves energy flows. By merge IoT sensors, AI/ML analytics and high speed communication the paper’s approach supports the combination of renewable, improves efficiency and reduces emissions. The authors come to the conclusion that this synergy of 5G and DT technologies is not just technical progress but it can help build a greener energy system.

The work in[85] continues the discussion about scheduling tasks considering energy use, carbon output and exploring what we can call “smart intelligence” for 5G and 6G networks. The authors used frameworks developed by ETSI and 3GPPP, to find ten parameters that are important for energy efficiency evaluating. These parameters cover how the system communicates, the type of energy

sources used to AI/ML processing and also what mechanisms has for recovering from failures. The article also highlights ten big gaps in current standards, such as insufficient attention to protocol energy costs, security issues and features about specific jobs.

Furthermore, in[85]M., Petersen et al., exploring 6G networks, propose nine research questions, in coordination with IMT-2030 use cases helping to reduce energy consumption. However, it is crucial to understand that the fact that 5G is more energy efficient than 4G, it does not mean that the general energy footprint is lesser. Therefore, the article emphasizes that we must improve the standardization and develops better ways to measure results.

In addition to the articles above, the work in[86]addresses the carbon emissions challenge byproposing a comprehensive framework for environmentally friendly 6G mobile networks. It focuses, mainly on two goals: reducing to the minimum the use of energy and simultaneously reducing the carbon impact that depends on the system design. Furthermore, taking on account the Kyoto Protocol, the Paris Agreement and also the UN SDGs, the study highlights how quickly the telecom industry needs to eliminate its carbon footprint. Innovative regulatory approaches, such as carbon pricing and carbon reporting are presented, with the aim to make greener telecommunications.

Moreover, the study suggests three key approaches. First, minimize the power consumption in low power network layers and in lazy receivers. Second, improve the way of data transmission via new, more energy-efficiency ways and third, to introduce networks with the ability to consider carbon impact when or where to transmit data. Thus, 6G networks will not only enhance connectivity, but also contribute to carbon neutrality. In conclusion, this article provides a plan for making future networks work aligned with the sustainability goals.

The work in [87] introduces an intelligent framework that combines DT, as a virtual copy of a physical network, and AI to solve the energy challenges of 6G networks. The system organizes into four parts that support adaptive a model, a simulation, an agent and an evolution, that support adaptive and energy-aware orchestration. The system, using DRL, send users dynamically to different connections and shutting down the connections that are not used much. This saves energy and keeps QoS in good condition. This DT-AI architecture is shown in Figure 28, which shows the real-time data transmission from the physical to the virtual network. The system copies the network, test policies with simulations, the agent uses DRL to improve decision-making and the evolution part adapts to changing conditions. This system works in a cycle and enables the continuous orchestration of resources.

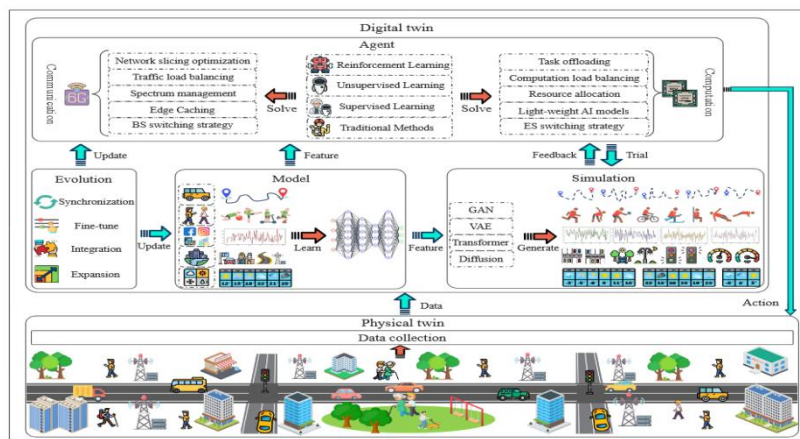


Figure28 DT–AI framework for sustainable 6G orchestration using DRL-based optimization [87]

A case study in Beijing’s 5<sup>th</sup> Ring Road shows how much this method could help, reducing energy consumption as much as 73% while also lower latency compared to current ways of doing things. The authors believe that the combination of cloud and edge computing will help future 6G networks work more efficiency.

Last but not least, authors in [88] investigate energy-based and QoS-aware load balancing of O-RAN in 6G networks. In contrast with the theoretical contributions, the authors demonstrate a framework, which has been established and tested in practice that transfer users from one node to other and shut down the ones that are “lazy” for reducing energy consumption and simultaneously ensuring the QoS.

The proposed O-RAN architecture layout is given in Figure 29. The Non-Real-Time RIC (using rApps), defines policies, informed by the traffic behavior analyzed, that drive long-term energy savings, while the Near-Real-Time RIC, (using xApps) enacts short-term decisions like handover performance and load balancing. The Service Management and Orchestration (SMO) layer organizes these into processes, monitors KPIs to provide consistent policy enforcement. At the bottom, the E2 Nodes, BS, enact decisions and communicate this feedback upward. This architecture design a feedback loop that policies are generated and improved in real time, showing how O-RAN can become a cornerstone of sustainability in future networks.

The reviewed studies in this subsection show that energy- and carbon-aware orchestration is becoming a key part of how we design 5G and 6G networks. The studies above present several strategies and approaches, from integrating RE sources, improving how BS work to taking advantage of technologies like AI, ML, DT and O-RAN architectures. However, there are also some obstacles to overcome. For instance, there are challenges like energy costs of all these technologies and establishment of fundamental principles for business area.

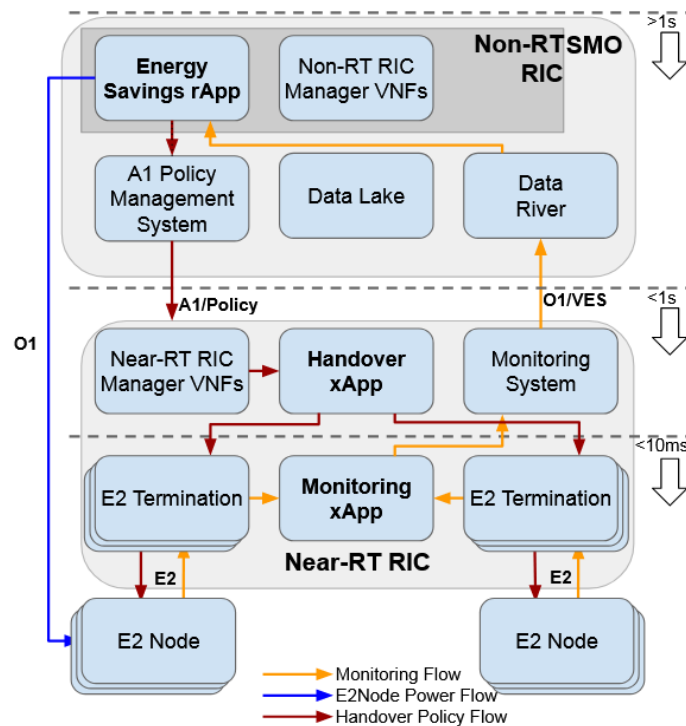


Figure29Proposed O-RAN architecture enabling energy- and QoS-aware load balancing in 6G[88]

### 5.2.5 Emerging Practices

Following the vision presented in recent studies, where sustainability is shown as a guiding principle for 6G networks, it is clear that new practices are starting to take shape. These practices are not just improving existing solutions but also propose new approaches to manage networks, to keep them secure and to build them physically. In this section, we turn our attention to some of these emerging practices, which start making communication networks more energy-efficient, more eco-friendly and socially responsible.

C. Lehmann et al. [89] present a comprehensive vision for making sustainability a core part into the design and operation of 6G networks. Authors organize the article in three key dimensions: SNM, sustainable security and sustainable hardware. Firstly, they suggest the using of AI and ML along with O-RAN architectures to create a self-sustainable orchestration, moving beyond proactive approach with close-loop decision making. Furthermore, for making networks secure, they highlight the need to shift away from resource-hungry hardware solutions to more software-based, virtualized and energy efficient methods. This will help to shrink the environmental impact of security measures. Finally they introduce innovative directions for sustainable hardware, including the use of biodegradable materials and development of metasurface antennas.

A high-level architecture of sustainable 6G networks is depicted in Figure 30 of this study. It shows how different layers and radio access technologies can be combined through these loosely connected feedback systems. Generally, this visualization shows the main point: that achieving sustainability in 6G is not just a modification of a technology but it is a complete rethink of how we design, build and secure these networks.

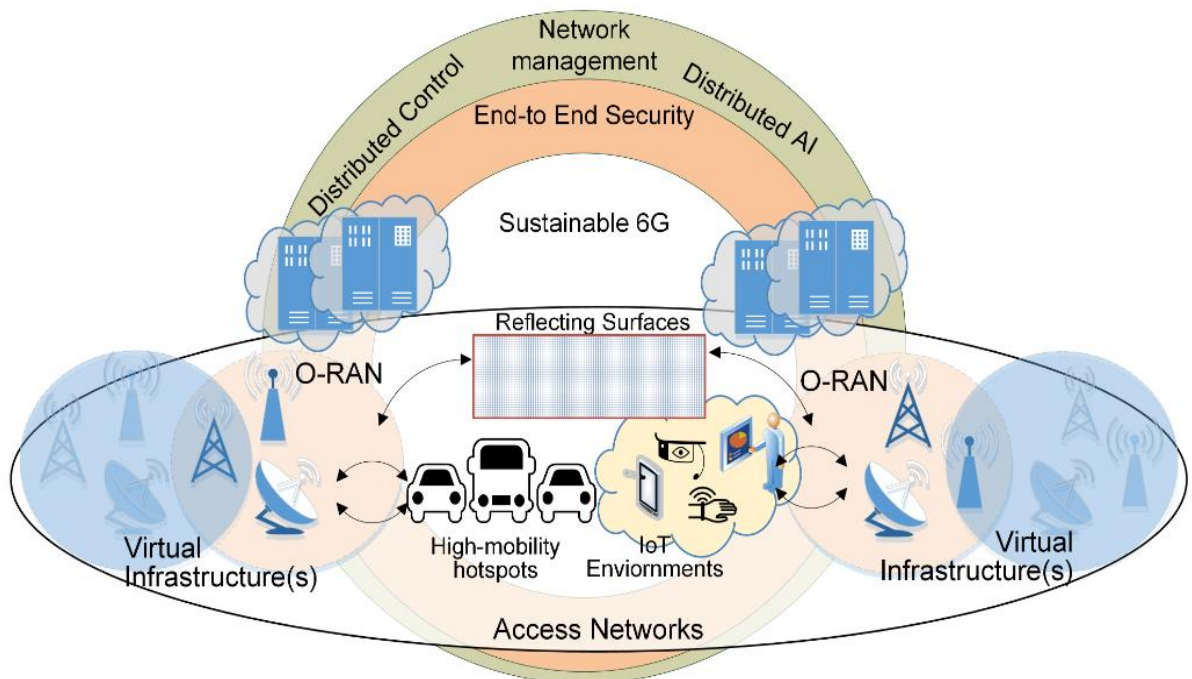


Figure 30 High-level architecture of sustainable 6G networks based on loosely coupled feedback systems[89]

Another paper that turns into another emerging practice of 6G, is the work in[8]. This 6G4society deliverable dives into the societal aspects of 6G technology, focusing on three key ideas: how society is affected, the values involved and how acceptable the technology is to people. One important contribution of this project is the Social Acceptance of Technology (SAT) framework. This is a way to measure how well technology is received at different levels: big picture (macro), community (meso) and individual (micro). This framework is not just a traditional performance-based assessment but also goes further by weaving in ethical, cultural and social factors.

This really interesting SAT framework depicts in Figure 31, which mapping how acceptance processes work across different layers of society. It highlights how factors like shared values, trust and the way governance is set up influence whether new technologies like 6G take the green light or resisted. With the help of this graphic, it is easy to be understood that social acceptance is not a simple yes or no, but a dynamic process.

Another alternative and very impressive approach introduced in[90] and suggests a framework to explain how the whole 6G ecosystem is coming together. Instead of just looking at 6G as another tech upgrade, this study digs deeper and identifies three key areas that are all connected: antecedents, components and consequences. Antecedents include drivers such as AI, the data economy and societal demands for sustainability. Components refer to the technological, social and business elements that make up the ecosystem. And finally consequences are the wider effects of 6G, such as new services popping up, industry transforming, shifts in society and challenges that are faced, like cybersecurity issues and ethical dilemmas.

This framework with these three key parts and the way how these three are connected depicts in Figure 32. First of all, the antecedents feed into the components, which then lead to the consequences. This figure makes it clear that 6G is not just a bunch of tech tools, but it is a complex socio-technical ecosystem influenced by various factors and can change both technology and society as a whole.



Figure 31 The SAT framework illustrates the multi-level process of social acceptance in 6G technologies [8]

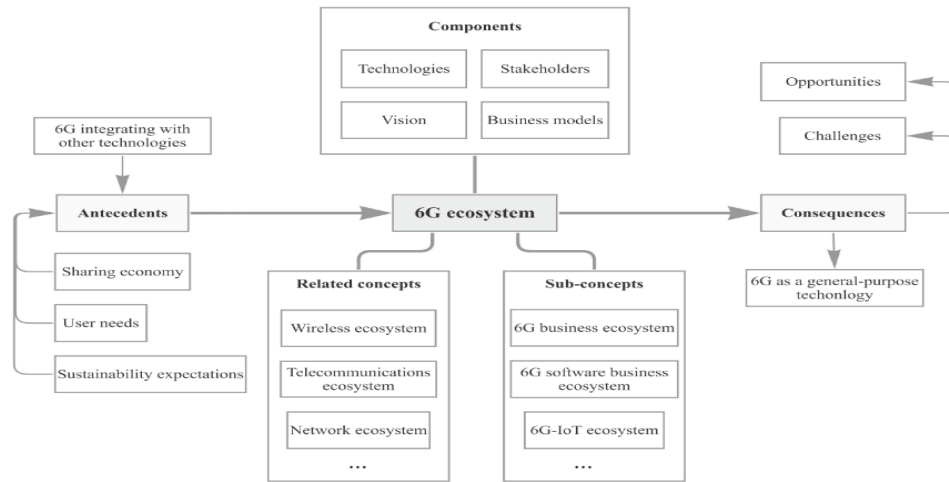


Figure 32 Conceptual framework of the emerging 6G ecosystem, linking antecedents, components, and consequences [90]

The study in [57] take a deep dive into the environmental impacts of 6G by looking at it through a lifecycle perspective. Instead of just focusing on how energy-efficient these technologies are while they are in use, the authors explore it from the initial research and development stages, through standardization and deployment, all the way to maintenance and how users behave. Thus, it is clear, that there are some significant sustainability challenges, like high energy use, greenhouse gas emissions, electronic waste and troubling use of toxic materials.

A crucial and central contribution of the paper is the emphasizing of new practices which aimed at reducing these negative impacts. For instance, it discussed incorporating principles of the circular economy, adopting eco-design strategies and using biodegradable and recyclable materials. Furthermore, there is a push for renewable-powered infrastructure and stronger policies, like Extended Producer Responsibility (EPR). Figure 33 shows the lifecycle of 6G technologies across various stages. By framing sustainability as an ongoing process instead of just a onetime goal, this study offers a solid framework for making environmental considerations a core part of how 6G systems develop over time.

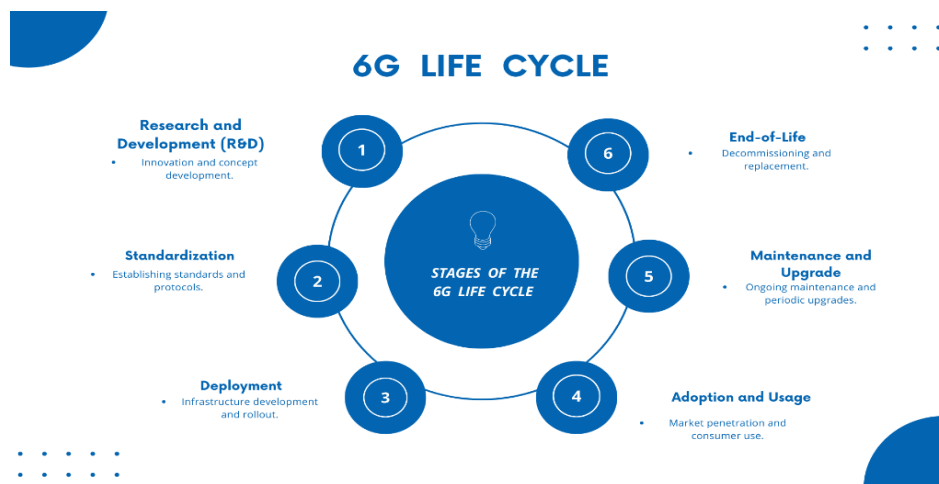


Figure 33 Lifecycle stages of 6G technologies and potential entry points for sustainability interventions [57]

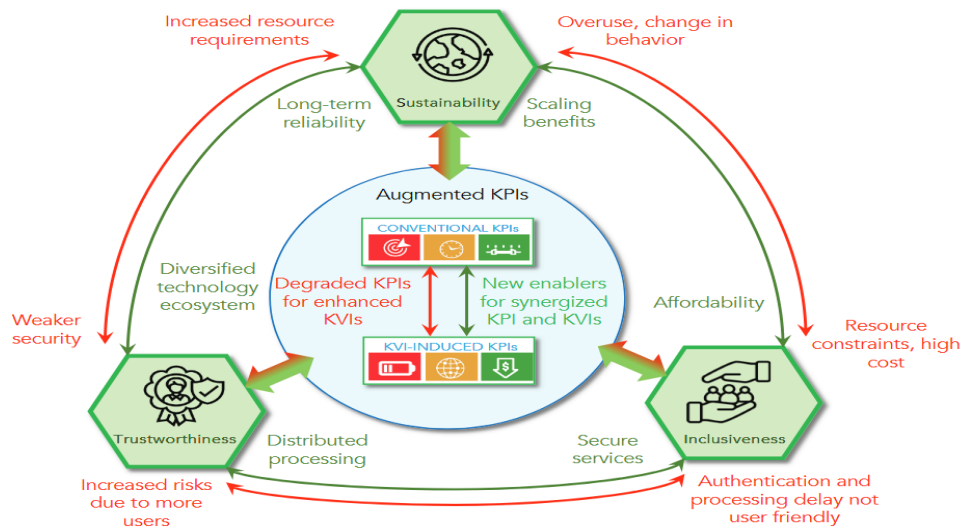


Figure 34 Synergies and trade-offs between conventional KPIs and emerging KVI (sustainability, inclusiveness, trustworthiness) in 6G design [91]

Furthermore, the work in [91] introduces a new take on how we evaluate performance. It goes just beyond the usual KPIs and introduces a new metric called KVIs. While KPIs measure technical efficiency, KVIs bring in those bigger picture goals, like sustainability, inclusiveness and trustworthiness. The whole idea is to make sure that when we are optimizing 6G positioning and sensing, we do not sacrifice our environmental or social values.

One key characteristic of the paper is the illustration of the relationship between KPIs and KVIs that is depicted in Figure 34. The figure shows the synergies (green lines) and the trade-offs (red lines) of them. For instance, when we improve positioning accuracy, it can actually lead to less energy consumption, which supports sustainability, but on the other side, if we want to expand coverage to ensure inclusiveness that might mean that we need more infrastructures which could lead in energy use and material costs. Thus, Figure 34 makes it clear that technical and societal indicators are really connected. This approach is becoming more and more common in network design that it is crucial to keep the balance between efficiency, equity and environmental responsibility.

Building on previous work that introduced lifecycle assessment and circular economy principles for 6G, authors in [92] dive deeper. This work takes a closer look at the technical perspective by examining the trade-offs we face, like the balance between performance and environmental sustainability. It highlights how we can mesh the latest technological advancements with our need to be environmental aware. Furthermore, it points out some serious challenges we face, like energy-hungry systems, the e-waste problem and the extraction of raw materials. To address these challenges, the authors discuss some innovative methods, such as energy harvesting, which sounds promising, the concept, called SWIPT and circular economy principles to push for recycling and using materials sustainably.

A unique feature in this approach is the Multi-Objective Optimization Algorithm (MOOA), which balances network lifetime with power efficiency. Additionally, the work in [92] shows key trade-offs between performance and sustainability, like the tense between how much power we transmit and how energy-efficient we can be, or how dense BS are versus the carbon emissions that it is caused. Thus, this paper shines a light on new practices that could help shape 6G systems to be both innovative and environmentally friendly.

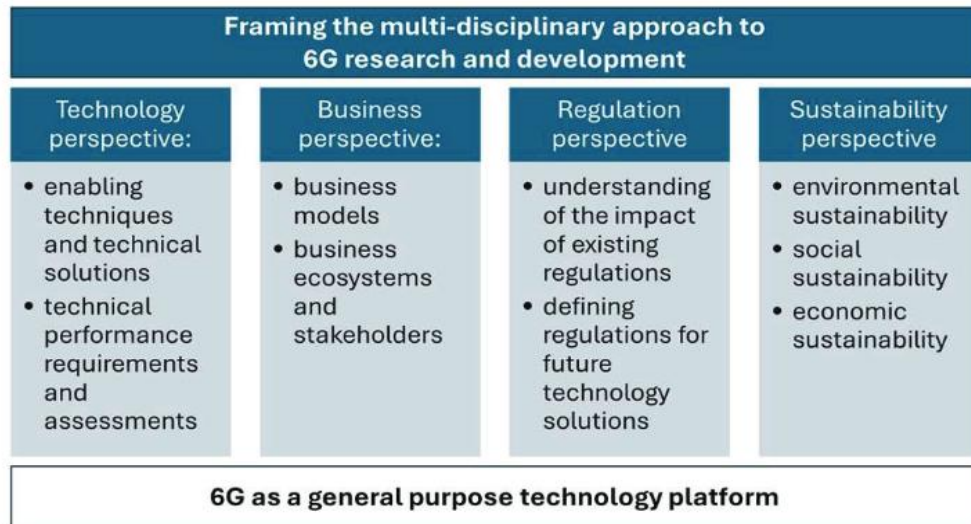


Figure 35 Proposed multi-disciplinary framing for 6G research and development, integrating technology, business, regulation, and sustainability perspectives [2]

Another interesting approach is the one that developed in [2]. Authors make compelling case that we cannot just look at technological performance metrics when designing 6G. Instead, they suggest a more holistic view that brings together four key perspectives: technology, business, regulation and sustainability. This approach reflects a growing trend in 6G research and development, where focusing on value-driven strategies are becoming essential to handle the societal, environmental and economic issues of the 2030s.

Furthermore, in Figure 35 is depicted a conceptual framework that shows how these four perspectives interact with each other, around 6G as a general-purpose technology. By putting sustainability front and center, with regulatory, business and technical aspects, the authors present a solid methodology for creating communication systems that are built to last.

In addition to the works above, the one in [14] dives into the exciting vision of the 6Green project, which seek to combine observability and sustainability into future network management. It introduces a framework that goes beyond the usual KPIs to include things like energy consumption and carbon footprint tracking at various levels like infrastructures, network slices and edge applications. Thus, this framework encourages transparency and push people in the direction of making greener choices.

The more interesting thing in this study is that highlights three innovative practices. First is Edge Agility that lets applications and services shift around dynamically in the edge-cloud. This helps the reducing in unnecessary energy use. Second is Green Elasticity, which use hardware acceleration and elastic scaling to find the ideal spot between performance and energy efficiency. Lastly, Energy-aware Backpressure ensures that energy and carbon metrics are shared across different domains, promoting teamwork in sustainability. In Figure 36 is shown how sustainability info flows between different areas, demonstrating how sharing data can lead to more accountability and more responsible network operations. The authors also note that such information sharing can be selective. For instance, an infrastructure provider might be open about how much computational power a slice uses, but they could decide to keep the location of the hosting datacenter under cover. Thus, it is to be understood that energy-aware backpressure is not just about technological stuff, but also there are important choices regarding transparency and the responsibilities. Table VI presents a detailed list of the papers that have been categorized, including the most important issues that they address.

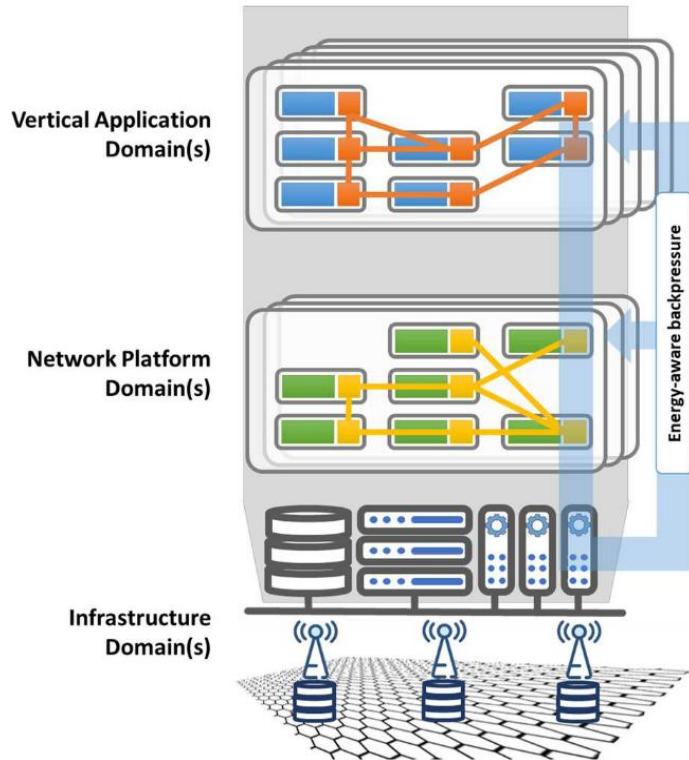


Figure 36 Energy-aware backpressure enables energy and carbon footprint data to flow across stakeholders, fostering transparency and sustainable decision-making in 6G networks[14]

Table VI List of Papers in Sustainable Networks Management category and coverage issues

Article	Sustainable Network Management					Focus and Coverage (Key Findings)	Type of Study	Year
	Network Slicing for Sustainability	O-RAN and Open Architectures	E2E QoE & Performance Management	Energy- & Carbon-aware Orchestration	Emerging Practices			
[15]	X					Network slicing, energy/carbon-aware orchestration within sustainable network management. SFI2 architecture to improve efficiency and reduce energy/carbon impact.	Methodological Paper	2025
[62]		X				O-RAN as a game changing model, energy/carbon-aware orchestration within sustainable network management	Survey / Review Paper	2025
[3]			X			Hexa-X E2E 6G architecture, integrating AI/ML, cloud-based functions, and sustainability principles to optimize performance, energy efficiency, and alignment with SDGs	Conceptual / Theoretical Paper	2022
[63]			X			An E2E QoE framework for 6G that links technical performance, applications, and user experience to improve energy efficiency and service quality	Methodological Paper	2023
[64]			X			A 5G slicing prototype using SDN, NFV, and ML to enable flexible slice management, improve QoS/QoE, and support energy-efficient, sustainable 6G evolution	Experimental / Simulation Study	2023
[65]			X			A QoE sustainability framework using AI/ML with functions like NWDAF, MEC, and slicing to balance user experience with energy efficiency in 5G and future 6G networks	Experimental / Simulation Study	2023
[48]				X		How IoT and 5G, combined with the GSO	Experimental /	2021

Mapping Enabling Technologies towards Sustainable 5G/6G Communications

Article	Sustainable Network Management					Focus and Coverage (Key Findings)	Type of Study	Year
	Network Slicing for Sustainability	O-RAN and Open Architectures	E2E QoE & Performance Management	Energy- & Carbon-aware Orchestration	Emerging Practices			
						algorithm, can optimize real-time energy management to reduce losses and enhance renewable energy use in smart environments	Simulation Study	
[66]				X		A neutral host business model for ultra-dense networks, enabling shared infrastructure, lower costs, and reduced energy use to support sustainable 6G deployment	Methodological Paper	2022
[67]				X		Energy-efficient techniques in 5G, such as renewable energy, storage, AI-based management, and D2D communication, to support sustainable Industry 4.0 and future 6G networks	Experimental / Simulation Study	2022
[68]				X		High energy demand of OTT video by proposing a hybrid 5G multicast-unicast framework with VVC coding and Green-MPEG metadata to enable greener video streaming in 5G and future 6G networks	Experimental / Simulation Study	2022
[49]				X		A holistic view of 5G's energy footprint, covering operational, embodied, and indirect effects, and the fact that true sustainability requires both technical innovation and policy measures	Survey / Review Paper	2022
[69]				X		An energy-efficient microstrip diplexer for 5G-enabled IoT in metaverse transport and smart grids, showing how hardware design can lower energy use and support sustainable network operations	Experimental / Simulation Study	2023
[70]				X		An ultra-efficient GSM triplexer for 5G-enabled IoT, showing how device-level hardware innovations can cut energy use and support sustainable smart grid and metaverse applications	Experimental / Simulation Study	2023
[71]				X		The carbon impact of China's large-scale 5G rollout and the proposal of DeepEnergy, an AI-based framework to reduce emissions through smarter base station management and renewable integration	Experimental / Simulation Study	2023
[72]				X		CEERP, an AI-driven routing protocol for 5G/6G wireless sensor networks that reduces energy use and extends network lifetime to support sustainable deployments	Experimental / Simulation Study	2023
[50]				X		CREG and DREG models with a Resource-on-Demand strategy to reduce emissions and enhance energy efficiency in ultra-dense 5G/B5G networks	Experimental / Simulation Study	2023
[73]				X		A framework combining renewable microgeneration, traffic-aware offloading, and ASMs to improve energy efficiency and sustainability in 5G HetNets	Experimental / Simulation Study	2023
[74]				X		The algorithm ECOA, which dynamically manages user assignments between macro and pico base stations to cut energy use while maintaining QoS in 5G networks	Experimental / Simulation Study	2023
[75]				X		Decentralized, AI/ML-driven orchestration frameworks for 6G, highlighting the MonB5G project as a scalable approach that improves energy efficiency and supports zero-touch	Experimental / Simulation Study	2024

Article	Sustainable Network Management					Focus and Coverage (Key Findings)	Type of Study	Year
	Network Slicing for Sustainability	O-RAN and Open Architectures	E2E QoE & Performance Management	Energy- & Carbon-aware Orchestration	Emerging Practices			
						automation		
[5]				X		The concept of SDG enablers in 6G, showing how features like ultra-low power IoT, satellite-terrestrial integration, and distributed AI can be orchestrated to advance global sustainability goals	Conceptual / Theoretical Paper	2024
[76]				X		A sustainability-oriented 6G architecture that integrates layers of applications, functions, and hardware with technologies like explainable AI, semantic communications, digital twins, and blockchain to align performance with environmental and societal goals	Conceptual / Theoretical Paper	2024
[77]				X		A Stackelberg game-theoretic model for traffic offloading in ultra-dense 5G/6G, showing how incentive-based resource allocation can improve performance while reducing energy use and emissions	Conceptual / Theoretical Paper	2024
[78]				X		A flexible energy modeling framework for 5G RANs that estimates consumption at each signal processing stage, helping identify bottlenecks and guide energy- and carbon-aware orchestration	Methodological Paper	2024
[79]				X		DTNs within a sustainability-oriented 6G architecture, combining SDN/NFV and in-network computing with KVIs to enable energy-efficient and ethical orchestration	Methodological Paper	2024
[80]				X		5G capabilities such as massive MIMO, spectrum sharing, slicing, SDN/NFV, MEC, and energy harvesting, showing how they can cut energy use and CO <sub>2</sub> emissions while supporting smart city and SDG applications	Survey / Review Paper	2024
[81]				X		Network sharing of BSs and spectrum as a strategy for energy- and carbon-aware management, showing how it can cut consumption by up to 40% and support sustainable 5G/6G infrastructures	Experimental / Simulation Study	2024
[82]				X		AI-driven architectures for 6G sustainability, including the Hybrid Quantum Deep Learning Model (HQDLM) for slice allocation and BSONet for base station optimization, achieving high accuracy and energy savings	Experimental / Simulation Study	2024
[1]				X		The open letter from EU projects such as BeGREEN, 6G-TWIN, and GGreen calls for sustainability to be the guiding principle of 6G, stressing AI-driven orchestration, renewable integration, and the use of sustainability indicators	Conceptual / Theoretical Paper	2024
[83]				X		How IAB with NDT and ZTM can improve energy efficiency and flexibility in sustainable 5G+ deployments	Methodological Paper	2024
[84]				X		The integration of 5G and DT technologies with IoT and AI/ML to enable real-time monitoring, renewable integration, and more sustainable energy systems	Survey / Review Paper	2025

Mapping Enabling Technologies towards Sustainable 5G/6G Communications

Article	Sustainable Network Management					Focus and Coverage (Key Findings)	Type of Study	Year
	Network Slicing for Sustainability	O-RAN and Open Architectures	E2E QoE & Performance Management	Energy- & Carbon-aware Orchestration	Emerging Practices			
[85]				X		ETSI and 3GPP frameworks to identify key parameters and gaps for energy efficiency in 5G/6G, proposing research directions to improve standards and reduce carbon impact	Survey / Review Paper	2025
[86]				X		A vision for carbon-neutral 6G, proposing energy minimization, greener transmission methods, and carbon-aware operations aligned with global climate agreements and SDGs	Methodological Paper	2025
[87]				X		A DT-AI framework with DRL-based orchestration for 6G, enabling dynamic user allocation, energy savings of up to 73%, and improved QoS through continuous simulation and adaptation	Experimental / Simulation Study	2025
[88]				X		An O-RAN framework for 6G with rApps and xApps in the RIC layers, enabling energy-aware load balancing and QoS preservation through real-time policy feedback and orchestration	Experimental / Simulation Study	2025
[89]					X	A vision for sustainable 6G across three dimensions—management with AI/ML and O-RAN, security via virtualized solutions, and hardware through biodegradable materials and metasurface antennas	Conceptual / Theoretical Paper	2023
[8]					X	The SAT framework from the 6G4Society project, assessing 6G adoption at macro, meso, and micro levels by integrating ethical, cultural, and societal factors	Conceptual / Theoretical Paper	2024
[90]					X	A 6G ecosystem framework linking antecedents (AI, data economy, sustainability), components (technical, social, business), and consequences (new services, societal shifts, ethical challenges)	Conceptual / Theoretical Paper	2024
[57]					X	An analyst of 6G through a lifecycle framework, highlighting challenges like energy use, e-waste, and toxic materials, while promoting circular economy, eco-design, renewable power, and EPR policies for sustainable development	Survey / Review Paper	2024
[91]					X	KVIs alongside KPIs in 6G design, linking technical performance with broader goals like sustainability, inclusiveness, and trustworthiness	Methodological Paper	2025
[92]					X	Trade-offs between performance and sustainability in 6G, highlighting challenges like e-waste and raw material use, while proposing methods such as SWIPT, energy harvesting, circular economy practices, and MOOA	Experimental / Simulation Study	2025
[2]					X	A holistic 6G framework that integrates technology, business, regulation, and sustainability, emphasizing value-driven strategies for long-term societal and environmental impact	Conceptual / Theoretical Paper	2024
[14]					X	The 6Green framework, extending KPIs with sustainability metrics and introducing Edge Agility, Green Elasticity, and Energy-aware	Experimental / Simulation Study	2024

Article	Sustainable Network Management					Focus and Coverage (Key Findings)	Type of Study	Year
	Network Slicing for Sustainability	O-RAN and Open Architectures	E2E QoE & Performance Management	Energy- & Carbon-aware Orchestration	Emerging Practices			
						Backpressure to enable transparent, energy-efficient 6G management		

### 5.3 Smart Mobility – V2X

When we talk about the future of ITS, it is becoming really clear that the combination of integrating edge computing with V2X communication is the key. This mixture, often known as edge-assisted V2X, utilizes the power of MEC to process safety-critical data where it's created, ensuring low latency and high reliability. Within this context, the following studies explore how these edge-assisted setups can boost network intelligence. Furthermore, they also look at how they can support advanced driver assistance systems and enable large-scale sustainable mobility projects, showing the pivotal role of 5G and beyond in shaping the future of cooperative and efficient transport.

#### 5.3.1 Edge-assisted V2X and MEC

Edge-assisted V2X and MEC becomes game-changers for the future of smart transportation, because it shifts critical communication and computation tasks closer to vehicles, where decisions must be made in real-time. With the power of low-latency 5G and 6G connectivity and distributed edge resources, this whole system can support some pretty intense data and safety-critical services, such as cooperative awareness, collision avoidance, traffic efficiency and advanced driving assistance. In this subcategory, the focus is on how V2X networking modes and MEC-based architectures work together. They improve reliability and responsiveness, which is super important. Furthermore, they pave the way for a more sustainable IoV and ITS by making resource management smarter and reducing end-to-end overhead.

The work in[19] presents the creation of a testbed for the IoV based on 5G+MEC, which is designed to find out sustainable ways to operate the next-generation vehicle networks. The authors introduce a hierarchical framework that divides IoV operation into six levels of intelligence, from L0 to L5, which is an interesting twist on the Society of Automotive Engineers (SAE) taxonomy for autonomous driving. These levels range from L0, where everything is done manually, to L5, where the system operates in a fully intelligent, closed-loop manner. This is a structured way to assess how smart IoV systems are.

This testbed combines multi-source data fusion through MEC and Cellular Vehicle-to-Everything (C-V2X), enabling various applications, like pedestrian crossing warnings, alerts for road events, prioritizing special vehicles and even spotting illegal parking. A key contribution of the paper is the presentation of the C-V2X networking solution. Figure 37 shows on the right side the Uu interface, which allows vehicles, communicate through a base station that is under cellular coverage and on the left side, the PC5 interface that lets vehicles connect with other roadside units. This dual-interface approach enhances communication reliability and provides redundancy. This framework and its scenarios were validated in the Greater Bay Area (a major Chinese initiative integrating Hong Kong, Macao and nine cities in Guangdong province to create a high-tech urban cluster).

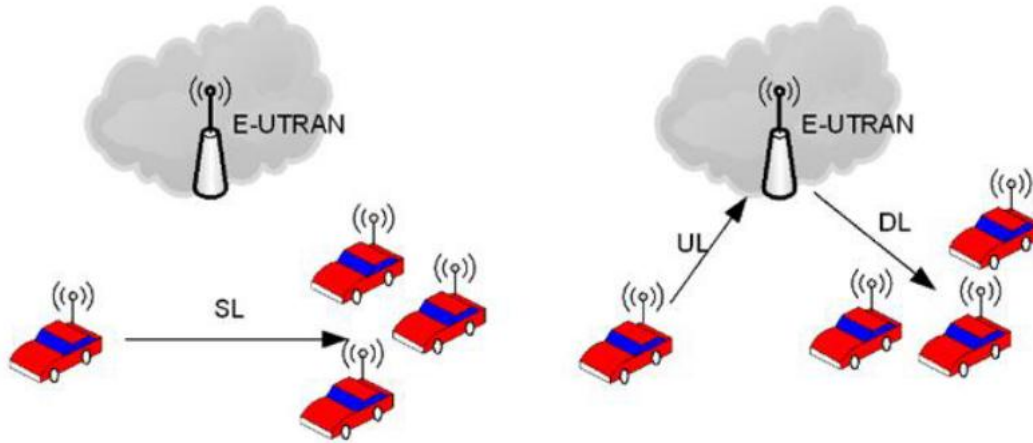


Figure 37 Illustration of the C-V2X networking solution integrating Uu and PC5 interfaces for reliable edge-assisted V2X communication [19]

In the broader context of upcoming smart mobility, there is a lot of attention around how Advanced Driver Assistance Systems (ADAS) are coming together with these new V2X technologies. Authors in[22] highlight that on the one side, ADAS rely on a rich set of in-vehicle sensors, including cameras, radar, LiDAR and ultrasonic devices, to spot obstacles, help drivers out and prevent crashes. On the other side, 5G New Radio (NR)-V2X, is bringing advanced features such as URLLC, network slicing and the ability to connect multi devices at once. This means that vehicles have the ability to share critical safety information in real time, between cars (V2V), with infrastructures (V2I) and with pedestrians (V2P).

Furthermore, the study also considers the ITS – G5, a wireless protocol which operates in the 5.9 GHz band, and compares its performance with 5G NR-V2X and the forthcoming 6G V2X, which promises serious benefits, like pinpoint positioning accuracy, super low latency and terahertz (THz) spectrum utilization. A crucial contribution of the paper is the Table VII, which shows how each protocol measures up in terms of range, speed, location accuracy and flexibility. The authors highlight that ADAS and V2X should not be compared as substitutes. ADAS improves safety through all those sensors inside the car but V2X enhances also safety beyond just the vehicle itself. V2X is extending in a more cooperative and predictive way.

Table VII Comparison of 6G V2X, 5G NR-V2X, and ITS-G5 in terms of range, latency, accuracy, and adaptability for ITS[22]

Characteristic	6G V2X	5G NR V2X	ITS-G5
Communication Range	Several kilometers	Up to several kilometers	300-500m
Latency	0,001ms	<5ms	<20ms
Location Precision	Approximately 10cm	Approximately 1 to 5 meters	Approximately 1 to 5 meters
Obstacle Detection	Yes	Yes	Yes
Communication with Infrastructure	Yes	Yes	Yes
Proactive Collision	Yes	Yes	Yes

Characteristic	6G V2X	5G NR V2X	ITS-G5
Prevention			
Adaptability to Road Conditions	High	High	Moderate
Level of Driving Automation	Can support full autonomous driving	Can support full autonomous driving	Generally suited for human drivers
Modulation	QAM, OFDM	QAM, OFDM	Various (e.g QPSK, OFDM)
Frequency	95 GHz – 3 THz	5G frequency range (sub-6GHz and mmWave)	Dedicated frequencies (5.9 GHz)
Data Rate	Very high (several Gbps)	High (up to several Gbps)	Moderate (up to a few hundred Mbps)
Detection Time	Very fast	Very fast	Very fast

While the previous study was diving into sensor-based driving assistance and V2X communication technologies, the one in [93] focuses to the European Mobilities for EU project that shows how 5G communication can operate as a key player in creating sustainable and smart urban mobility. Dresden which is the lead city, complete a bunch of solutions, such as autonomous cargo transport, electric buses, mobile charging robots and even bidirectional charging, known as V2G. At the core of this project, there is a private 5G network, paired with edge computing, which allows for super reliable and speedy communication in many different urban mobility services.

A special element of this study is the Figure 38, which shows the integrated communication setup in Dresdens' Ostra district. In this figure is depicted how mobile robots, smart traffic lights, electric vehicles and cameras connected all together through that private network to their control centers, when simultaneously edge processing ensures that safety critical tasks are operated in real time. Furthermore, the study also uses correctly the CIVITAS evaluation framework, a methodology developed by the European Commission to assess the environmental, social and economic impacts of urban mobility strategies. For example, the Dresden V2G pilot shows how electric vehicles can function as distributed energy storage units, which help with integrating RE and reducing CO<sub>2</sub> emissions.

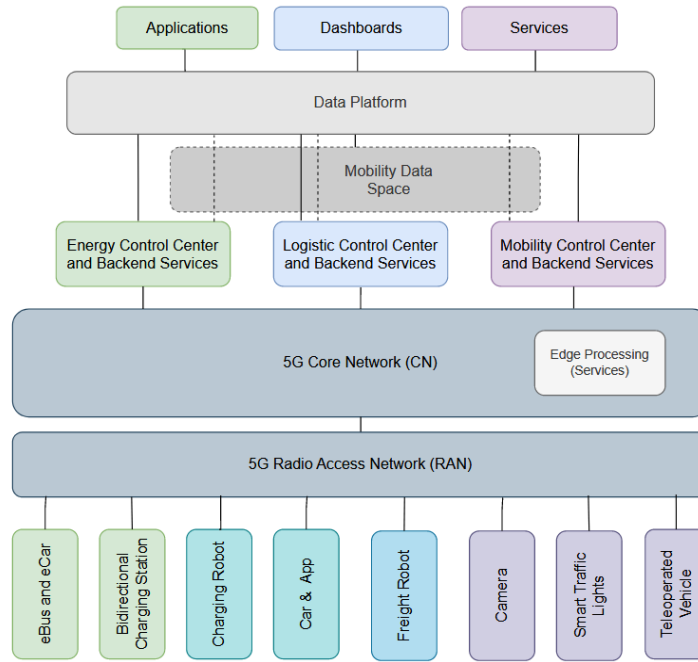


Figure 38 Integrated 5G communication architecture connecting vehicles, infrastructure, and control centers in the Dresden Ostra district pilot[93]

### 5.3.2 AI-Based Cooperative Perception & Traffic Optimization

After diving into edge-assisted V2X and MEC as the foundation of next generation mobility, this subsection turns focus to the intelligence that drives it: AI-driven cooperative perception and traffic optimization. AI enables vehicles and infrastructure to share and blend data. This means that they can anticipate traffic conditions and sync up their movements. By combining AI with 5G/6G and edge computing is like taking individual sensing and transforms it to collective intelligence, making a smarter, safer and greener transportation system.

By examining how digitalization plays a role in mobility, S. Sun et al. [21] present a big picture view of how 6G-enabled Information and Communication Technology (ICT) can support sustainable and smart transport systems. The study points three key areas: Cooperative, Connected and Automated Mobility (CCAM) for road, Maritime Autonomous Surface Ships (MASS) and drones/UAVs. In parallel with these modes, authors point out some common requirements like sensing, navigation and cooperation, that all of which depend on advanced wireless communication solutions.

One of the big points from this study is the idea that AI and ML-based cooperative perception, along with edge intelligence, are going to be crucial for the future of mobility. The work in[21]also highlights Figure 39 that connects UN SDGs, with enabling 6G technologies such as THz communication, VLC, RIS and integrated localization for sensing. In addition, the authors promote a roadmap to 2030, pointing out chances to develop 3D hybrid networks that mix together terrestrial, non-terrestrial and maritime connections. Furthermore, this article places 6G as a key player in making smart, sustainable mobility happen.

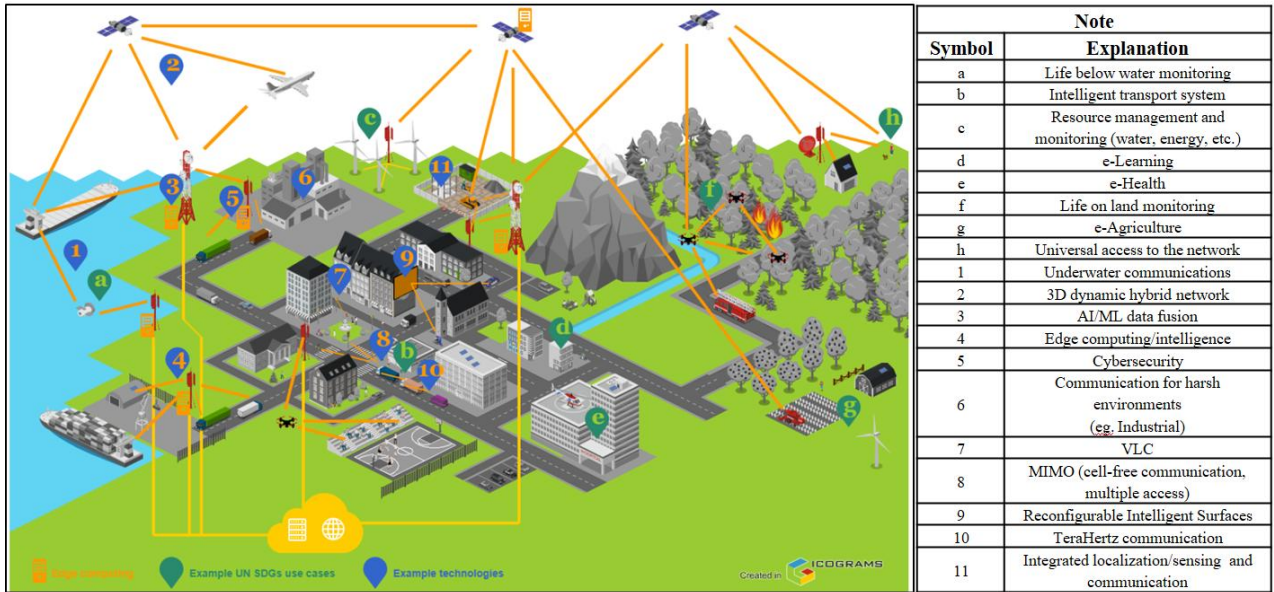


Figure 39 Mapping of sustainability scenarios (a–h) and advanced 6G technologies (1–11) that enable smart mobility and cooperative perception[21]

In addition to the above, the interesting method introduced in[94] for transmitting data in real time, focused on 5G tech for smart cities and Electric Vehicles (EVs). All starts when packets of data sent out from the base station. Then these packets get received and temporarily stored in a buffer on the receiver side. In this point, multiple sensors monitor continuously channel conditions and data integrity. If they spot any issues, such as problems with signal propagation, collision or if the receiver is busy, the system sends a feedback signal back to the transmitter. On the contrary, if everything check out fine and no error be found, the buffered data are processed and sent off for use in higher level applications.

This functional flowchart is shown in Figure 40, as a closed-loop process, where packet transmission, buffering, sensor verification and feedback work all together in harmony. This method reduces latency, improves reliability and makes sure that the communication between the base station and EVs remains sustainable, even in real time situations.

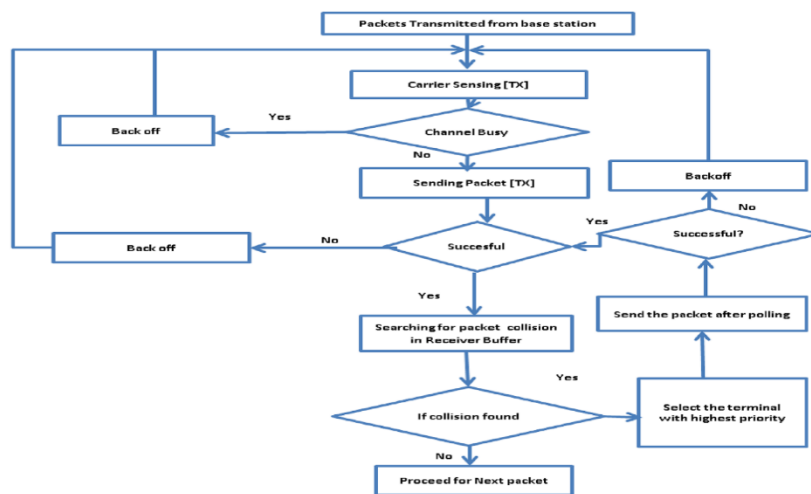


Figure 40 Functional flowchart of the proposed multi-sensory workflow[94]

In addition to the above and building on previous 5G and 6G mobility conversations, the work in [20] provides a systematic review of emerging technologies for V2X communication and Vehicular Edge Computing (VEC) in the 6G era. The authors use the PRISMA methodology to identify and categorize the key enabling technologies, like THz communication, holographic MIMO, IRSs. Furthermore, there is a lot of focus on edge computing, Big Data management and AI methods such as ML, DRL and FL. Especially, it is very important that authors give a big emphasis to sustainability dimension, like reducing energy use, making better use of resources and creating traffic management strategies, better for the environment.

Furthermore, this study also highlights the main technology areas shaping the field of V2X communication, vehicular edge computing, big data management, AI and security. By bringing these elements together, the authors show how AI-driven solutions can really step up when they are combined with the latest wireless and computing technologies, helping with cooperative perception and optimizing traffic in what called IoV. In the end, the study highlights both technical (interoperability, maintaining QoS and spectrum allocation) and non-technical (regulations, business models, user adoption) challenges that need some serious attention for a more sustainable and smart transport system.

Diving into the fascinating world of 6G-enabled vehicular communication, authors in [23] explore how B5G and 6G networks can support the way for sustainable mobility, with a focus on V2X technology and smart city applications. The authors spotlight three major trends: building climate-neutral infrastructure and vehicular equipment, embracing cloudification and edge computing and utilize Big Data and AI.

A central element of the study is Figure 41 that cleverly merges the Doughnut Economics model with the UN SDGs and the latest technologies in ITS. This figure shows how V2X innovation is framed within the balance between environmental limits and social needs. On the one hand, it encourages sustainability by reducing emissions and improving energy efficiency. On the other hand, it also aims to make mobility safer, easier to access and proper for everyone. Around this doughnut space, it maps where key B5G/6G technology enablers linking technical progress to societal benefits. Thus, the reader can see how ITS technologies are designed not only to find engineering solutions but also to promote to sustainable and inclusive mobility.

This study also highlights six interesting use cases: green driving, vehicle platooning, smart routing, smart parking, speed harmonization and coordinated maneuvers. Each of these has sustainability benefits like using less energy, reducing emissions and making traffic flow more efficiently. Thus the study offers a comprehensive vision of how B5G/6G V2X can lead to smarter, eco-friendly transportation systems in future smart cities.

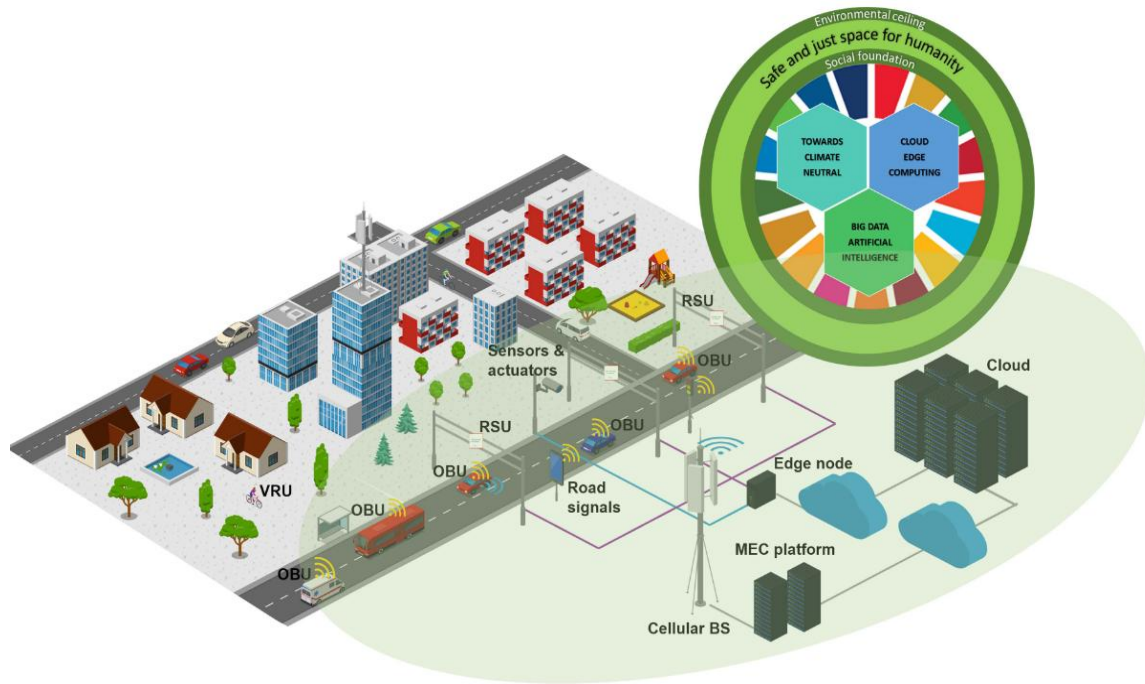


Figure 41 Representation of an ITS framework in the context of smart cities, combining the Doughnut model (green), the UN Sustainable Development Goals (color wheel), and the cross-sectoral impacts of B5G/6G technology trends [23]

### 5.3.3 NR-V2X PHY-MAC Protocols/ Radio Resource Management

After exploring how AI can improve cooperative and perception and optimize traffic for better mobility intelligence, we also need to take a step back and focus on the network mechanisms that support all of the above. In this subsection, we will present how communication resources are allocated, shared and optimized across a various vehicular services, discussing about slicing, spectrum allocation and low latency reliability. These elements are crucial for ensuring that everything will run smoothly in real-world situations.

Thus, shifting from AI-driven optimization to the network layer, the work in[16] explores how 5G can be improved to support a variety of vehicular needs, in the context of the EU-funded 5G HEART project. The authors focus on four key use cases: platooning, autonomous or assisted driving, remote driving and vehicle data services and connect what each of these use cases needs to specific KPIs, such as latency, reliability and throughput. Thus, to cover these demands, the study highlights the role of network slicing, which permit different services share the same 5G infrastructure while receives the resources it requires.

In Figure 42, we can see the comparison of the four use cases across various KPIs. For instance, the radar chart shows that platooning needs super high reliability and extremely low latency. On the other hand, vehicle data services are more demanding in terms of throughput. As we looking up these differences, we understand why flexible resource management and slicing are so crucial for supporting a variety of V2X services in a sustainable way.

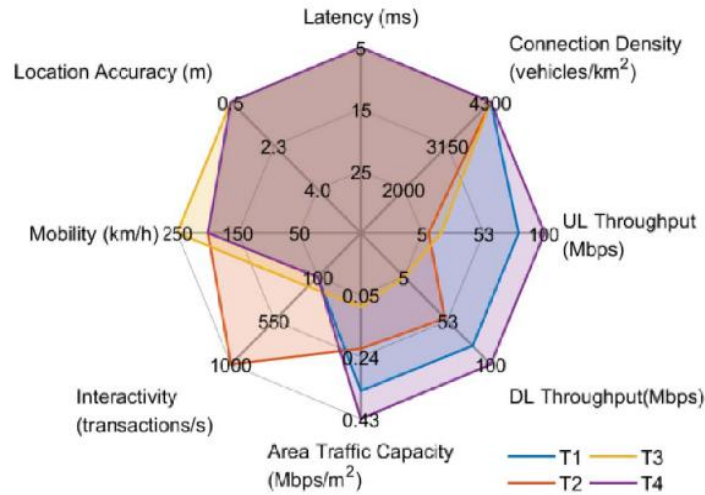


Figure 42 Radar chart comparing four transport use cases (T1-Platooning, T2-Autonomous/Assisted Driving, T3-Support for Remote Driving, and T4-Vehicle Data Services) across multiple KPIs[16]

While the previous work focused on how 5G slicing can accommodate diverse vehicular use cases, the one in[95] provides a comprehensive overview of how 6G technologies could really change the ITS. It discusses lots of things like the standards, enabling technologies and some of the big challenges we have to overcome when trying to integrate 6G into vehicle networks. The authors also highlight some of the key features of 6G, such as ultra high data rates, super low latency and smart orchestration. They also cover some pretty advanced applications, like cooperative collision, avoidance, self driving vehicles and better traffic management, focusing on sustainability.

A special and very helpful graphic is the Figure 43, which maps various ITS domains, like platooning, fleet management, maritime and aviation systems, EV charging and V2G to their respective communication types (V2V, V2I, V2N, V2P). This figure highlights the diversity of each ITS application and shows how 6G-driven V2X communication could become the backbone of a more interconnected mobility ecosystem.

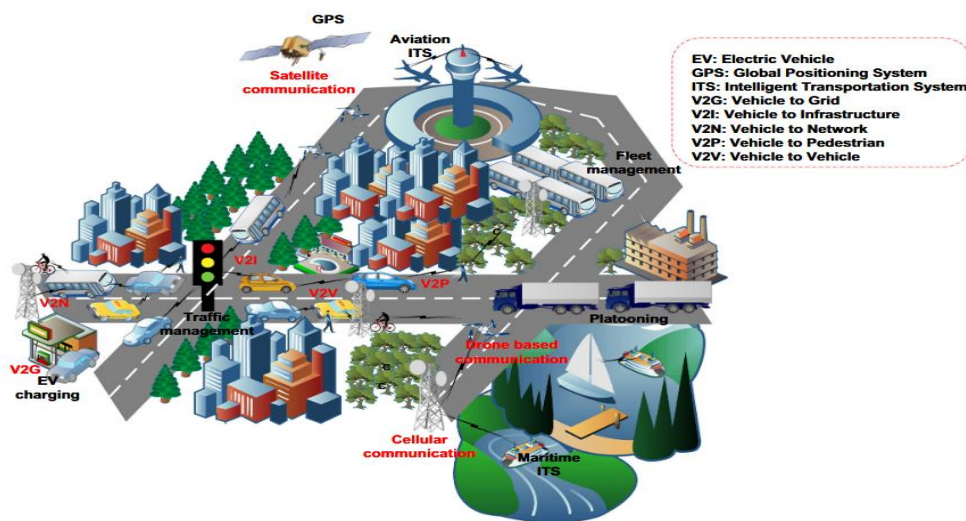


Figure 43 Overview of ITS domains and applications, mapped to corresponding V2X communication types in the 6G era [95]

### 5.3.4 Infrastructure Planning, Coverage & Energy Efficiency

After discussing how PHY-MAC protocols and radio resource management help create reliable communication for vehicles at the network layer, attention now turns to the bigger pictures, such as infrastructure, planning, coverage and energy efficiency. This subsection explores that 5G and 6G networks can make wonders in combination with EVs and sustainable IoV ideas, reducing energy use, improving coverage and support green mobility.

D. Pradhan et al. [17] introduce the idea of the Green IoV, as a roadmap for making vehicle communications more sustainable as we moving forward to 6G era. It analysis five key areas: V2X communication, vehicular edge computing, traffic management, EV energy management and energy harvesting/sharing, which is examined from the perspective of reducing energy use and improve overall efficiency. Furthermore, the work also raises some important questions about the challenges of future infrastructures, like the rising energy costs of mmWave and THz bands and the frequent handovers when we have dense deployments.

This concept is illustrated very well in Figure 44 that shows an SDN-based architecture for the Green IoV. This setup is organized into three main parts. At the top, it shows various green applications (such as V2X, edge computing, traffic control) while at the bottom there are the vehicular and network infrastructure, where these applications are placed. In the middle, the SDN controller is the heart of this system that coordinate resource allocation, routing and scheduling. This architecture shows how energy efficiency can be systematically insert into infrastructure planning, resource allocation and coverage strategies for a sustainable vehicular networking.

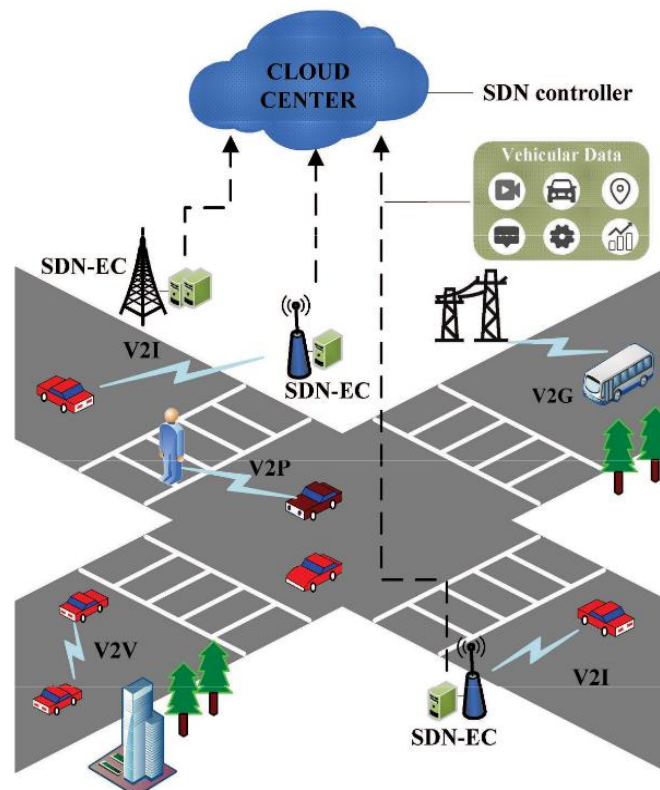


Figure 44 An SDN-based Green IoV architecture [17]

Furthermore, another study that explores about vehicle communications and the intersection between them and 5G technology is this in [18]. This study takes a closer look at how EVs and 5G technology come together to push sustainable transportation forward. From an environmental perspective, the authors highlight some of the tough issues surrounding EVs, such as the life cycle challenges, from making batteries and raw material extraction, to figuring out what to do with them when they are no longer useful. Moreover, it emphasizes how crucial is to use RE sources for charging. In addition to this, it also explores how 5G can really improve EVs work, through V2X communication, support for self-driving and smart grid integration. All of this is able to increase safety and efficiency.

However the rapid global increase in EVs demands new requirements on charging networks, energy supply and communication systems, driving to the need for some solid planning regarding capacity, coverage and energy efficient operations. By combining environmental impacts with digital side of things, the paper provides a comprehensive view of both opportunities and obstacles we face in integrating EVs into future transportation system.

### 5.3.5 Security, Privacy & Trust in V2X

While before we focused on infrastructure planning and energy efficiency, this subsection dives into something equally crucial, one of the key elements that makes V2X systems work: security, privacy and trust. Making certain that data exchange in vehicular networks is very important for the protection and reliability of the system, and it is fundamental for a safe and sustainable transportation system.

The work in[96] explores how Location-Based Services (LBS) fit into the picture of sustainable 5G networks. It focuses on some key issues, like access control, clustering and privacy. It suggests ways to adjust user privileges based on where someone is geographically located, ensuring that services are not just secure but also relevant to the context. Furthermore, the authors talk about clustering techniques that make service distribution smarter, while simultaneously keeping the system strong and reliable.

Thus, the study illustrates a proposed LBS architecture that works in layers. Firstly, user devices and sensors collect location data like coordinates, timestamps and even some contextual information. These data are then sent through the network and processed by specific modules that prepare everything for policy enforcement. Finally, the privileges resulting from this process are delivered to LBS applications, which with their turn provide tailored, secure and privacy-aware services to end users. Table VIII presents a detailed list of the papers that have been categorized, including the most important issues that they address.

Table VIII List of Papers in Smart Mobility – V2X category and coverage issues

Article	SmartMobility/V2X					Focus and Coverage (Key Findings)	Type of Study	Year
	Edge-Assisted V2X & MEC	AI-Based Cooperative Perception & Traffic Optimization	NR-V2X PHY-MAC Protocols & Radio Resource Management	Infrastructure Planning, Coverage & Energy Efficiency	Security, Privacy & Trust in V2X			
[19]	X					A 5G+MEC IoV testbed to validate sustainable ways to operate, putting together a hierarchical grading model (L0-L5) which helps measure how smart the IoV network can be. Multi-source fusion scenarios also introduced such as pedestrian warnings and traffic event detection, which have practical applications in the Greater Bay Area	Case Study / Application Paper	2022

Article	SmartMobility/V2X					Focus and Coverage (Key Findings)	Type of Study	Year
	Edge-Assisted V2X & MEC	AI-Based Cooperative Perception & Traffic Optimization	NR-V2X PHY-MAC Protocols & Radio Resource Management	Infrastructure Planning, Coverage & Energy Efficiency	Security, Privacy & Trust in V2X			
[22]	X					The convergence of ADAS sensor systems with 5G NR-V2X, ITS-G5, and upcoming 6G V2X, showing how low-latency connectivity and cooperative communication boost collision avoidance, traffic safety, and open the door for fully autonomous driving	Survey / Review Paper	2023
[93]	X					The Mobilities for EU project, exploring how private 5G networks, edge computing, and network slicing support experimental applications such as mobile charging robots, autonomous cargo transport and V2G systems in Dresden. Also, evaluation of their sustainability impacts using the CIVITAS framework aligned with the European Green Deal	Case Study / Application Paper	2024
[21]		X				A visionary roadmap for 6G-enabled smart mobility across cars, ships, and drones, connecting the ICT and wireless innovations, while simultaneously it keeps the sustainability perspective. Highlighting, also enabling technologies such as 3D hybrid networks, edge intelligence, and AI/ML for sensing and navigation, while also diving into the tough challenges of making both transport systems and ICT infrastructures greener and more sustainable	Survey / Review Paper	2022
[94]		X				A multi-sensory 5G-based approach for real-time and energy-efficient video transmission in EVs, using various sensors to monitor battery, speed, and temperature. The single-buffer architecture reduces propagation, sensing, and collision errors, increasing QoE and sustainability in dense smart city environments	Experimental / Simulation Study	2023
[20]		X				Emerging 6G technologies for V2X and Vehicular Edge Computing, illustrating challenges, like spectrum allocation, interoperability, and regulation, while highlighting sustainability opportunities in safety, emissions, and efficiency	Survey / Review Paper	2023
[23]		X				The combination of B5G/6G with V2X communication, especially concerning with climate-neutral infrastructure, edge computing, and AI with Big Data. A discussion also about use cases like green driving and platooning, emphasizing their role in reducing energy use and emissions	Survey / Review Paper	2024
[16]			X			The different types of vehicular services that are part of the 5G-HEART project, like platooning, autonomous/assisted driving, remote driving, and vehicle data services. Designing the connection of user needs with network KPIs and providing initial network slice dimensioning for a sustainable transportation system	Methodological Paper	2021
[95]			X			Analyze of 6G's role in ITS, focusing on important technologies, standards which needed for smooth operation, and challenges which have to be overcome, while simultaneously emphasizing sustainability and applications such as autonomous driving and smart traffic management	Survey / Review Paper	2024

Article	SmartMobility/V2X					Focus and Coverage (Key Findings)	Type of Study	Year
	Edge-Assisted V2X & MEC	AI-Based Cooperative Perception & Traffic Optimization	NR-V2X PHY-MAC Protocols & Radio Resource Management	Infrastructure Planning, Coverage & Energy Efficiency	Security, Privacy & Trust in V2X			
[17]				X		Green IoV in the 6G era, focusing on energy-efficient V2X communication, edge computing, traffic and EV energy management, and energy harvesting. Highlighting also strategies to optimize these systems and mentions challenges related to sustainability	Survey / Review Paper	2022
[18]				X		An analysis of how EVs affect the environment by examining life cycle. Highlighting also challenges in EVs like battery production, disposal, and energy sourcing. An exploration of how 5G-enabled V2X, autonomous driving, and smart grid integration can improve EV efficiency, connectivity, and sustainability	Survey / Review Paper	2024
[96]					X	An examination of LBS in 5G, presenting methods to access privileges and clustering based on user location. How using different types of location data (such as position, time and context) in a step-by-step process can make services more efficient while also addressing important security, privacy, and trust issues in 5G networks	Experimental / Simulation Study	2023

### 5.4 Green Communication Technologies for Smart Cities

When we talk about moving towards greener and more sustainable smart cities, we cannot leave unnoticed the role of communication technologies. They need to be both energy-efficient and eco-friendly. This section explores how innovations in different network layers, from IoT and edge computing to spectrum optimization and AI orchestration, can collectively reduce carbon emissions and improve urban way of living. It is pretty exciting to see how 5G and 6G are changing the game, making possible the cutting down of carbon emissions.

#### 5.4.1 Energy-Efficient IoT & Urban Sensor Networks

The most important thing for building sustainable smart cities is ensuring that IoT and urban sensor networks are energy efficient. These technologies are very important because they enable to monitor continuously the environment, gather useful data and manage resources more effectively and in addition to reduce energy consumption while improving urban resilience and quality of life. Recent studies show that the combination of IoT with 5G can create smart sensing systems that are scalable and low power.

When the main issue is the green communication technologies in smart cities, one of the key foundations is the development of energy-efficient IoT networks and urban sensors. The work in [27] dives into the interesting idea of Sustainable IoT (S-IoT) looking at how 5G smart antennas and the 4E antennas can really boost energy efficiency and improve communication in smart cities. (4E antennas are designed to be Energy-efficient, Environmentally Friendly, Economical and Effective, offering sustainable performance through recyclable materials and low power operation). The authors make a good point: the most important features for really sustainable IoT networks, is to be truly sustainable, this means environmental friendly, affordable and secure. After some simulations in

MATLAB and OPNET, authors propose a model which showed some serious gains in coverage, throughput and overall QoS, reaching the point of 95-98% network performance.

This presented algorithm is shown at Figure 45 which is proposed for managing multimedia data streams in 5G-based S-IoT networks. The best part of this algorithm is that can modify things like codec type, traffic load and coverage area, so to keep communication smooth and efficient. The results show that smart antenna technologies can play a critical role in creating large-scale, energy efficient IoT systems that are perfect for upcoming smart cities.

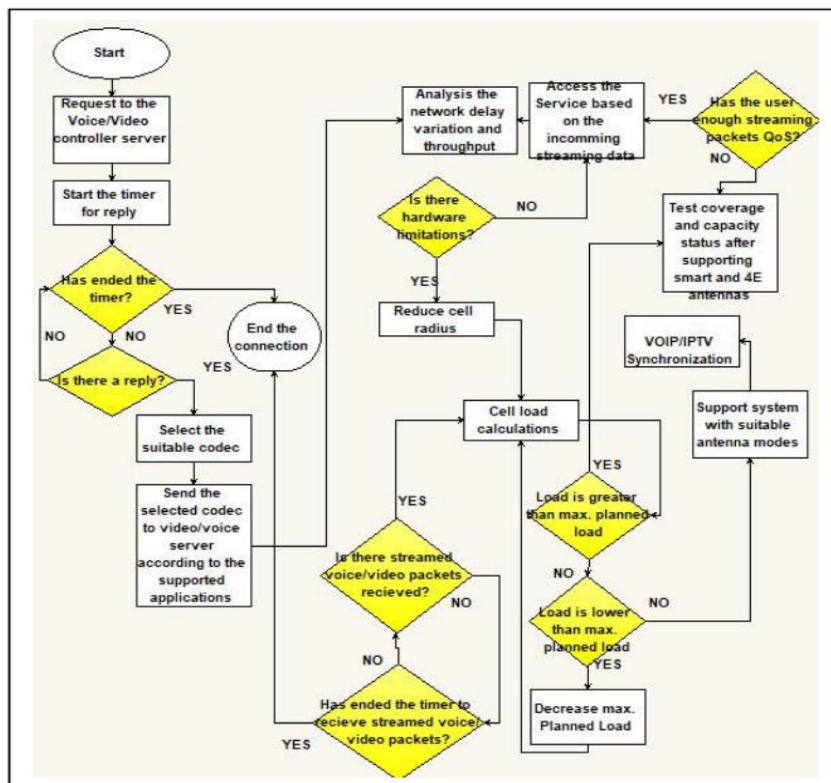


Figure 45 Algorithmic framework for sustainable multimedia streaming over 5G-based S-IoT networks using smart and 4E antennas[27]

Building on what we have seen with energy efficient IoT systems powered by 5G smart antennas technology, the approach introduced in [25] explores how 6G could take sustainability, scalability and intelligence in smart city networks to the next level. Thus, after chatting about S-IoT systems and those advanced antennas, this study presents a really interesting framework. The authors have envisioned a six layer structure for mixing 6G and IoT technologies, from energy efficient sensing and network layers to business and application layers, to create communication systems that are not only secure and quick but also eco-friendly and efficient.

This six-layer framework is shown at Figure 46 that shows how the different elements like sensing, communication and data analysis come together to manage urban services, such as energy consumption, transportation and monitoring the environment. This is one example of how 6G has the ability to bring sustainability, reliability and scalability in future smart cities.

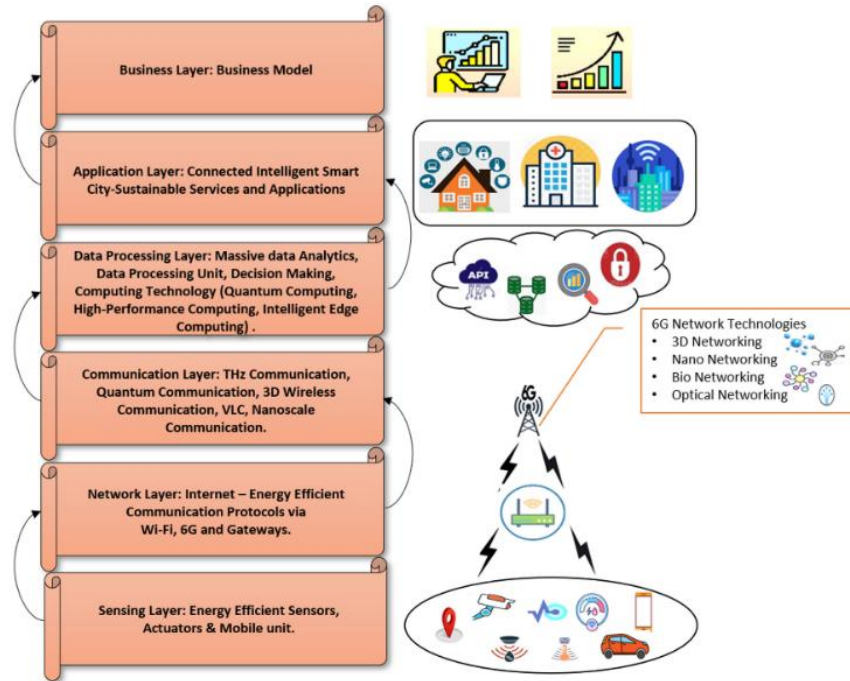


Figure 46 Six-layer 6G-IoT framework for sustainable smart city communication & management[25]

Furthermore, another work that examines how combining IoT and 5G technologies can support automation and sustainability in smart cities is the one in[28]. IoT networks enable sharing data in real time between sensors and devices and in combination with 5G, which offers super fast and dependable connections for all that communication, cities have the chance to improve some very important things like traffic flow, waste management, energy efficiency and tracking environmental conditions.

However, the study highlights some obstacles that we have to overcome, like high costs for operation of this system, issues with different systems working together and security challenges. To address these problems, the author suggests that we need strong teamwork between the public and private sectors, along with strong rules.

Another work that explores how blending 5G and IoT technologies can really boost the sustainable development of Green Smart Cities (GSC) is the one in[26]. It covers some exciting opportunities like energy efficiency, smart transportation, public safety and even healthcare. However, the authors highlight the challenges that we face, like interoperability, cyber security and getting citizens involved. These obstacles will be improved critically if we level up IoT technology and we will achieve intelligent and environmentally aware urban systems.

One very special contribution of this paper is the layered approach to smart city architecture. This framework shows the interaction between the six layers of physical, network, data, service, application and governance layers (Figure 47). Thus, this structure really helps in understanding how sensors, data analytics and management systems can combined for smoother and more sustainable city operations. In conclusion, the authors try to find out how the combination of 5G and IoT can lead to greener and more sustainable cities.

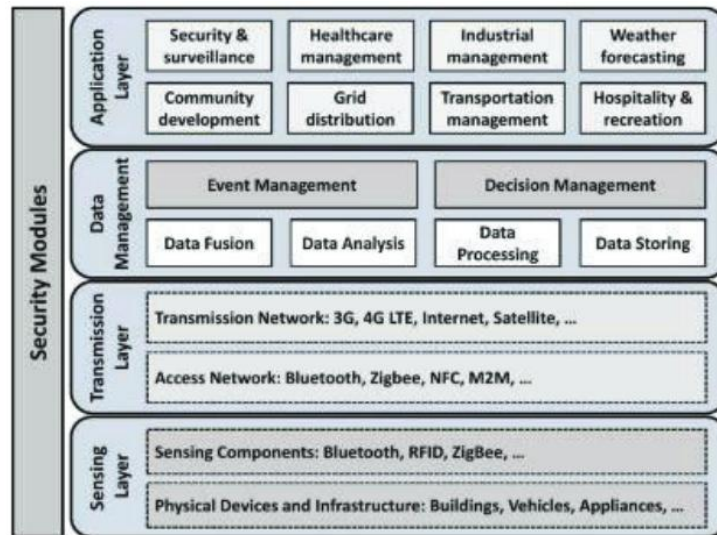


Figure 47 Layer architecture for Smart Cities[26]

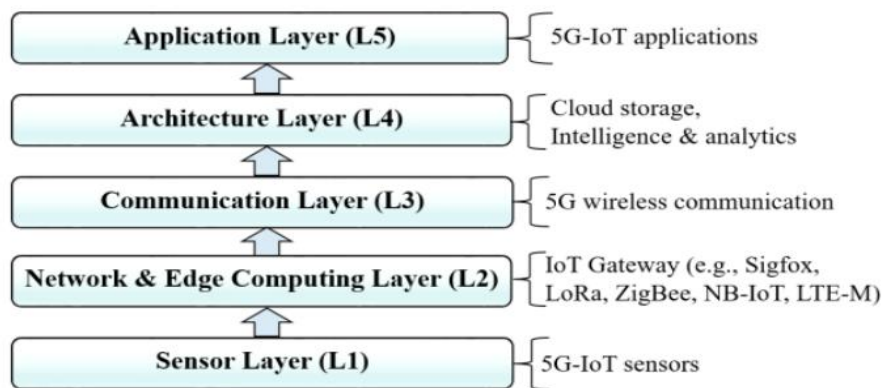


Figure 48 Layered 5G-IoT architecture illustrating data flow [97]

Following the previous study that highlights 5G as a key player in driving sustainable growth, the one in[97] explores carefully how combining 5G and IoT technologies can actually help create sustainable smart cities. The authors come up with a interesting five-layer architecture for 5G-IoT, which connects the basic physical layer of sensors and IoT devices to higher layers of data processing service management and smart applications.

Figure 48 shows how data flows upward. It starts with sensors and network infrastructure, then moves through the communication and edge layers, to smart city services, such as smart energy, healthcare, and transportation. This level shows how 5G-IoT systems make it possible to monitor things in real time, improve energy efficiency and keep everything operating well between devices and city platforms. Thus, the study highlights the importance of synergy between 5G and IoT for a sustainable urban environment.

### 5.4.2 EdgeCloud Platforms for Green Smart-City Services

When we talk about smart cities, we know that the combination of edge and cloud platforms is really a game changer in the evolution of sustainability in them. These technologies allow the distributed data processing and real time decision making, so have the ability to bridge the gap between connected IoT devices and intelligent urban services.

In addition to the studies above about energy efficient IoT and sensor networks, the next step for building sustainable smart cities is to leverage edge and cloud computing. With these platforms we can pick up, operate and make sense of all that huge amount of data flowing from our connected urban systems. Thus, the first study in this subsection [98] investigates how 5G and its use cases, like IoT, cloud computing and Digital Twins, are set to shake up logistics and supply chains, making them more efficient and eco-friendly. Based on findings from European project 5G-LOGINNOV, the authors highlights that 5G is the key technology for real time data sharing, automation and smart resource management in things like ports and logistics networks.

The thing that is really impressive in this study is how authors point out that combining edge computing with cloud platforms helps process a ton of data without latency and reduces energy consumption. This entire digital environment is leading the way for greener and tougher logistics systems. With cloud analytics and IoT sensors, businesses can manage things better and waste less. However, the study suggests that these 5G powered cloud systems could be the key for sustainable smart city services and the digital makeover of industrial spaces in the future.

In comparison with the above study, the one in [99] explores how 5G technology will really transform cities into greener, smarter places to live. It dives into recent research and shows that when you combine 5G with tools like IoT, AI and edge/cloud computing, you have the ability to collect and process data in real time. Thus, cities can improve services like transportation, healthcare and environmental monitoring.

The most interesting thing in this paper is that the authors really emphasize how 5G is the key technology of smart city applications, like being scalable, having low latency and being energy efficient. Furthermore, the authors highlight all the obstacles that we have to overcome, like interoperability, keeping energy use in check and protecting our data. In the end, this study really puts 5G in the spotlight as a crucial player in building sustainable, data driven cities.

Another interesting approach introduced in [100] and explores how 5G networks with VR can really boost sustainability and efficiency in healthcare systems. The authors highlight the fact that 5G has low latency and high bandwidth, something that enable real time telemedicine, remote surgeries and constant patient monitoring. The combination of VR and AR technologies supports training, rehabilitation, and keeping patients engaged. The COVID-19 pandemic really sped up this whole digital shift, showing us just how powerful the blend of 5G and VR can create smarter and more resilient healthcare systems.

In the same way of thinking, the work in [101] explores how 5G wireless technology can act as a boosting economic growth and making cities more sustainable. The authors highlight that 5G is like the digital backbone of smart cities, that supports the data driven and energy efficient services, healthcare and industry. The most interesting thing is how 5G supports both edge and cloud platforms and boost connectivity, automates processes and helps optimize resources. In conclusion, the study highlights 5G as a crucial player in driving green digital transformation. It connects advances in 5G technology, with the goals of economic development and environmental sustainability.

In conclusion, the studies reviewed in this subsection show that 5G-enabled edge and cloud ecosystems play a crucial role in making smart city operations not only scalable but also energy efficient and flexible. This finding shows us in which direction we have to turn for a more sustainable future of our cities.

### 5.4.3 SpectrumPHY-Layer Green Techniques

At the core of sustainable wireless communication is the physical layer that there are some very important techniques for managing spectrum and power. These innovations are crucial because of helping in reduce of energy use and improve the efficiency of the entire network.

In addition to the studies above, the work in [52] explores how 5G physical layer technologies can really boost sustainability and energy efficiency in smart cities. The authors highlight some interesting points about techniques like massive MIMO, millimeter wave communication, ultra-dense networks and small-cell deployment. These methods, not only keep high data speeds and reliable connections, but also reduce energy consumption. Thus techniques like that improve how we use both spectrum and power, creating the technical base for greener wireless networks.

Furthermore, the study dives into how RE and energy harvesting solutions have the ability to use power BS and IoT devices. This fact could reduce the carbon footprint of communications in urban areas. Thus, the study shows that 5G is something bigger than a technology that bring speed upgrade, but also a more eco-friendly way of connecting, emphasizing smart management of both spectrum and power as essential to creating greener cities.

In parallel with the study above, the one in[24] analyzes how 5G and 6G communication networks can really help create smart cities that are both sustainable and energy-efficient. The authors explore the differences between these two generations of technology, focusing on some important KPIs and the adoption of PHY-layer green communication techniques such as IRS, Non-Orthogonal Multiple Access (NOMA), massive MIMO, millimeter-wave, THz communication, SWIPT and energy harvesting. The goal of these technologies is to boost both the efficiency with which we use spectrum and energy, while keeping the carbon footprint of wireless infrastructure as low as possible.

Furthermore, the Figure 49 shows how these green communication technologies are combined with key sustainability indicators. This figure is like a visual map connecting all the technological elements of 5G and 6G with the bigger picture of social and environmental effects. In conclusion, the study shows that PHY-level green techniques, especially when supported by RE and smart AI management, are crucial for building urban communications systems that are sustainable and future-proof.



Figure49 Overview of key 5G/6G green communication technologies and their relationship with sustainability indicators [24]

In general, exploring the studies above of this subsection, it is really clear that improving PHY-layer through advanced transmission methods and designs, powered by RE, is crucial. The main goal of this is the creating of a communication system that are not only greener and more efficient but also ready for the future, especially in smart cities.

#### 5.4.4 AI/ML-Enabled Green Orchestration for Smart Cities

As smart infrastructures get more complex and data-driven, it is very interesting to see how AI and ML play key role in efficient and sustainable orchestration. In this part we explore the way of AI-driven management systems, especially in the context of 5G and 6G networks, can actually collaborate to manage energy, data and services, building urban environments that are not only flexible but also environmentally friendly.

While the previous subsection focused on spectrum and PHY-layer techniques that boost the energy efficiency of wireless networks, authors in [55] explore how we can smartly manage 6G infrastructures, where AI and ML play crucial role in making smart city operations more adaptive, self sufficient and sustainable. Thus, this work dives into how AI and ML-driven orchestration have the ability to change 6G networks into smart systems which support sustainable urban development. The authors describe a future where everything is connected, like 6G, IoT sensors and cloud-edge computing working together because of AI management systems.

These systems could operate autonomously, in real time based on what users need and environmental conditions. These systems in combination with the RE sources and smart grids, will make the whole 6G setup not only efficient but also adaptable. Furthermore, the study highlights the importance of governance and international collaboration to make sure that these AI-driven infrastructures grow in a responsible way. This balance between innovation and sustainability is a huge challenge to overcome.

Another paper in this subsection that dig into the combination of 6G networks and AI technologies is the one in [102]. This work explores the idea of the 15-minute city and how it could really benefit from some cutting-edge technology like 6G, IoT and DT. The fact that these technologies allow for real-time sensing and data sharing means that systems have the ability to run smoother and more sustainably.

Figure 50 shows the framework of 15'-minute city that is built around four principles: proximity, diversity, density and ubiquitousness, supported by IoT connectivity and AI-based orchestration. The authors also argue that by bringing in 6G and DT, we can improve energy use, mobility and resource distribution. Furthermore, it shows that these digital tools are the key players in driving green urban development and this is bond together into the UN's SDG 11 "Sustainable Cities and Communities".



Figure 50 The 15-minute city framework[102]

In addition to the studies above, the one in [103] provide a scoping review, which dive into how 6G technology, supercharged by AI and edge intelligence, can drive to smarter and more sustainable societies. The study identifies three main areas of impact: healthcare applications, smart infrastructure and ethical governance. Furthermore, the most interesting is how the authors explain that AI orchestration in 6G can dynamically manage resources, enable real-time healthcare services and reduce energy use in these interconnected systems.

However, they also emphasize the need for solid policies and ethical guidelines. It is crucial that 6G promotes development that is not only secure and environmentally friendly but also human-centered. In conclusion, this study highlights that AI enabled orchestration is the key player for future smart cities and societies, balancing technological progress and sustainability.

In summary, the studies of this subsection show that AI and ML are more than just cool technologies. They are also the groundwork for how we will make sustainable cities in the future. Intelligent automation can really help finding the balance between technology innovation and environmentally friendly. Table IX presents a detailed list of the papers that have been categorized, including the most important issues that they address.

Table IX List of Papers in Green Communication Technologies for Smart Cities category and coverage issues

Article	Green Communication Technologies for Smart Cities				Focus and Coverage (Key Findings)	Type of Study	Year
	Energy-Efficient IoT & Urban Sensor Networks	Edge/Cloud Platforms for Green Smart-City Services	Spectrum/PHY-Layer Green Techniques	AI/ML-Enabled Green Orchestration for Smart Cities			
[27]	X				S-IoT framework that combines 5G and 4E antennas to boost energy efficiency, capacity, and coverage for smart media data services. The results from simulations show that the combination of massive MIMO, beamforming, and sustainable antenna design improves QoS metrics (level up to 95%)	Experimental / Simulation Study	2022

Mapping Enabling Technologies towards Sustainable 5G/6G Communications

Article	Green Communication Technologies for Smart Cities				Focus and Coverage (Key Findings)	Type of Study	Year
	Energy-Efficient IoT & Urban Sensor Networks	Edge/Cloud Platforms for Green Smart-City Services	Spectrum/PHY-Layer Green Techniques	AI/ML-Enabled Green Orchestration for Smart Cities			
[25]	X				A 6-layer framework for 6G-IoT, which integrate sensing, networking, communication and AI/ML-based data processing to create a secure and energy efficient smart city system. Mentioning of some advanced technologies, like THz communication as a key player for making sustainable smart cities	Conceptual / Theoretical Paper	2024
[28]	X				Examination of how the integration of IoT and 5G can allow automation, sustainability and energy efficiency in urban systems. Also, highlighting applications in mobility with the traffic management, in waste management with sensors, in reducing energy consumption and showing challenges such as cost, privacy and interoperability	Survey / Review Paper	2022
[26]	X				A comprehensive overview of how the 5G-IoT ecosystems have the potential to speed up the development of green smart cities. Furthermore, it talks about the way that 5G and IoT can improve the energy that is used in cities, the transportation system and the citizen engagement with the help of applications and platforms, while simultaneously shows the key challenges.	Survey / Review Paper	2023
[97]	X				Examination of how 5G and IoT technologies contribute to making more sustainable smart cities, using some key enablers like network slicing, D2D communication and MIMO with the participation of sustainability KPIs	Survey / Review Paper	2024
[98]		X			Investigates how technologies like 5G, IoT, AI and cloud computing change the logistics and port operations through the 5G-LOGINNOV project aiming o create a more sustainable and efficient system.	Case Study / Application Paper	2023
[99]		X			Exploration the 5G-driven transformation of smart cities, highlighting key areas of connectivity, IoT integration, edge computing and AI applications. Also, an analysis of how 5G improves urban efficiency and how data management and low latency make systems operating smoother and faster.	Survey / Review Paper	2023
[100]		X			Exploration of how 5G and other digital technologies can drive sustainable transformation in small and medium sized enterprises (SMEs) in Hungary. It is based on a national survey to estimate SME's awareness, how prepared they feel and what business benefits they have of adopting 5G-enabled technologies. Also, highlighting a significant lack of 5G's technical awareness but spots the opportunities gor innovation and efficiency through networks	Experimental / Simulation Study	2023
[101]		X			Examination of the effecting of the economic, industrial and sustainability impact of 5G deployment, especially in job creation, GDP growth and emission reduction. Also, introducing some techno-economic assessments of the potential of 5G to boost productivity support Industry 4.0 and make smart cities more sustainable.	Survey / Review Paper	2023

Article	Green Communication Technologies for Smart Cities				Focus and Coverage (Key Findings)	Type of Study	Year
	Energy-Efficient IoT & Urban Sensor Networks	Edge/Cloud Platforms for Green Smart-City Services	Spectrum/PHY-Layer Green Techniques	AI/ML-Enabled Green Orchestration for Smart Cities			
[52]			X		A systematic macroscopic review of how 5G networks can contribute to sustainability in smart cities, talking about environmental, social and economic factors. Furthermore, it analyzes various sustainability indicators like energy efficiency, CO <sub>2</sub> emissions, power consumption and others focusing mainly in researches with environmental aspects. Also, exploration of technologies which are key players like MIMO and mmWave making match with several of the UN SDGs.	Survey / Review Paper	2022
[24]			X		The shift from 5G to 6G networks especially everything about building sustainable and energy-efficient smart cities. Also, highlighting green PHY-layer techniques like IRS, NOMA, SWIPT, mmWave and THz technologies and connect them with environmental, social and economic sustainability. Moreover, a roadmap that connect AI, IoT and renewable energy with main aim to support the UN SDGs.	Survey / Review Paper	2022
[55]				X	A comprehensive review and a research roadmap about 6G potential to foster sustainable smart infrastructures. Firstly, it provides a historical flashback from 1G to 6G identifying technologies which are key players like AI, RIS, UAVs, THz comm., Blockchain and connecting them with environmental, social and economic sustainability. Furthermore, it highlights 6G use cases and discusses various challenges, including ethical, health and commercialization concerns.	Survey / Review Paper	2021
[102]				X	A technology driven framework which combines 6G, IoT and Digital Twins with main goal to make "15-minute city" project reality. The work also focuses on three main pylons: proximity, accessibility and sustainability. Furthermore, it highlights the importance of AI-based orchestration and real-time sensing in improving mobility, energy efficiency and citizen engagement.	Conceptual / Theoretical Paper	2022
[103]				X	A scoping review of how 6G technologies can transform healthcare and smart urban systems. It recognizes three main domains: 1) 6G applications in real time healthcare, remote monitoring and personalized medicine, 2) infrastructure and communication systems like MIMO, RIS for making smart cities more sustainable and 3)ethical political and governance challenges for responsible development of 6G	Survey / Review Paper	2025

## 5.5 Energy-efficient Hardware & Power Transfer Technologies

While the previous section focuses on how systems and frameworks can help in the connection of people sustainably in urban environments, this section shifts and dives into the hardware and energy foundations that actually make these smart networks operate. In this section we highlight research efforts dedicated to low power radio and baseband design, energy efficient BS and cooling systems

that have appropriate energy consumption. Furthermore, we explore renewable power solutions that focus on energy sustainability starting from the physical layer and building up from there. This section makes a technological base that allows future eco-friendly 5G and 6G infrastructures to work more sustainable.

### 5.5.1 Low-Power Radio and Baseband Design (BS/UE/RF/ASIC)

This subsection focuses on the development of energy-efficient communication hardware across all layers of wireless system design, from BS, to UE, to RF front-ends and Applications-Specific Integrated Circuits (ASICs). It also explores studies that cover low-power 5G and 6G radio architectures and introduce advancements in energy-efficient communication protocols. Last but not least, it proposes clever hardware designs, like RIS and adaptive baseband circuits aiming to reduce energy usage but simultaneously maintain high performance and reliability.

Studying about energy-efficient wireless architectures, the work in[30] explores how IRS can be integrated into 6G networks to improve communication performance and make energy use more efficient in sustainable energy setups. The authors propose an AI-assisted IRS-based design that uses a DRL framework that improves the IRS phase shifts to maximize the Signal-to-Noise Ratio (SNR) while simultaneously keep the transmission power as low as possible. This approach can really make a difference in the reliability of connections to remote winds or solar farms.

Figure 51 shows how IRS elements can be cleverly placed to redirect RF signals towards nodes that are not many possibilities to reach. Thus, it makes a strong argument for IRS-assisted 6G systems as a solid basis for low power and high efficiency radio design.

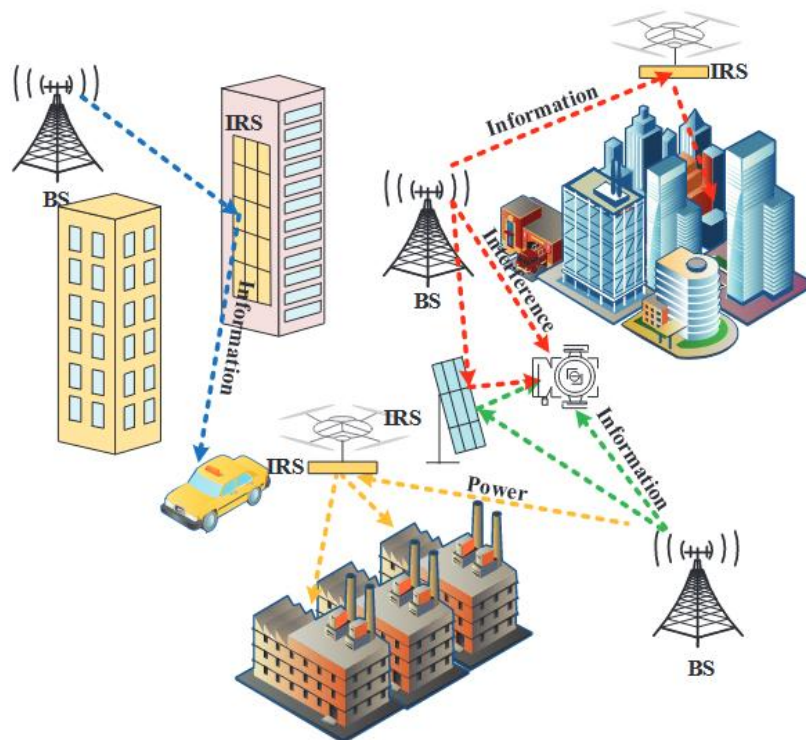


Figure 51 IRS deployment for improving wireless connectivity and energy efficiency in sustainable energy systems [30]

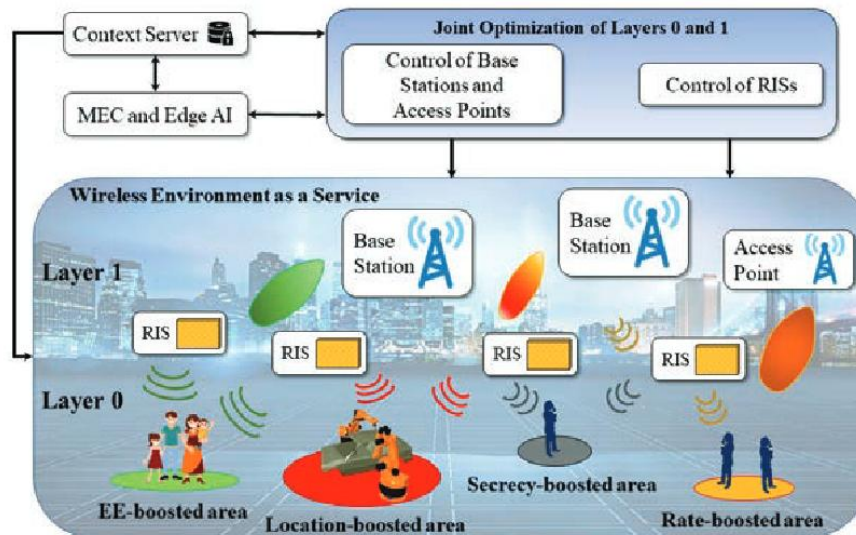


Figure 52 RISE network architecture illustrating the WEaaS concept [104]

Focusing on low-power radio design for B5F systems, I. Marasco et al. [104] introduce the very interesting idea called Reconfigurable Intelligent and Sustainable Environments (RISE) aimed at 6G smart connectivity. This approach integrates RISs, which are low power and almost passive components and have the ability to flexibly manage how radio waves propagate in the wireless network. Figure 52 shows the main RISE network architecture that brings together RIS hardware, AI orchestration and MEC functions. The system works in two main layers: Layer 0, labeled as the Wireless Environment as a Service (WEaaS) which manages the wireless environment using RISs that help create specific boosted zones, the Performance Boosted Areas (PBAs), zones specifically optimized for goals like energy efficiency, secrecy, location accuracy or data rate improvement. The other layer is Layer 1, which controls BS and APs under AI coordination, to maintain system in high performance. Thus, these two layers together enhance radio signals and reduce energy consumption, even when network conditions are changing.

The author also highlights that through WEaaS framework, the radio environment can be organized to achieve various performance targets, like high throughput, low latency, energy efficiency, controlled electromagnetic exposure and security.

Another paper that belongs to this subsection is the comprehensive review in [29] which examines energy efficiency and power control strategies in Ultra-Dense Cell-Free massive MIMO (UD CF-mMIMO) networks, focusing on sustainable 6G communications. The authors describe item by item of the energy consumption model of CF-mMIMO systems, analyzing it into different parts like circuit, signal processing, transmission and backhaul components. Furthermore, they explore some green communication techniques like energy harvesting, sleep modes and smart resource allocation. This study also provides novel power control algorithms, like convex optimization, fractional control and DL-based methods, to find that spot of balancing between performance and energy use in these dense MIMO networks. A typical next-generation CF-mMIMO network is shown in Figure 53 that combines distributed APs and centralized processing for better communication.

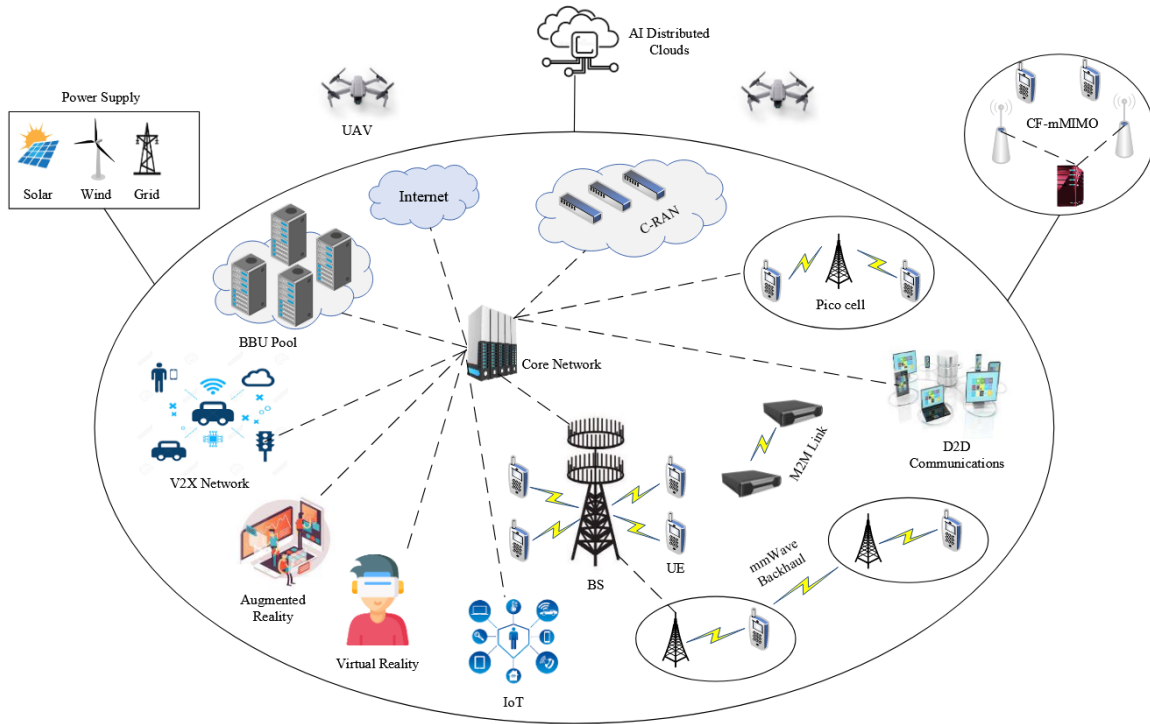


Figure 53 A typical next-generation communication system [29]

Subsequently, the work in[105] introduces an industry approach on reducing of energy footprint and simultaneously boosting power efficiency as we try to create sustainable 6G systems. The authors highlights that power-efficiency need to be a KPI from the start, and it have to cover all protocol layers and hardware components. They introduce the Big-Little modem concept which introduces a dual-subsystem design that allows 6G devices to turn from high-performance to ultra-low-power states, reducing the average energy use significantly. Furthermore, the study points out that it is possible to have devices that have a zero energy balance when they are inactive, through energy harvesting and smart housekeeping, that cuts down those unnecessary wake cycles.

On the network side, the authors execute some interesting strategies like energy-aware scheduling, activating and deactivating nodes dynamically, and like device-assisted wake-up to sync up activity between devices and BSs that shown in Figure 54. Making a footstep towards, they propose a carbon-aware planning that focuses on using renewable sources of energy when this is possible. In conclusion, this study underlines that this paradigm turn of radio and baseband design for low power and carbon neutral 6G systems is very important for the future networks.



Figure 54 Dynamic activation and deactivation network node[105]

Building on the studies before, the comprehensive survey in [106] of Approximate Computing (AxC), showing how it could be a key player in energy efficiency in 5G and 6G systems. AxC refers to an interesting idea where we allow on purpose for some inaccuracies, whether in hardware or algorithms, to reduce things like computational complexity, power use and latency. It is basically a giving up in a tiny bit of precision so as to gain more efficiency. This is very useful in situations like mobile broadband or AI applications that we do not need to be accurate all the time. It also highlights that the ability to have controlled computational imprecision can lead to significant reductions in power consumption and latency, not only in hardware, but also in the algorithms that drive these future networks. The authors, reviewing 80 studies, reveal how AxC can help in sustainable operation in areas with high energy demand like massive MIMO, beamforming, channel estimation and network slicing. However, the authors point out some open research challenges, regarding the implementation of AxC in the continuous Cloud-Edge.

Another paper with an interesting approach is the one in [107] that proposes a cost effective Radio-over-Fiber (RoF) transmitter, which is designed for 5G and 6G networks. This architecture uses a Mach-Zahnder Modulator (MZM) operating in a precisely tuned linearized mode to cancel the nonlinearities from both interferometric and phase-modulation effects. This method reduces distortion in those downlink transmissions that use OFDM and QAM. Furthermore, it boosts both spectral and power efficiency for Centralized Radio Access Networks (CRANs). In this study, the authors use two modulation schemes: 64-QAM and 256-QAM, showing clear improvements in how sharp the constellations looked and a drop in the Bit Error Rate (BER). The study has a lot of figures that illustrate a schematic of the proposed RoF transmitter link and the results of improvements in signal quality thanks to linearization method. This is very impressive because it not only reduce power usage but also keep the transmission quality high.

Additionally, authors in [108] introduce an eco-friendly, adaptable Planar Inverted-F Antenna (PIFA), which is entirely designed from biodegradable materials, a conductive polymer called PEDOT: PSS and a chitosan substrate which is basically waste from the food industry. This antenna works in the sub-6 GHz 5G band, specifically at 4.5 GHz and it is performing quite well, achieving high efficiency while simultaneously eliminating environmentally harmful materials. The most impressive of this study is that proves it is possible to create sustainable, non metallic antennas that still perform efficiently.

Another approach to RIS architecture for sustainable communication in 5G and 6G is proposed in [109]. Unlike traditional methods that deal with both amplitude and phase, this design is limited to phase encoding. This change reduces hardware complexity, lowers power consumption and eases the RF chain demands. By modify the reflection phase of the metasurface unit cells, this system can create multiple pencil beams aimed at different UEs all at once. This means that people have the ability to communicate simultaneously indoors with 5G without any problem.

The results of the authors' simulations are shown in figures of the study and prove that phase-only RIS control could pave the way of low-cost, energy efficient and scalable wireless connectivity. It is a promising step towards massive MIMO and multi-user 6G networks.

Last but not least, a comprehensive framework is proposed in [54] for low-power 5G protocols aimed at making sustainable communication, especially in rural and remote areas. They are using energy efficient modulation and layering protocols that can change and some power-saving tricks like sleep modes and smart wake-up functions. All of these get mixed in with edge computing, network slicing, and satellite backhaul links, which helps bring 5G connectivity to places that usually struggle with

energy and infrastructure. Furthermore, this study also presents some important KPIs, like energy efficiency, reliability, scalability and cost effectiveness to guide how we will work in these low power networks, especially when resources are very tight. Furthermore, the author, as shown in figures, shows us how he has combined technologies like NB-IoT, LoRaWAN and Low-Power Wide-Area Network (LPWAN) with BSs powered by RE. Thus, this architecture is provided solid and low cost connectivity

In summary, the studies that we explore show how important low-power radio and baseband design is for making future 5G and 6G systems more sustainable. Various approaches, from energy-aware protocols and AxC to RIS and bio-based hardware architectures, help reduce power use, while connectivity and performance is still strong.

### **5.5.2 Energy-Efficient Base Stations and CoolingPower Systems**

After the exploration of low-power radio and baseband designs, this subsection turns our attention to optimizing energy use in network infrastructures, especially in BS, cooling systems and power management frameworks. BSs are almost the biggest consumers in wireless networks. The research will explore how edge computing, intelligent resource allocation, AI-driven cooling and even the use of RE can improve the energy efficiency and sustainability of both 5G and 6G systems.

In this context, authors in[110] proposes an interesting framework aimed at making IoV networks more sustainable and energy efficient as we are starting to live in the 6G IoT era. The study presents the Edge-based Efficiency Coordination for VANETs (EECV) mechanism, which is designed to improve response times, reduce computational costs and lower the power use in V2X systems. As it is shown in Figure 55, the framework combines edge computing architectures, where data from vehicles and roadside units are processed locally, instead of being sent off to cloud server. This local processing boosts scalability, reliability and energy efficiency, which is very important for real-time autonomous vehicles and smart traffic systems.

Simulation results that are shown in figures inside the work in[110] show that the proposed EECV mechanism can actually reduce energy consumption and computation costs by as much as 50% in comparison with the traditional cloud-based methods. Furthermore, this framework secure the edge services running smoothly even if there are disconnections between the cloud and the vehicles, thanks to the intelligent collaborative overlay between edge servers, that is often referred as Super-Peers. Thus, the authors present a promising foundation for energy-efficient computing infrastructures in intelligent systems in 6G.

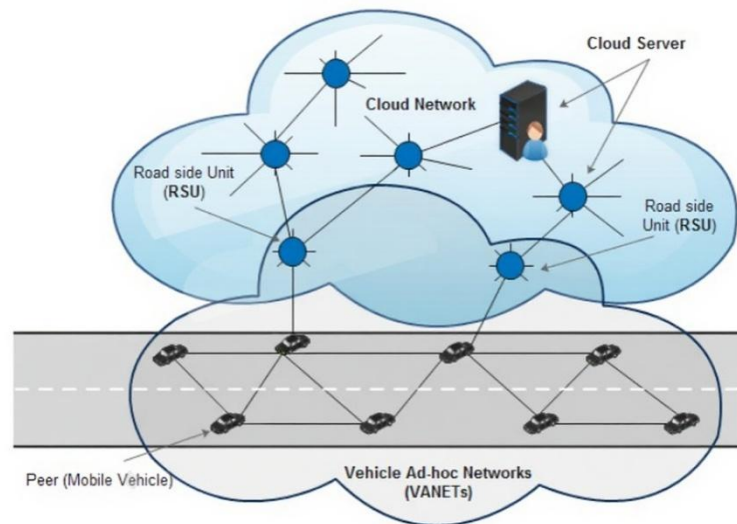


Figure 55 The Edge Computing-based VANETs Architecture[110]

Another paper of this subsection is the comprehensive overview of the technological, environmental and policy-related challenges in [111] which are relevant with sustainability in 5G networks. Firstly, the chapter explores the key 5G technologies, like mmWave, massive MIMO, small cells, beamforming and full-duplex communication. Basically, it focuses on their energy needs of the technologies above and what might mean for the environment. Furthermore, it reviews studies about Radio Frequency/ Electromagnetic Fields (RF/EMF) exposure, highlighting how crucial is the strict compliance with radiation safety standards and to manage radio resources with energy efficiency in mind.

Later in this chapter, it highlights several important green networking initiatives, including EARTH, Green Meter, OPERA-NET2 and 5GrEEen. These projects concern tries to reduce energy use in base-station level and make communication system more energy-efficient. As the energy demand rising, it is essential to redesign 5G infrastructure to be more environmentally friendly.

In contrast with the articles above, the work in [112] proposes an interesting scheduling algorithm, EEPS-MTCN, that aimed to make especially 6G O-RAN more sustainable and more energy-efficient. More specifically, it evaluates computational and transmission energy costs, looking at both NOMA and OMA frameworks. For more accurate calculations, the authors used instruction-level energy modeling based on the specific design of the Reduced Instruction Set Computer-V (RISC-V) instruction Set Architecture. The proposed model combines Signal-to-Interference-plus-Noise Ratio (SINR)-based resource allocation with QoS aware power control, achieving reduction in energy by up to four times compared to some of the leading NOMA schedulers, like Energy Savings and Performance-aware NOMA (ESAP-NOMA) and Resource Allocation And Power-saving NOMA (RAAP-NOMA), while simultaneously keeping multiple ubiquitous massive Machine Type Communications (umMTC) users connected.

Looking at results of their simulation, it is impressive that EEPS-MTCN reduce energy consumption by 48% in radio transmission and 29% in total consumption compared to the traditional methods. In summary, we can say that this framework really boosts energy efficiency and sustainability in O-RAN systems, while the study lays strong foundations for reducing the energy footprint of planning and processing tasks in 6G BS.

In additionally, K. K. Pramanik and P. Kishori Shekokar in[113] present a comprehensive Energy Efficiency Sustainability Framework, SEF-CCEE, aimed cloud and quantum data centers with 6G on the horizon. The most interesting in this study is how it combines software engineering principles with quantum computing models and mathematical energy optimization based on the Green Function from quantum mechanics. Furthermore, the framework explores requirements that take into consideration energy, design integration and algorithmic efficiency to make computing environments more sustainable.

Moreover, the authors make a practical case study on Mass Spectrometry Simulation as a Service (MaaS), which shows an impressive energy efficiency of up to 99% thanks to this Green Function-based optimization, something that proves that the cloud and quantum infrastructures are crucial for the upcoming 6G networks.

Another interesting framework is proposed in [60], which come up with a multi-objective optimization framework aimed at 3D cell deployment in sustainable B5G/6G networks. Its main goal is to increase energy efficiency and the general performance of base station infrastructures. The authors introduce a hybrid approach called Virtual Force and Annealing-Non-dominated Sorting Genetic Algorithm II (VA-NSGA-II), which is designed to improve a few key factors like Received Signal Strength Indicator (RSSI), the coverage area and the costs of deployment. Furthermore, it takes into account both Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) propagation, with the losses of building penetration.

As Figure 56 shows, the study dives into some very complex situations because it comes to signal propagation and LOS and NLOS scenarios, which really helps in understanding how buildings and different materials can affect signal strength. Moreover, the proposed algorithm VA-NSGA-II, shows quicker convergence and more accurate optimization compared to the usual evolutionary methods available and thus it manages to balance the deployment of BS which means maximization in signal coverage while simultaneously is also energy-efficient. This hybrid approach is very promising because it can improve energy efficiency by up to 25% and lower infrastructure deployment costs by about 15%, without reducing QoS.

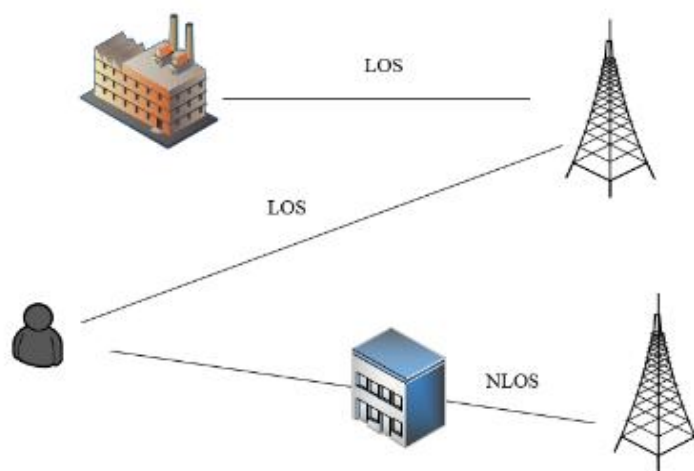


Figure 56 Multi-path transmission in outdoor scenarios[60]

Another approach in sustainability in 6G networks and especially in Industrial Internet of Things (IIoT) networks is introduced in [114] which proposes a really interesting resource control framework aimed at IRS-assisted MEC. It is very impressed the way of how the authors combine NOMA with IRS to help with low-latency and energy-efficient computation at the network edge. Furthermore, they introduce a new resource control algorithm that links cell-edge user clusters with specific IRS units based on how well they are connected and the best phase shift criteria, improving both spectral and energy efficiency.

The results of their simulations are impressive achieving a very low outage probability of  $10^{-5}$ , meaning that the connection will almost never drop and a rate of 5.6 bps/Hz using only 20dBm transmit power and 64 reflecting elements. In comparison with traditional methods like Channel-Aware Random Selection (CARS) and Channel-Aware Minimum Distance (CAMD), this approach reduces power use by about 5dBm and boosts signal reliability by up to 6dB. In conclusion, the study shows how using IRS-assisted design can improve edge-based 6G setups, both more energy-efficient and more stable.

Last but not least, the research in [115] dives into eco-friendly strategies for sustainable 5G networks and it highlights how crucial is to find the spot of balance between technological progress and caring for our planet. The authors point out three big areas for improvement: using energy-efficient hardware, integrating RE and improving cooling systems with AI.

Furthermore, they mention techniques like SDN, NFV and ML for power management. These tools can help save energy in real time, especially in BS and data centers. Companies like Vodafone, T-Mobile and Ericsson have shown real results, where they have managed to reduce power usage by up to 30% and shifted to 100% RE for their operations.

The study also introduces some global regulatory frameworks, like EU Green Deal and ITU Green Standards, which are pushing telecommunication operators to aim for carbon neutrality by 2050. To conclude, it shows how smart infrastructure design, RE integration and advanced cooling systems can help to create more sustainable world (Figure 57).

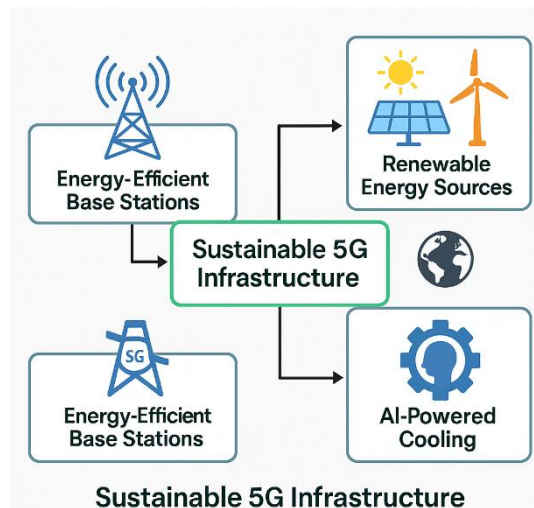


Figure 57 Sustainable 5G infrastructure model for reduced carbon footprint

In conclusion, the research in this subsection highlights how important energy-efficient base station designs, smart scheduling methods and green cooling solutions are for achieving low-carbon and cost-effective network operation. These innovative technologies that are proposed above can help us rely less on traditional power sources and make wireless networks more sustainable.

### 5.5.3 Energy Harvesting & Renewable Integration

Expanding the discussion on energy-efficient communication infrastructures, this subsection focuses on how we can connect RE sources with the upcoming wireless networks. The studies examine how technologies like RF-based energy harvesting, hybrid renewable systems and AI-driven smart grids can turn networks into self-sustaining and low-carbon ecosystems, reducing our dependence on the traditional power grid and make a step towards to a more sustainable future.

First of all, a comprehensive review in [31] reveals renewable energy-powered architectures for sustainable 5G networks. It explores how mobile data traffic is escalating, which leads to a significant increase in energy consumption and CO<sub>2</sub> emissions from all those dense 5G infrastructures that created everywhere. Furthermore, the authors suggest integrating RE sources as a solid long-term solution for these ultra-dense small-cell setups. They examine different types of base station configurations, like hybrid or off-grid that combine solar, wind and battery systems along with some smart energy management strategies.

One of the most impressive features of the paper is the illustration that is shown in Figure 58 and shows how RE sources can either back up or even take the place of traditional grid power in 5G BS. It shows how we can move toward self-sustaining, eco-friendly cellular networks. This turn to the RE sources is very important for reducing operating costs and hitting the ambitious net-zero energy goals that we are want to succeed in future communication systems.

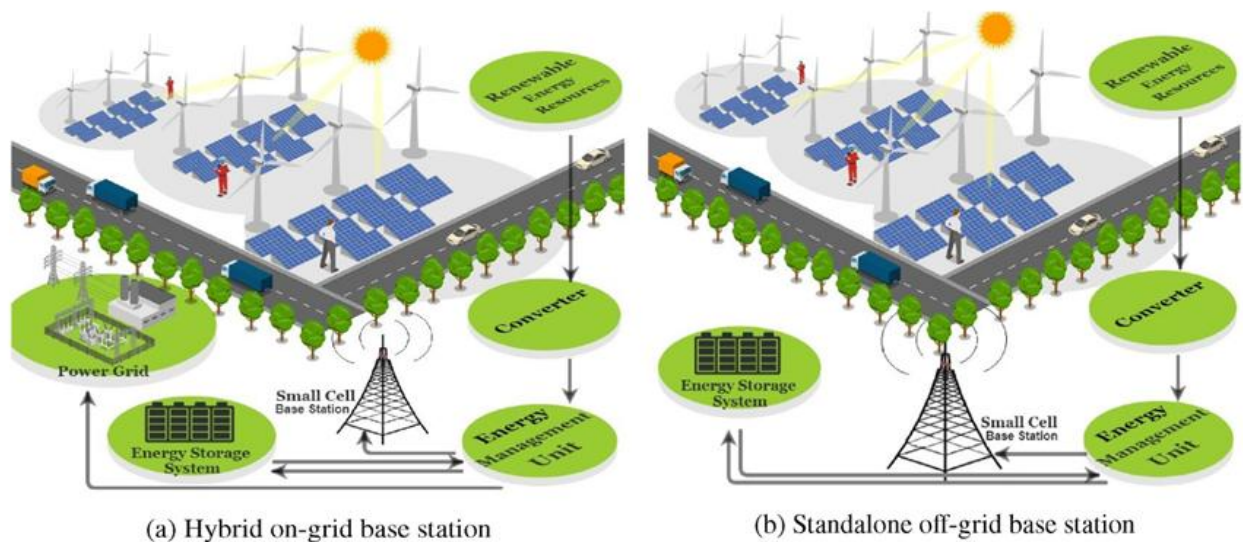


Figure 58 Hybrid and standalone RE configurations for 5G BS[115]

Building upon the previous discussion on renewable-energy powered 5G networks, the work in[56] takes the idea further by exploring how we can make full-spectrum 6G systems energy self-sustainable. Thus, the authors introduce a hierarchical three-layer Energy Self-Sustainable (ESS) 6G architecture, combined with AI-empowered Central Units (CU), distributed Access Units (AU) and

zero-energy IoE devices. They leverage a mix of technologies like sub-6 GHz, mmWave, THz and even visible light, to make sure data flows smoothly and Wireless Energy Provision (WIEP) is seamless. To do so, they are focusing on energy efficiency through some innovative strategies like cell-free coordination, airborne access networks and IRSs, which change the radio environment to improve power transfer for the best possible results.

Figure 59 is very helpful to clarify the concept, showing the CU-DU-IoE layered architecture of ESS-6G, highlighting how energy management is distributed and controlled by AI. In other words, the authors try to illustrate a self-sustaining communication ecosystem, which will build strong foundations for zero-energy radio transceivers in the future of communications.

On the contrary, a comprehensive overview in [33] reveals massive Wireless Energy Transfer (mWET) as a game-changer for powering big IoT networks that we will meet in the upcoming 6G era. The paper analyzes the different parts of RF-based Energy Harvesting (EH) systems, like rectifier circuits, Complementary Metal Oxide Semiconductor (CMOS) low-power receivers and power management units. It also explores some interesting technologies, like Energy Beamforming (EB), Distributed Antenna Systems (DAS), IRSs and even Unmanned Aerial Power Beacons (UAPBs) that help make wireless power delivery more scalable.

Furthermore, this study highlights that when you combine these technologies, you can improve how energy is delivered, how efficiently systems operate and how much they can cover, making RF-based WET more adaptable compared to the traditional methods like inductive or capacitive coupling. In conclusion, this study places mWET in the bigger picture of energy harvesting and renewable-powered IoT.

Building on the concept of mWET for sustainable IoT systems, the work in [116] take a closer look at how RF-based energy harvesting (RF-EH) can work hand-in-hand with D2D communication, to create fully sustainable and energy-efficient 5G networks. It also explores green network architectures that are connected with RF-EH, D2D communication, mMIMO, HetNets, cloud-RAN and MEC. All these technologies together can really help reduce on power usage in both BS and user devices while still maintaining high data rates and low latency.

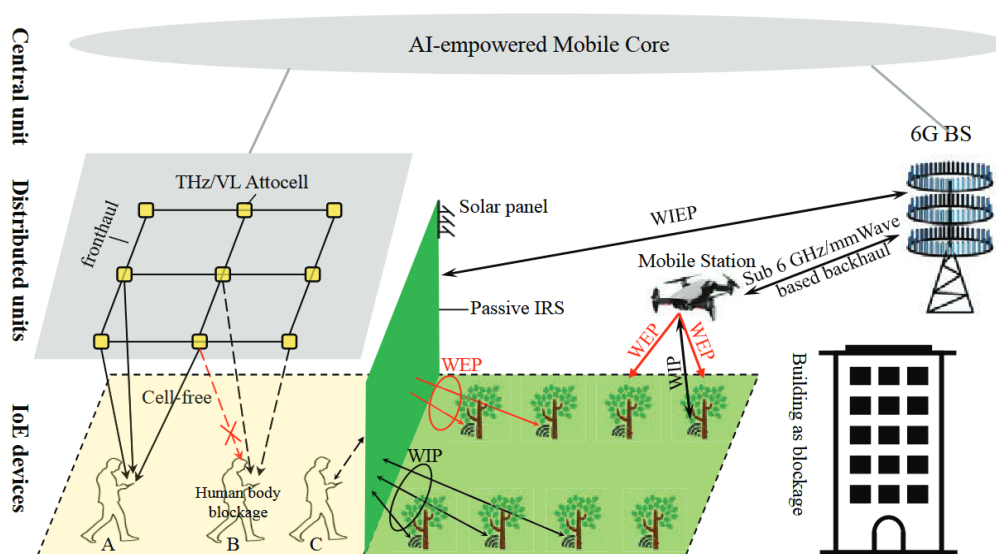


Figure 59 Architecture of ESS-6G network [56]

The authors really focus on RF-EH architectures giving us some details about the steps of collecting, storing and converting energy from various sources, like RF, solar, wind and even thermal energy. Thus, we can conclude that the study highlights how integrating wireless energy harvesting with efficient communication mechanisms can drive the development of self-powered and low-carbon network infrastructures.

In addition to the above, the work in [117] explores mWET, as a key enabling technology for powering up huge 6G IoT ecosystems that have already started to create in front of the 6G era. The authors take a closer look at various architectures and methods for sending energy wirelessly, comparing the pros and cons of CSI-based versus CSI-free strategies for mMTC networks.

Furthermore, the study also explains that the using of precise CSI can improve beamforming accuracy but is often impractical for large and dense IoT networks due to high energy demand and computation costs. For this reason, the authors suggest CSI-free methods in combination with use of DAS and EB because this combo is more scalable and uses less power. Moreover, the results of their simulation show that these techniques can boost harvested energy and reduce power outages, make them more effective for creating sustainable and large-scale IoT networks.

Diving into the world of renewable-powered networks, the approach introduced in [51] examines a hybrid power system that is designed for sustainable operation of 5G cellular sites. Using a solid long-term weather dataset and the HOMER Pro simulation tool, the authors have calculated the best sizes and costs for providing clean reliable power, especially when the grid gets a little unstable.

The proposed configuration, which combines solar panels, wind turbines, hydrogen fuel cells and electrolyzers reach a RE rate of 98%. Furthermore, the cost of energy is so small that is an impressive 91.5% reduction in energy cost compared to traditional grid-diesel systems. Furthermore, this study provides details of the system's architecture and how energy gets distributed. It also highlights how this hybrid setup balances energy production from solar, wind and hydrogen sources to keep everything operating smoothly. Moreover, it includes an economic analysis that shows a return on investment and a short payback period, proving that renewable-powered hybrid systems can deliver both energy independence and significant saving of costs for future cellular networks.

In addition to the above, a comprehensive review in [118] reveals how AI, IoT and 5G technologies can combine together to shape the future of smart grids. The authors want to illustrate a smart energy system that is not only sustainable but also really smart, with features like monitoring, making predictions and managing energy in an adaptable way. They use AI for analytics and ML to spot faults, predict energy demands and help the grid in self-healing. They also use IoT-based wireless sensor networks for better connectivity, more scalability and automation. Furthermore, the introduction of 5G and network slicing provide that solid communication foundation that we need for reliable and quick data exchanges and also for managing distributed energy resources.

However, the study goes further on how we move away for traditional grids to fully digital and autonomous networks. The authors also focus on how important is the combination of AI, IoT and 5G for helping overcome the big challenge of energy need. They also highlight the challenges of cybersecurity, interoperability and standardization, and suggest some key strategies for making system more secure and seamless. In summary, this paper underscores how 5G-enabled smart grid could be foundational for creating energy systems that are more efficient and sustainable.



Figure 60 Model of V2Fog as a decentralized data and energy management node [119]

Another comprehensive review in the smart grid era is the one in [119] which gather a thorough review about how 5G networks can work together with Smart Grids. The authors believe that the Vehicle-to-Fog (V2Fog) systems are a key player in promoting sustainable energy and managing data effectively. They also use the Technological Innovation System (TIS) framework to collect 370 publications and 147 patents to understand how academia, industry and regulatory bodies can collaborate. The interesting is that they suggest decentralized 5G setups, especially when it is combined with RE sources like solar-powered electric vehicles. This could help smooth out the big energy demands that we usually meet in centralized cloud systems.

Figure 60 shows how the V2Fog model transforms electric vehicles to mobile fog nodes for local data processing and grid balancing, while improving both energy efficiency and making the network more resilient. The authors also think that it is crucial for organizations like 3GPP, IEEE and ITU to act quickly and create some new standards that could support these decentralized approaches in Smart Grids.

Additionally, Settapong Malisuwan in [120] suggests an interesting bi-level optimization framework that brings together distributed PhotoVoltaic (PV) systems and battery energy storage into 5G BSs, to boost sustainability and reduce carbon emissions in IoT networks. Thus, the external model identifies the best PV and storage options for maximizing Return On Investment (ROI) while on the other hand, the internal model works to dynamically allocate transmission power, aiming to improve carbon efficiency in the BS level. This framework takes into account fluctuating electricity prices, solar radiation patterns and traffic fluctuations which help balance the energy supply with communication needs.

The results of the authors' simulation show that the system manages to save up to 18.7% on grid power, boasts an ROI of over 900% and almost zero energy waste. This is a sign that 5G infrastructures with the integration of RE sources could be feasible. In summary, it highlights how crucial data-driven and carbon-efficient energy management will be for the future IoT ecosystems.

On the contrary, the work in [121] develops an interesting fuzzy optimization model that aims to create a sustainable 5G-enhanced Power Distribution Network Design (PDND), which shows the way it brings together distributed RE resources, dynamic pricing strategies and 5G-based IoT

communication. Basically it helps to understand the best setup for RE generation sites, how much to invest in 5G infrastructure and what the electricity prices should be to maximize the power company’s profits, even when demand and generation conditions are uncertain.

As shown in the study, the using of 5G networks upgrade the “game” by improving real-time data sharing between utilities and consumers, enabling dynamic demand response and reduced operational costs. The sensitive analysis shows that if you increase 5G coverage up to 80% seems to be the point where there is the highest profitability, but if you go beyond that, the costs start to outweigh the benefits.

In summary, the studies above discuss about how energy harvesting and networks powered by renewable sources can show the path to a more sustainable communication system. The combination of hybrid renewable systems with smart power management and AI-driven energy optimization shows that not only is achievable but also it is crucial for a more sustainable and independence communication system. Table X presents a detailed list of the papers that have been categorized, including the most important issues that they address.

Table X List of Papers in Energy Efficient Hardware and Power Transfer category and coverage issues

Article	Energy-efficient Hardware & Power Transfer Tech.			Focus and Coverage (Key Findings)	Type of Study	Year
	Low-Power Radio and Baseband Design (BS/UE/RF/ASIC)	Energy-Efficient Base Stations and Cooling Power Systems	Energy Harvesting & Renewable Integration			
[30]	X			A new 6G network setup that uses IRS and DRL to boost communication efficiency and energy management in sustainable energy infrastructures. Also, IRS can redirect wireless signals to improve coverage, reduce power use and allow real-time monitoring of renewable energy systems	Experimental / Simulation Study	2021
[104]	X			The RISE idea that basically it uses RIS to build wireless environments that are not only energy-efficient but also adaptable and programmable. Also, some new concepts, like WEaaS and PBAs to dynamically manage energy, coverage and connectivity using AI orchestration and edge-computing	Conceptual / Theoretical Paper	2021
[29]	X			A comprehensive review of energy efficiency and power control strategies within ultra-dense CF- mMIMO networks for sustainable 6G. Also an exploration of some models for power consumption, various green networking approaches, energy harvesting techniques and optimization algorithms to reduce network energy use with simultaneous high performance	Survey / Review Paper	2022
[105]	X			Energy-focused system design, Big-Little modem architecture and carbon-aware operations that integrate renewable energy and turn on and off the network control when it is needed. It is also vital to consider energy efficiency as a top priority when talk about 6G standardization	Conceptual / Theoretical Paper	2022
[106]	X			This study reviews how AxC can boost energy efficiency, latency and scalability of B5G and 6G networks. It highlights some AxC techniques like inexact arithmetic, reduced precision and heuristic algorithms that plays crucial role in simplifying the complex calculation in mMIMO, beamforming and resource allocation, while the performance stands in a reasonable level	Survey / Review Paper	2023
[107]	X			The RoF fronthaul architecture, which uses MZMs modulators and QAM-OFDM modulation for 5G and beyond centralized RANs. Simulation results show improved linearity, a notable drop in the BER and importantly lower power consumption, revealing a potential for energy-efficient fronthaul links	Experimental / Simulation Study	2023

Article	Energy-efficient Hardware & Power Transfer Tech.			Focus and Coverage (Key Findings)	Type of Study	Year
	Low-Power Radio and Baseband Design (BS/UE/RF/ASIC)	Energy-Efficient Base Stations and Cooling Power Systems	Energy Harvesting & Renewable Integration			
[108]	X			The design and creation of a super eco-friendly Planar Inverted-F Antenna, which is made by conductive polymer, the PEDOT:PSS and a biodegradable chitosan substrate, especially great for 5G wearable gadgets and health-monitoring devices. The antenna is very impressive because of: strong mechanical flexibility, 85% radiation efficiency, minimal SAR, plastic-free materials	Experimental / Simulation Study	2024
[109]	X			Introduces a phase-only RIS strategy that aims to boost sustainable communication for multiple users in 5G and future networks. It enables multi-beamforming without needing any complicated hardware, allowing multiple users to connect simultaneously, saving energy and lowering costs. Thus it shows that it enhances energy-efficient and scalable connectivity, especially in crowded environments	Experimental / Simulation Study	2024
[54]	X			A framework of low-power 5G protocols specifically designed for rural and remote areas. It uses some smart techniques, like adaptive protocol layering and energy-efficient modulation to reduce energy consumption and simultaneously keep the network reliable. If this combined with renewable energy sources, it will improve digital inclusion which is important for sustainable connectivity	Conceptual / Theoretical Paper	2025
[110]		X		An edge-based computing framework, the EECV, which is designed for IoV within 6G networks. It is aimed to boost energy efficiency, speed up response times and keep simultaneously reliability high, processing and storing data where it is needed. The study shows that we can save 50% of costs and energy compared to the older setups, making vehicular communication more sustainable	Experimental / Simulation Study	2023
[111]		X		The environmental effects of 5G technology and try to find strategies for sustainable network design. The authors review energy-efficient components like mmWave, mmMIMO and small cells. Furthermore, it highlights some green initiatives, like EARTH, Green Meter, OPERA-NET2 and 5GrEEn, focusing on Ai-driven energy management which in combination with renewable powered BSs can lead to the balance of technology and sustainability	Survey / Review Paper	2023
[112]		X		A new energy-efficient scheduling algorithm, the EEPS-MTCN, which designed specifically for 6G O-RAN to optimize how resources are allocated using both NOMA and OMA schemes. This model evaluates computational and radio energy use by employing instruction-level power modeling on the RISC-V architecture. The results of the simulations shows reducing in energy consumption and boosting efficiency in comparison with ESAP-NOMA and RAAP-NOMA baselines while simultaneously it keeps the QoS high	Experimental / Simulation Study	2024
[113]		X		The Software Engineering Sustainability Framework for Cloud Computing Energy Efficiency (SEF-CCEE), making the cloud and quantum data centers operate more efficiently in terms of energy use. Furthermore this framework integrates sustainability into every phase of Software engineering, achieving energy efficiency rated of up to 99% in simulations. The authors include a mass spectrometry case study demonstrating the application of Green Function modeling for large-scale and energy-efficient computation.	Conceptual / Theoretical Paper	

Mapping Enabling Technologies towards Sustainable 5G/6G Communications

Article	Energy-efficient Hardware & Power Transfer Tech.			Focus and Coverage (Key Findings)	Type of Study	Year
	Low-Power Radio and Baseband Design (BS/UE/RF/ASIC)	Energy-Efficient Base Stations and Cooling Power Systems	Energy Harvesting & Renewable Integration			
[60]		X		A multi-objective optimization framework for 3D cell deployment in B5G and 6G networks, trying to find the balance between coverage, capacity and energy consumption. This model uses some smart algorithms, like PSO and GA, to find the best setup for BSs and aerial cells. The results show that it does not only make dense 3D networks more effective but also more sustainable	Experimental / Simulation Study	2025
[114]		X		A new framework that uses IRS-NOMA to help with MEC in IIoT applications, especially with the upcoming 6G networks. The authors also introduces a resource control algorithm that assigns edge user clusters to specific IRSs based on how well the channels correlate and what the best phase shifts are. The results of the simulations shows that is better than the traditional methods like CARS and CAMD in outage probability	Experimental / Simulation Study	2025
[115]		X		Exploration of sustainability strategies for reducing energy consumption and CO <sub>2</sub> emissions in 5G networks, using AI-based energy management, renewable energy integration and eco-friendly infrastructures design. Exploring the real-world results, that companies like Vodafone and t-mobile are doing, showing 40% energy savings aligned with UN SDGs	Case Study / Application Paper	2024
[31]			X	A comprehensive survey paper that dives into how we can integrate renewable energy into 5G mobile networks. It highlights solar, wind and hybrid-powered BSs, energy cooperation mechanisms and smart grid interactions as key players in reducing carbon emissions and operational costs. It also compares on-grid and off-grid setups, analyzes energy efficiency techniques, like mMIMO, HetNets and BS sleep modes	Survey / Review Paper	2020
[56]			X	The Energy Self-Sustainable 6G concept, proposing a three-layer structure (central units, distributed units, zero-energy IoE devices) to boost energy efficiency across the entire network. It also explores cell free and airborne access, IRS-based smart environments and wireless information and energy provision (WIEP) as a crucial approach for making zero-energy IoT devices real. Experimental results show that cell-free access and IRS-aided systems can reduce energy consumption up to 50%, making ESS-6G a foundational model for future sustainable networks	Conceptual / Theoretical Paper	2021
[33]			X	A comprehensive review of WET as a key enabler for powering massive IoT deployments in the 6G era. It also explores the different architectures and the various challenges of WET, including EB, DAS, IRS and CSI-limited and -free strategies. The authors show that EB in combination with smart placement of DAS can really improve scalability and efficiency.	Survey / Review Paper	2021
[116]			X	A review of energy-efficient 5G architectures, especially those that mix D2D communication with RF energy harvesting to reduce power consumption and emissions. It also explores some exciting technologies like mMIMO, HetNets, mmWave and C-RAN. These technologies are the key players of sustainability in networks. However, it also presents some challenges, like security issues, privacy concerns and finding ways to optimize energy use.	Survey / Review Paper	2021
[117]			X	WET as an eco-friendly way to power the huge IoT networks that we expecting with 6G. It also dives into different setups that mix EB, DAS and methods based on CSI to boost efficiency and reliability. Furthermore, it also suggest using strategies without	Experimental / Simulation Study	2023

Article	Energy-efficient Hardware & Power Transfer Tech.			Focus and Coverage (Key Findings)	Type of Study	Year
	Low-Power Radio and Baseband Design (BS/UE/RF/ASIC)	Energy-Efficient Base Stations and Cooling Power Systems	Energy Harvesting & Renewable Integration			
				CSI or partial CSI so can help broaden coverage and reduce energy costs		
[51]			X	A hybrid energy system, like wind, solar PV, hydrogen fuel cells, for sustainable 5G base station operation. It also uses HOMER Pro simulation to evaluate this model and the results is very impressive, with reduction in carbon dioxide emissions	Experimental / Simulation Study	2022
[118]			X	A comprehensive review of how the combination of AI, IoT and 5G integration can help building the next wave of smart grids that are intelligent, secure and sustainable. It also highlights that AI's role in decision making, fault detection and energy optimization. However, it underlines some challenges that we have to overcome, like cybersecurity, interoperability and standardization	Survey / Review Paper	2024
[119]			X	Where 5G and B5G meets Smart Grids, emphasizing V2Fog as an innovative industrial solution for improving energy efficiency in data processing. The authors introduce the framework TIS and dig into how decentralized 5G setups along with solar vehicle fog networks can help reduce energy demands, make system more resilient and make greener and more sustainable the digital future	Survey / Review Paper	2024
[120]			X	A dual-layer modeling algorithm which combines solar photovoltaic systems and battery storage into 5G BS to improve energy efficiency and carbon performance for IoT connectivity. The results of simulation show that it can reduce carbon emissions and operating costs.	Experimental / Simulation Study	2025
[121]			X	A fuzzy optimization model, the PDND, which brings 5G connectivity into the picture for power distribution network design, to effectively manage distributed renewable energy resources alongside dynamic pricing. This model decides the right amount to invest in 5G, how much renewable generation capacity is needed and what the best pricing strategy would be. The findings show how leveraging 5G-enabled IoT communication can boost sustainability and improve operational performance in our smart energy grids.	Experimental / Simulation Study	2024

## 5.6 Non-Terrestrial Platforms for Sustainable Communications

As we look ahead to the world of 6G, it is clear that NTN, including satellites, HAPS and UAV-based systems, will be crucial for the global and sustainable connectivity. These networks will not only solve the coverage challenge but also will reduce energy consumption, boost the resilience and build greener communication systems.

### 5.6.1 Satellite and High Altitude Platforms

When exploring sustainable non-terrestrial communication systems, satellites and HAPS are key enablers of global connectivity. In contrary of traditional ways, they give an incredible ability to cover vast areas, while simultaneously they can bring strong foundations in save energy, especially if they combined with RE sources.

When we talk about sustainable communication systems that reach beyond our planet, we start with HAPS, which they are in the stratosphere, just like a bridge between ground-based networks and satellites. The work in [37] explores how HAPS can help future 6G systems to be more sustainable. The authors take a closer look at how these stratospheric platforms, operating as Super Macro Base Stations (SMBS), can reduce the workload on terrestrial RANs. This offloading will allow BS to go into sleep mode which will consequently lead to impressive reduces in energy use from the grid. They also use a detailed case study based on real traffic data, which shows that using HAPS for offloading, along with smart resource-on-demand tactics and RE strategies, we could see energy savings increase by up to 70% while QoS stands in acceptable levels.

Figure 61 shows how a HAPS can fit into a terrestrial RAN, in a more agile way, while also relying on RE sources. These platforms using solar power and adjusting bandwidth on the fly can add a level of flexibility that is very important for the development of sustainable 6G. In conclusion, the study highlights that if we combine HAPS, as part of the aerial layer, with other heterogeneous networks we can make our communication infrastructures greener.

Following the discussion about mix of HAPS into a terrestrial RAN, the work in[41] focuses on satellites and high altitude technologies, to understand how sustainable 6G non-terrestrial links can help achieve reliable and energy-efficient communication for next-generation air mobility. More specifically, the study proposes a design for an Air-to-Ground (A2G) link that uses the Inmarsat GX GEO satellite constellation, to ensure that aircraft flying at different altitudes have reliable communication. The authors create a detailed channel propagation that takes into account various factors, like free-space and atmospheric losses, various in antenna gain and changes in carrier-to-noise ratio along realistic flight paths.

The results of their simulations shows that as altitude increases, propagation losses decrease, while simultaneously, they found that atmospheric conditions can affect link stability and energy efficiency. Furthermore, the study introduces the proposed data link setup that combines high-altitude and space-based elements in the 6G framework. It highlights that the key takeaway for establishing sustainable and robust connectivity we have to use precise propagation modeling and smart satellite link management.

An interesting framework introduced in [122]aimed at making GEO satellite communications more sustainable. It wants to boost energy and spectral efficiency, especially in 6G NTN. Thus, the authors proposed a model which has RIS installed on the ground to bounce satellite signals back to users, even when there is no direct LOS. This means that we can achieve better connectivity without transmitters, hence less power use.

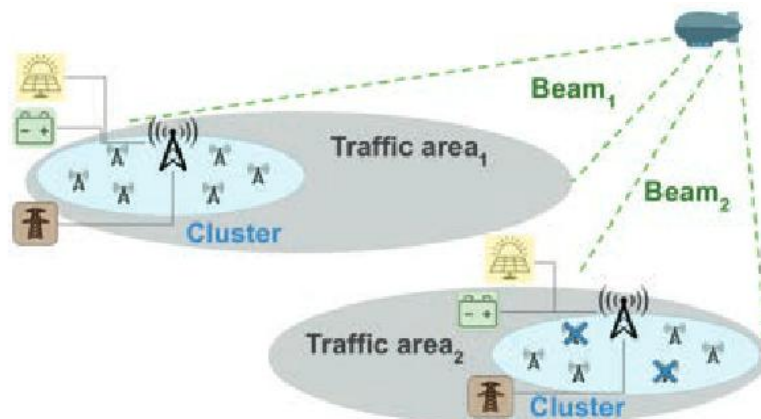


Figure 61 Integration of HAPS into a terrestrial RAN [37]

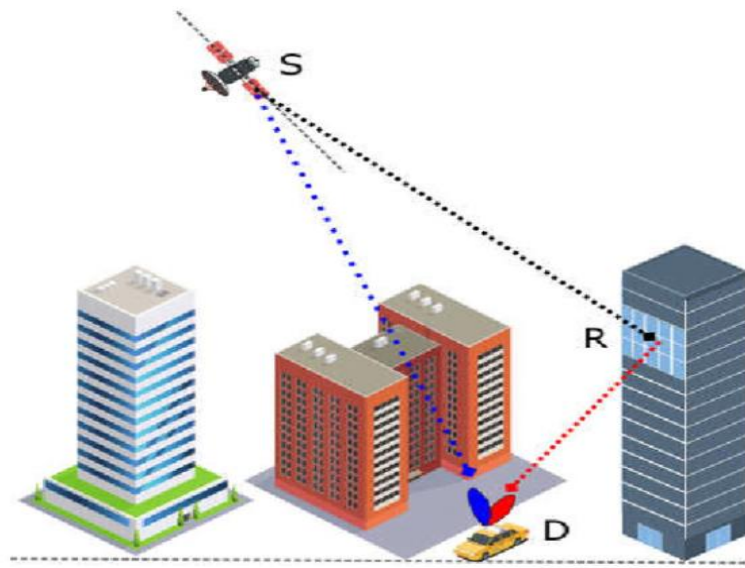


Figure 62 RIS-assisted satellite communication model

Furthermore, they also create a smart algorithm, called Joint Power Allocation and Phase Shift (JPAPS), that is based on Mesh Adaptive Direct Search (MADS) optimization technique, and it is designed to improve both satellite's transmit power and the phase settings of the RIS. The results of their simulations show that the RIS-assisted system (which is shown in Figure 62) can make capacity boosts by up to 10% and save 20% on energy in comparison with more traditional GEO satellite communication setups. In this situation we can say that combining RIS and NTN we have hopes for sustainable global connectivity. In summary, the studies in this subsection show how satellite and stratospheric technologies, like HAPS, can contribute to greener and more energy-efficient 6G networks, forming the foundation for the sustainable upgrade of NTN.

### 5.6.2 UAV-Assisted and Airborne Networks

Exploring for more adaptive and energy-efficient communication systems, it is hard to ignore the role of UAVs and airborne networks. Their contribution is crucial for the development of the sustainable 6G ecosystem. While satellite and HAPS provide the backbone for wide-area sustainable connectivity, the UAVs and airborne networks are used for making more flexible and adaptive 6G infrastructures, supporting communication, sensing and energy transfer locally.

One paper that belongs to this subsection is the one in [34], which proposed a UAV-assisted communication framework that addresses both wireless information and energy transfer (WIT/WET) in smart sustainable 5G networks. Thus, we can use UAVs as a mobile transmitter to connect low-power ground terminals (GTs). The most impressive is that UAVs can take advantage of spectrum holes and change their transmission modes based on what happening with the primary user, A2G connection and the level of power of UAVs and GTs. However, to manage the complexity, the authors use a constrained Markov Decision Process (MDP) and proposed low complexity with threshold policies for UAV transmission control.

Furthermore, one of the key features of the paper is the fly-hover-transmit scheme, that basically, UAV moves in time between the GTs, hovering close to perform effective WET and WIT. The whole

idea illustrated in Figure 63 where, UAV work with multiple terminals while keeping in line with cognitive radio environment. The results of authors' simulation show that this smart approach can really improve system throughput and sustainability.

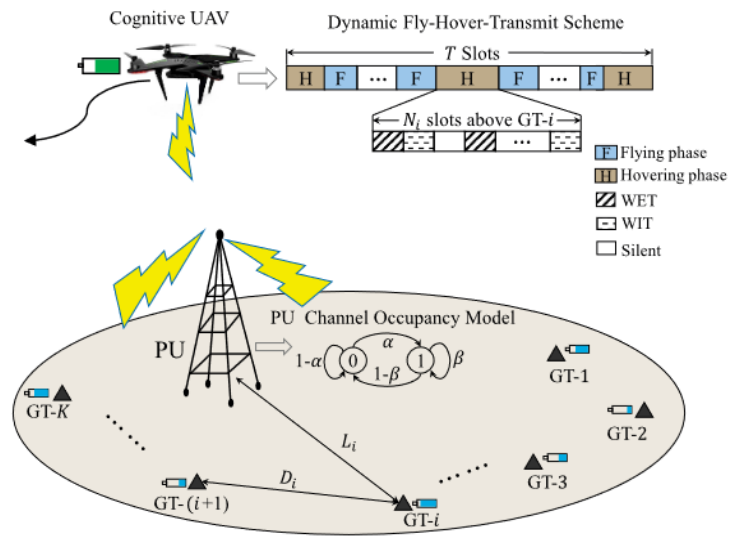


Figure 63 Dynamic UAV-aided WIT and WET [34]

Building upon UAV-assisted frameworks for cognitive and sustainable 5G communications, the work in[38] explores how we can apply similar ideas to agriculture. It shows how UAVs can help with both WET and wireless data collection, that is very important for making large-scale IoT systems more environmentally friendly. Thus, the article discusses complete multi-layer architectures and focuses on specific applications, showing how UAVs can play a crucial role in improving sustainability in precision farming.

The authors proposed a system that combines WPT with data collection, using a UAV fitted with an RF charging module. Thus, a UAV can both recharge sensor nodes spread out across farmland and also collect important environmental data while flying. The authors take this dual job as a dual challenge, a mix of picking Cluster Heads and planning UAV paths and they used a combination of enhanced K-means and Ant-Colony Optimization (ACO) algorithms to ensure the network lasts longer and uses energy more efficiently. The setup of this proposed system shown in Figure 64 and the UAV acting as both a mobile energy source and a data collector for a Wireless Rechargeable Sensor Network (WRSN). The results were very promising showing that the algorithms can really reduce energy use and find the shortest route that UAV needs to travel, boosting the sustainability in monitoring agriculture.

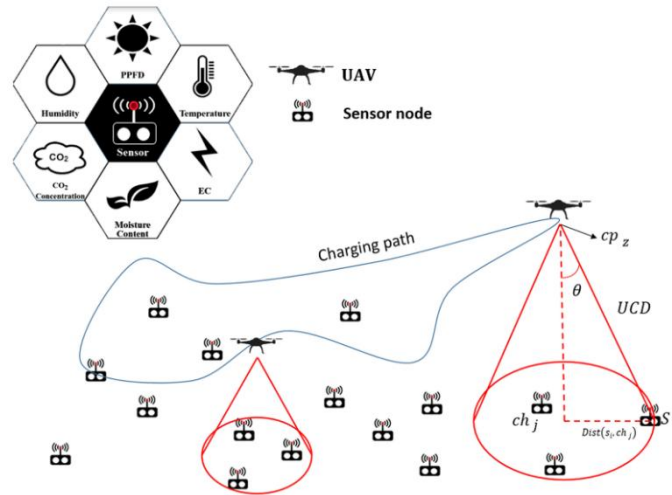


Figure 64 UAV-assisted WRSN Architecture for sustainable Agriculture [38]

Building on what we have discussed with UAV-assisted models that focus on energy and data optimization, authors in [40] make a step further introducing the idea of Robotic Airborne Base Stations (RABS) as a key enabler for energy-efficient 6G communications. Unlike the usual UAV-BSs that just hover around endlessly, RABS can temporarily anchoring onto urban structures, and thus significantly reducing the energy wasted while flying.

Furthermore, the authors proposed the challenge of deploying and managing RABS by design it as an Integer Linear Programming (ILP) optimization problem, aiming to boost the network's energy efficiency, especially since traffic demand can change over time and space. So they create a special algorithm to allocate and operate RABS based on real-time energy budgets and coverage needs. The Figure 65, which illustrates the proposed system model, shows how RABS are placed to balance between low traffic loads and low energy costs. Additionally, the results of the authors' simulations show that the algorithm is much more efficient than the method of UAVs. In conclusion, the study proposes the RABS as a promising evolution of airborne communications in building sustainable 6G networks, which will have the potential for further improvement via DRL approaches.

In summaries the studies in this subsection show how UAV-assisted and robotic airborne systems can improve the sustainability and efficiency of 6G networks. By allowing dynamic coverage, energy harvesting and intelligent operation, these platforms transform the 6G communication infrastructures into something greener and more resilient.

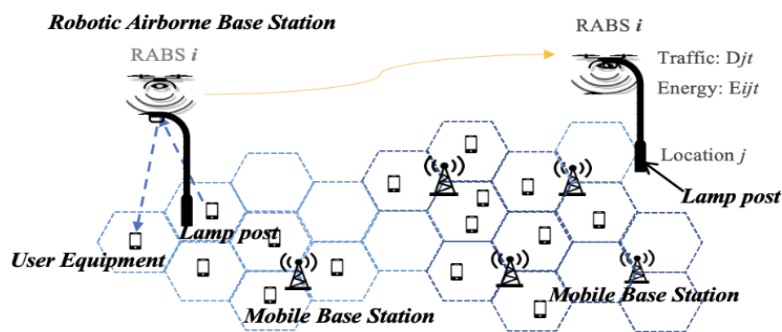


Figure 65 System model of RABS [40]

### 5.6.3 Integrated NTN–TN Architectures for Sustainable 6G

As we move forward with 6G, the thought of a global communication ecosystem comes closer, and a mix of TN-NTN is the key enabler that will lead to a sustainable, resilient and smooth connectivity. These architectures will bring together ground-based, aerial and satellite network to improve coverage, reduce energy use and minimize environmental footprint.

After the exploration of UAV-based solutions, the work in[36] expands the discussion in how we can combine both land and space infrastructures within sustainable 6G maritime networks. It suggests an AI-driven setup that combines satellites, HAPS and ground-based systems to ensure broadband coverage for vessels, harbors and offshore operations. The idea of 6G Maritime Networks (6G-MN) uses AI and ML to improve things like topology management, energy efficiency and real-time scheduling, which are very important in a dynamic maritime environment.

A key part of the paper is the integrated of 6G-MN framework that shows how TN and NTN can work together thanks to AI coordination. This research highlights how DL techniques, like DNNs and LSTMs can help improve energy efficiency and reduce the latency. It is another paper that shows the importance of AI in building sustainability, especially in communication systems, like that.

A coexistence of TN and NTN is proposed in[35] that takes a comprehensive Europe perspective on combined TN and NTN architectures, and it introduces a multi-layer system that unite satellites, HAPS and terrestrial infrastructures and bring social ,economic and environmental sustainability.

Figure 66 shows the three-dimensional multi –layer network, showing the interaction between ground, air and space between terrestrial, airborne and space segments coordinated through intelligent networking and edge computing. This setup captures the core of what integrated NTN-TN systems, aiming for global coverage, energy efficiency and maintaining site security in the long term. Combining technical innovation with political foresight, the study places Europe’s 6G strategy as a model for sustainability, integrated communications infrastructures.

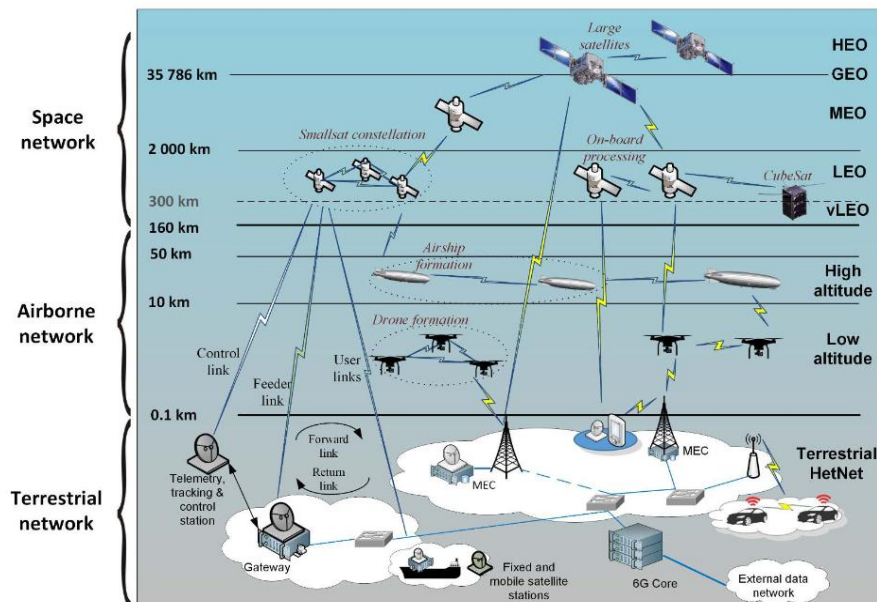


Figure 66 Multi-layer network architecture for 6G [35]

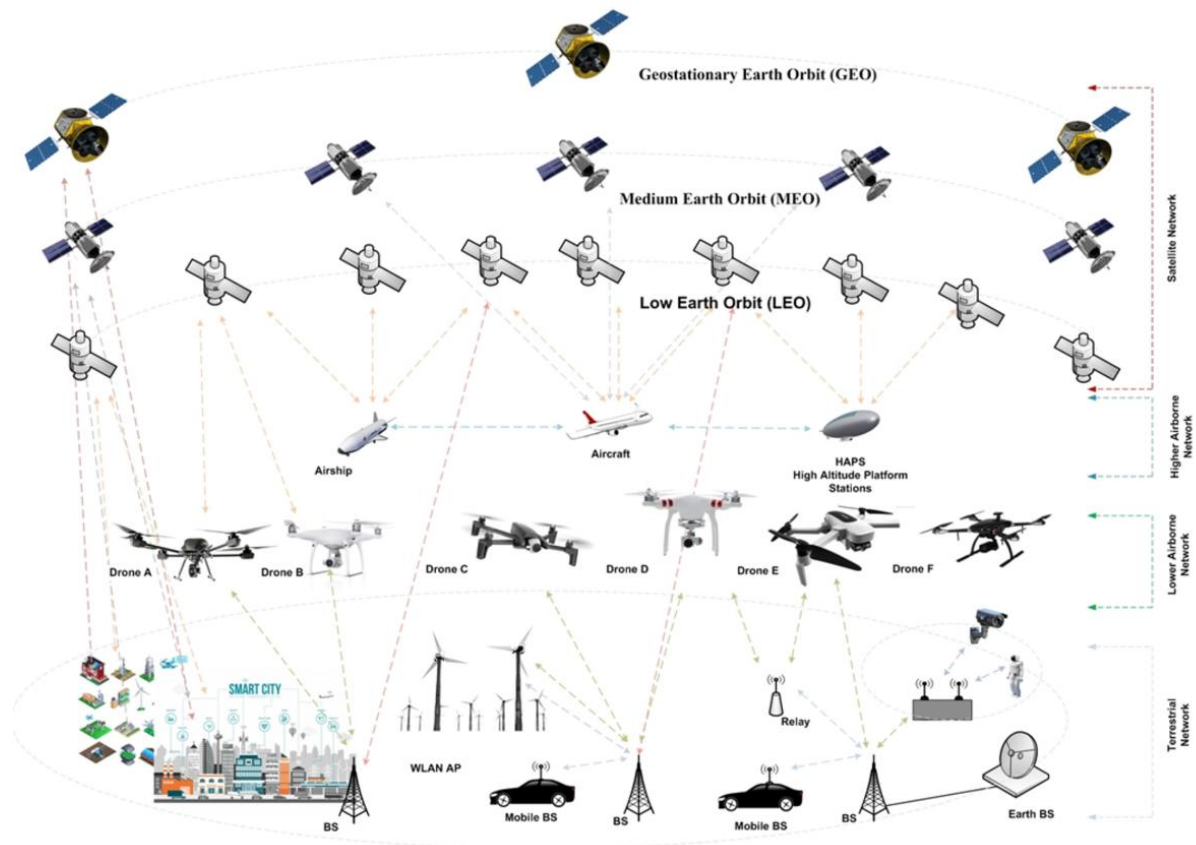


Figure 67 Large-dimensional integrated 5G-6G-IoT-LEO network architecture [123]

Additionally, authors in [123] explore how we can combine satellite and ground-based infrastructures, emphasizing the role of LEO constellations for improving and expanding sustainable 6G network coverage worldwide. More specific, the work provides a comprehensive survey of how LEO satellite networks work together with 5G, 6G and IoT infrastructures. The mix of TN and NTN can create genuine global connectivity, solving the coverage challenge and ensuring sustainable communication for all IoT devices. The authors also analyze the architectural frameworks and integration models that 3GPP Releases 16 and 17 proposed.

However, the study highlights some obstacles that we have to overcome, like managing dynamic spectrum allocation, dealing with Doppler shifts and intelligent handover mechanisms. 67 shows this proposed multi-dimensional integrated systems and explains how the terrestrial, airborne and satellite parks work together under a smart management layer that powered by AI, SDN, NFV technologies. In conclusion, this study provides some key trends, like Internet of Space (IoS), hybrid architectures, laser links between satellites and others that make LEO integration a crucial part of sustainability in 6G networks.

Another work that belongs to this subsection is the one in [124] that explores how we can mix together 5G and 6G networks, LEO satellites and IoT systems, to create a more sustainable global connectivity that aligns with the UN's SDGs. The author introduces the idea of combining ground, aerial and space infrastructures to build an intelligent and energy-efficient 6G ecosystem.

Furthermore, the study highlights some current initiatives of Excellence Center of Space Technology and Research (ECSTAR), like portable satellite terminals and LEO constellations that have the ability to provide broadband and remote sensing. Moreover, they have methane-monitoring satellites for

environmental protection. In conclusion, the author believes that these integrated NTN-TN architectures can drive the transition from IoT to the Internet of Intelligence (IoI), a smarter and greener way of communication.

Building on earlier research of LEO-integrated NTN-N frameworks, authors in[39] introduce a multi-tier cell-switching framework which aims to improve both sustainability and efficiency in 6G networks. More specifically, this framework brings together terrestrial networks ( macro/small BS) with UAV-based aerial platforms, HAPS and satellite networks (GEO, MEO, LEO). This is the first time that satellites are used in cell-switching mechanisms to help manage traffic that is not sensitive to delay, while UAVs and HAPS manage dynamic coverage and energy-efficient connectivity. The framework introduces two main strategies, an energy-focused approach to minimize energy consumption and another that focuses on URLLC needs.

Figure 68, which is an illustration of this four-tier structure, shows how traffic flows between these tiers based on factors like latency, coverage and energy limitations. The authors take it another step further by discussing about the Generative AI (GenAI) and how the use of GenAI will affect the future networks. There is no objection that it will take this to the next level by compressing data, predicting user movements and enabling smart handovers between network layers, but it will also bring new challenges. The results of authors’ simulations show that multi-tier framework can significantly reduce power use while it keeps still the QoS.

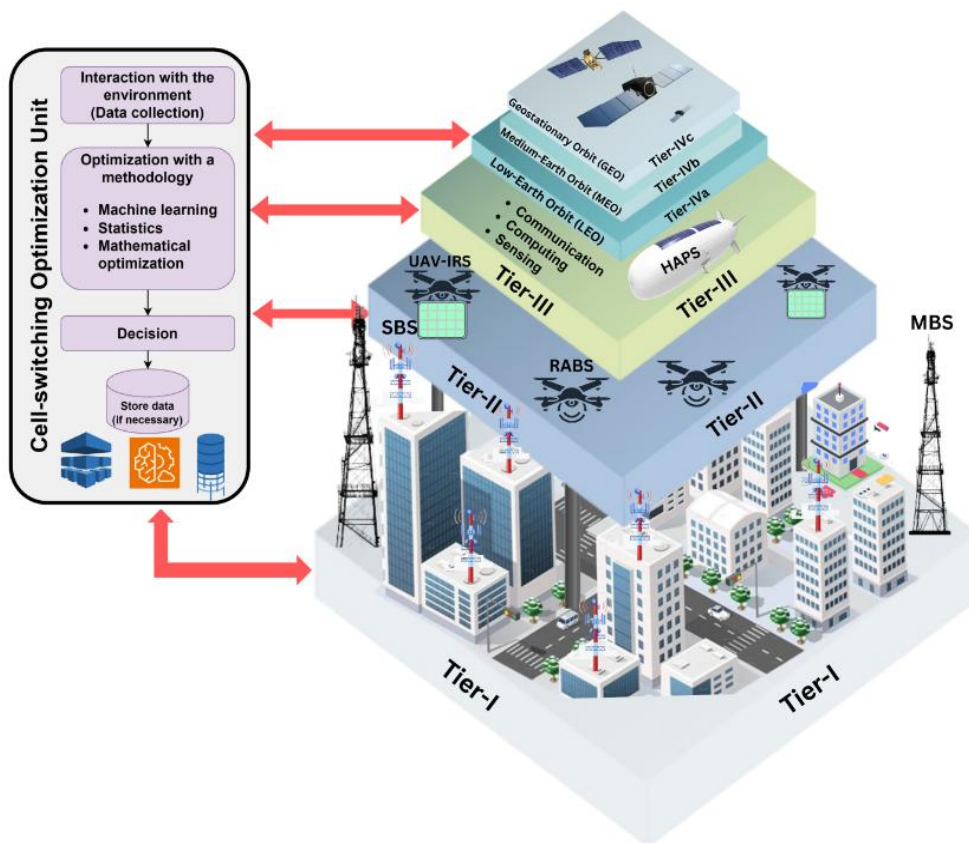


Figure 68 The multi-tier cell-switching approach. Tier-I is TN, Tier-II is UAV-based aerial network, Tier-III includes HAPS and Tier-IV is the satellite network [39]

To conclude, the studies in this subsection show that TN-NTN architectures can make 6G operations more sustainable, using advanced technologies, like AI and LEO constellations and some advanced frameworks like the multi-tier cell-switching framework that we study. This mix of technologies will create communication infrastructures that will not be only eco-friendly but also adaptable and globally connected. Table XI presents a detailed list of the papers that have been categorized, including the most important issues that they address.

Table XI List of Papers in Green Communication Technologies for Smart Cities category and coverage issues

Article	Energy-efficient Hardware & Power Transfer Technologies			Focus and Coverage (Key Findings)	Type of Study	Year
	Satellite & HAPS	UAV-Assisted and Airborne Networks	Integrated NTN-TN Architectures for Sustainable 6G			
[37]	X			The role of HAPS and how they can work alongside traditional radio access networks, to cut down on energy use and boost sustainability in 6G systems. It also use a case study on Milan's RAN and shows that by shifting some of the traffic to solar airborne BS, ground nodes can actually be put into a sleep mode. This shift can lead to a stunning reduction in grid demand, especially when you combine it with local renewable energy sources	Experimental / Simulation Study	2022
[41]	X			A NTN framework focusing on A2G and aircraft-to-satellite communication. The authors used the GX Inmarsat satellite system to create a mathematical model that helps with channel propagation, improve reliability, reduce delays, make energy use more efficient	Experimental / Simulation Study	2025
[122]	X			A GEO satellite communication framework that uses RIS to make things more efficient in terms of both spectral and energy use in 6G networks. The authors explore how both the satellite's transmit power and phase shift of the RIS can optimize the system's channel capacity, with the use of the MADS algorithm. The combination of RIS and satellite communication is the key enabler for a more sustainable non-terrestrial communication	Experimental / Simulation Study	2022
[34]		X		A UAV-assisted framework that enables simultaneous wireless information and energy transmission in 5G networks. A MDP model is configured to optimize UAV mobility, transmission mode and power allocation. The results of the simulations shows that the proposed dynamic transmission scheme significantly improves energy efficiency and performance compared to static or myopic benchmarks	Experimental / Simulation Study	2021
[38]		X		A UAV-assisted WRSN framework for sustainable precision agriculture in 5G environments. The main idea of this is that the UAV will be used not only to charge sensor nodes via RF energy transfer while simultaneously collecting data, addressing the limited battery capacity of field-deployed IoT sensors. Furthermore, the authors develop two optimization algorithms the KCHCPS and ACO-based path planning to improve charging efficiency and extend sensor network lifetime. The results confirm reducing in energy consumption	Experimental / Simulation Study	2022
[40]		X		How RABS can really boost energy efficiency and flexibility in the upcoming 6G wireless networks. The authors create an ILP model and proposed an energy aware deployment algorithm that dynamically adjusts RABS locations based on real-time traffic demands. Finally, the study also compares RABS with UAV-based BSs showing that RABS can reduce energy use	Experimental / Simulation Study	2024
[36]			X	An AI-driven framework for 6G maritime networking which combines terrestrial with non-terrestrial systems to create a maritime network that is not only efficient but also sustainable and resilient. The authors also using DNN and LSTM models, show how AI can help reduce power use and minimize delays in this 6G maritime setups	Experimental / Simulation Study	2022

Mapping Enabling Technologies towards Sustainable 5G/6G Communications

Article	Energy-efficient Hardware & Power Transfer Technologies			Focus and Coverage (Key Findings)	Type of Study	Year
	Satellite & HAPS	UAV-Assisted and Airborne Networks	Integrated NTN-TN Architectures for Sustainable 6G			
[35]			X	A comprehensive survey of sustainable 6G communication systems, focusing on multi-layer architectures, space safety and regulatory scene in Europe. It also highlights the combination of terrestrial, airborne and satellite layers to build efficient 3D networks while addressing space debris, frequency management, cybersecurity and environmental impacts. Finally, the study also highlights some European initiatives, like the big plan for a flagship satellite constellation aiming the improvement in connectivity	Survey / Review Paper	2022
[123]			X	A comprehensive review of how LEO satellite systems can combination with 5G, 6G and IoT networks. It also highlights their importance for creating global connectivity. The authors, firstly outlines the evolution of LMS systems and details the possibilities of LEO mega-constellations for universal broadband access. Furthermore, it reviews integration architectures, 3GPP standardization efforts and the main technical challenges. Finally, it also discusses future trends including AI-driven resource management	Survey / Review Paper	2024
[124]			X	A comprehensive analytical review of the combination with 5G/6G networks, LEO satellites and IoT systems in support environmental protection and sustainable development. It also highlights that this combination is crucial for the UN SDGs by improving resource management, enabling real-time monitoring and improving global connectivity	Survey / Review Paper	2023
[39]			X	A multi-tier cell-switching strategy that combines TN and NTN to improve energy efficiency, coverage and latency performance in sustainable 6G systems. It proposed two main approached, the one focuses on energy saving and the other on minimizing delays. This helps users to dynamically offloaded across different tiers which helps in power consumption without sacrificing QoS. Finally, it dives into the GenAI to make data compression and device handovers. The results of the simulations show that reduces the power use highlighting the framework s a potential for greener and adaptive 6G networks	Experimental / Simulation Study	2025

## Chapter 6: Dual Perspectives on 6G and Sustainability – “Sustainable 6G” vs “6G for Sustainability”

### 6.1 Introduction

As we dive into the 6G literature, we understand that sustainability is increasingly discussed through two different but related angles. The first which called “Sustainable 6G” is about ensuring that the communication infrastructure are environmentally responsible by reducing energy and carbon footprints throughout its entire lifecycle. The second is “6G for Sustainability” and emphasizes on how the advancements of 6G can actually help other fields become more sustainable, like cities, healthcare, agriculture and various industries. The idea is that 6G can support smarter monitoring, automation and data-driven decision making which can really help in the overall sustainability [4], [1]. Thus, we are exploring not just about making 6G itself sustainable but also how it can help other areas become greener too.

These two perspectives are not contradictory, but they actually go hand in hand in two different ways of thinking: one aspect looks at how sustainable the network is as a designed system and the other focuses on what kind of sustainability benefits the network can offer as a flexible digital infrastructure. It is very important to understand both views because a network that supports all sorts of sustainable applications but it consumes a big amount of energy, it may not be a beneficial network. Additionally, an energy-efficient network that it does not support services that are critical for sustainability, is not fully contribute to broader societal goals [57], [2].

### 6.2 Sustainable 6G

In the perspective of “Sustainable 6G”, we focus on how 6G networks impact the environment. A key takeaway from various studies that explore this angle, like the one in[1], is that we need to treat sustainability as a by-design requirement, not a secondary add-on. This involves energy efficient, operating with an awareness of carbon emissions and adopting engineering practices that consider the entire lifecycle, like ways that not only reduce the operational electricity bill but generally reduce the environmental impact [57].

#### 6.2.1 Reducing Operational Energy Consumption and Carbon Footprint

One of the big focus areas in 6G is operational sustainability. Future networks are expected to support denser deployments, much more devices and more computation. Due to this fact, several studies highlight the importance of energy-aware orchestration, intelligent automation and advanced RAN designs which are very crucial for cutting down waste and making sure that we are using resources according to actual demand [58]. Under these circumstances, AI/ML are usually seen as game-changers for making operations more sustainable. AI/ML models can help with adaptive control, predictive resource allocation and automation. However, researches also highlights that AI can add its own overhead and therefore it is necessary to adopt the “green AI” approach so as to ensure net sustainability gains. By the term “green AI”, we refer to efficient model design, efficient deployment and careful placement of intelligence [10].

Furthermore, another area of 6G with big interesting is the Open and disaggregated RAN paradigms and is fully connected with the sustainability. Studies with central topic the Open RAN in 6G, highlight opportunities, like better multi-vendor optimization and flexible control, but also emphasize

that it is necessary to designed carefully avoiding extra complexity and inefficiency [125]. In addition, researches that evaluate energy consumption in 6G O-RAN, show that scientists are still studying how to combine O-RAN with the less energy consumption so as to keep networks eco-friendly and sustainable [112].

### **6.2.2 Renewable Energy Use and Low-Carbon powering Strategies**

As we have already mention, sustainable 6G is not just about making networks run faster and more efficiently but it is also about rethinking how we power them. Recent studies have pointed out that we need to bring RE and manage low-carbon resources in our networks so as to hit the goals of sustainable 6G [57]. Thus, we will find the balance that we need between more efficient networks and less environmental impact.

Moreover, many studies connect renewable-powered 6G with energy storage and hybrid power solutions, especially when in areas where there are a lot of users or in places that do not have reliable grid access [56]. In this view, sustainability improves when network have the ability to adjust its operation based on the availability of low-carbon energy.

### **6.2.3 Lifecycle Sustainability, Recyclable Materials and E-waste Reduction**

As we have already mentioned before, one of the biggest differences between 5G-era sustainability discussions and the 6G vision is the much deeper focus on lifecycle impacts. It is not only about how we use the technology but it is also about everything that happens from the start to the end, including the development, manufacturing, deployment, operation and upgrades. Thus, sustainable 6G is fully connected with this lifecycle-aware perspective and a more holistic view about understanding the true impact of 6G [57].

Diving into this topic, e-waste and circular-economy become crucial parts of sustainability. Many studies highlight the importance of recyclable materials, strategies for reusing and repairing, modular designs and planning about what happens at the end of a product’s life. All these matters are very important to be designed by the start of this generation so as to make sure that sustainability is not compromised by continuous upgrades and the fast turnover of hardware [2].

## **6.3 6G for Sustainability**

The second perspective of “6G for Sustainability” focuses on how the capabilities of 6G can bring about some pretty significant sustainability benefits for society as whole. In this angle, we are thinking 6G as a powerful platform that helps with advanced sensing, control, automation and making data-driven choices for critical sectors in sustainability. This perspective is often connected to larger goals, like the UN SDGs. There are some detailed studies like these in[4] and[5], that explore the connection between 6G and these goals, and really highlight how leveraging 6G services can help in achieving those sustainability targets in various sectors. Figure 69 shows the UN SDGs and other sustainability approaches [4].



Figure 69 UN SDGs and other sustainability approaches [4]

### 6.3.1 Smart Cities and Sustainable Urban Services

Exploring smart cities, we easily understand that they mainly rely on ubiquitous connectivity, widespread IoT setups and the ability to analyze data in real time. In the 6G sustainability context, smart city frameworks are really focusing on combining connectivity with sensing, intelligence and new service layers that can help cities operate more efficiently, build resilience and keep monitoring the environment [25]. In this fact, there are use cases like better traffic management, environmental sensing, resource monitoring and sustainability-aware public services. In this setup, the network is an backbone infrastructure that helps cities make coordinated decisions for a more sustainable urban future.

### 6.3.2 Smart Mobility and Transportation Sustainability

Another frequently discussed domain where 6G really can be a big game changer is the transportation sustainability. There are many researches that dig into how 6G can support sustainable mobility. They emphasize how advanced connectivity and smart technologies can enhance ITS, collaborative perception and real-time traffic optimization [21]. In these kinds of setups, the positive impacts on sustainability comes not only from radio-level energy efficiency, but also from improved coordination, better situation awareness and more efficient system-level control.

### 6.3.3 Smart Health and Sustainable Healthcare

One of the big winners of 6G capabilities is healthcare. Many studies focusing on 6G and health highlight how 6G could transform health services through ultra-reliable low-latency communication, which means faster and more dependable connections. Furthermore, pervasive sensing and AI-enabled monitoring give us the ability to keep track of health data in real time. Remote healthcare services are giving us also a big step in enhancing service availability and better health management without

unnecessary travel [103]. At the same time, studies give big emphasize in challenges like privacy, security, interoperability and infrastructure readiness that are essential for responsible deployment which connect this domain to broader governance and trust requirements.

### 6.3.4 Smart Agriculture and Sustainable Food Systems

Another widely discussed topic in 6G which is connected to sustainability and the food-system efficiency is agriculture. Using technologies like IoT, sensing, automation and data-driven optimization we try to make things better. Studies like this in[5] and others which focused on the SDGs, highlight that farming services are actually key areas where 6G can really make a difference, helping with large-scale monitoring and control and ultimately leads to using resources more efficiently. The actual technical details might differ from one study to another but the main takeaway remains the same, that 6G has the potential to deliver the necessary communication and computing backbone. This means that we can achieve reliable sensing, make decisions and even automate processes in environments where resources are low.

### 6.3.5 Industry 4.0 and Sustainable Industrial Automation

Industry 4.0 and IIoT environments are also central to the “6G for Sustainability” conversation. By mixing connectivity with distributed intelligence and automation, we can see some pretty big improvements in efficiency, predictive maintenance and better coordination across industrial systems. Furthermore, one thing that keeps coming up in this domain is FL. It is often highlighted as a mechanism that can support learning from distributed industrial data while addressing privacy constraints and potentially reducing the need for centralized data transfer, which is relevant for both operational efficiency and sustainability. Figure70 illustrates the three key benefits-characteristics of FL-based IIoT applications [10].

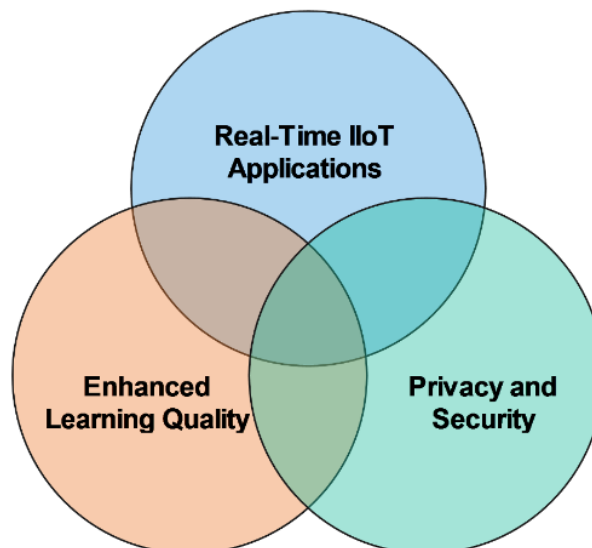


Figure 70 The Key Benefits-Characteristics of FL-based IIoT applications [10]

## 6.4 Comparison between “Sustainable 6G” and “6G for Sustainability”

### 6.4.1 Possible similarities

Even though Sustainable 6G and 6G for Sustainability focus on different outcomes, they actually have several things in common. Firstly, both these two perspectives are tied to the UN SDGs, either by showcasing the network as a responsible piece of infrastructure or by pointing out the sustainability benefits it can bring across various sectors [4]. Secondly, both perspectives need teamwork across different fields. Since sustainability depends on everything from energy systems to government policy, 6G development must combine technical, regulatory and business expertise. This need for collaboration is crucial in current 6G research [2].

Thirdly, both two viewpoints depend on clear targets and ways to evaluate them. Sustainable 6G requires metrics about energy, carbon emission and lifecycle and on the flip side, 6G for sustainability requires sector-level KPIs that actually reflect how things are evolving in the real world. Thus, it is very difficult to figure out the actual impact and to compare different solutions across deployments if we do not have standard measurement framework [2], [57].

### 6.4.2 Technologies Employed in each Case

Furthermore, the two perspectives highlight different technologies they focus on and the ways they make an impact. On the one hand, for sustainable 6G, the focus is on technologies and methods that minimize the network’s environment impact. For instance, we have energy-aware orchestration and green AI/ML strategies. Moreover, it is common to have the integration of RE and carbon-aware operations and energy-efficient RAN architectures which are pretty important for reducing e-waste and increasing recyclability [11]. Additionally, we do not have to forget the Open-RAN that can be a potential game changer for flexible complexities. However, it needs some thoughtful design which takes sustainability into account, because it is a continuous balance between trying for innovation and eco-friendly approach [112], [125].

On the other hand, in 6G for sustainability, the focus turns into technologies that dive specific sustainability goals. For example, this includes 6G-Iot frameworks for sustainable smart city services and mobility scenarios supported by advanced communication and intelligence. Furthermore, it includes sector-specific architectures and service models that align sustainability objectives with what networks can actually do [25], [21]. In areas like industry and healthcare, distributed intelligence methods like FL are being spotlighted as a key technology that can help maintain sustainable operations while keeping privacy and data governance in check [10], [103].

In conclusion, sustainable 6G concentrates on cutting down the environmental impact that comes with our communication infrastructure, while 6G for sustainability highlights the bigger picture, the overall value for sustainability that comes from services powered by 6G. Both perspectives are necessary and important for a balanced understanding of 6G sustainability, because the real benefit depends on two things: how much energy the network uses and how much it helps other industries save energy too.



## Chapter 7: Conclusions

This thesis examined how sustainability is shaping the transition from 5G to 6G, by conducting a thorough literature review, using the PRISMA approach. The synthesis of findings was driven by three key research questions that introduced in Chapter 3, focusing on (i) the current state of sustainability-focused research in 6G, (ii) the primary methods that promote sustainable development in wireless communication and (iii) how the goals, strategies and challenges around sustainability differ between 5G and 6G. Based on the comparative analysis (Chapter 4), the mapping of general application technology (Chapter 5) and the dual perspective discussion about “Sustainable 6G” and “6G for Sustainability” (Chapter 6), the following conclusions provide a clear answer to these questions and consolidate the overall contribution of the study.

Diving into the first research question, the reviewed literature shows clearly that sustainability in 6G is starting to take center stage as a core design principle. In comparison with previous generations, sustainability is no longer discussed only in terms of operational energy efficiency, but it includes carbon footprint reduction, lifecycle impacts, thinking about circular economy principles and finding ways to deal with electronic waste. This shift reflects the fact that future networks will be evaluated on more than just the usual performance metrics. They will also be judged on how responsibly they are designed, deployed and maintained over time. But at the same time the latest research highlights a bit of a contradiction in the current 6G sustainability landscape. On one hand, 6G promises highly advanced capabilities, like AI-driven networking and new spectrum bands, but on the flip side, these advancements could increase computational complexity and energy demand if we do not integrate sustainability “by design”. For this reason, a lot of studies emphasize that it is very important to have clear evaluation methods, standardized indicators for sustainability and consistent reporting practices that allow comparability beyond isolated case studies and theoretical ideas.

Addressing the second research question, the review shows that sustainable wireless development is not just about one single technology, but is actually a layered combination of different strategies that operate together across the entire network stack and throughout the technology lifecycle. A dominant direction of this is the rise of AI and ML and the use of them for optimization and automation, enabling adaptive resource allocation, predicting traffic, spotting anomalies and orchestrating processes in a closed loop way that can improve energy efficiency and resources utilization.

However, while AI is important for all the above, it also has an environmental footprint, leading to increasing interest in sustainability-aware or so-called “greenAI”, as well as lightweight and edge-friendly learning mechanisms that reduce training and inference overhead. At the same time, virtualization-driven architectures and sustainable network management practices are emerging as key players, because they allow flexible resource pooling, dynamic scaling and overall better use of infrastructure. Concepts like network slicing, cloud-native operations and programmable control are emerging as ways to avoid over provisioning and focus on energy or carbon-aware orchestration, particularly when combined with monitoring, analytics and interoperability-oriented architectural choices.

A further set of findings that supports the second research question shows how edge-assisted systems play a huge role in foresting application-aware sustainability. Mobile/Multi-access Edge Computing is often highlighted as a game-changer that can reduce backhaul load, lower E2E latency and allow for localized processing especially for data-heavy services. This becomes especially visible in domains

like smart mobility and V2X, where reliability and real-time decision making are essential. In those scenarios, edge intelligence does not only boost technical performance, but also enables smarter coordination and reduces unnecessary transmissions, creating opportunities for more efficient system-level operation, like improving traffic flow and safety services that indirectly reduce waste and congestion. However, just focusing on higher-layer strategies is not enough. The literature highlights that sustainability depends equally on the physical and infrastructure layer, including energy-efficient hardware design, improved radio and basement efficiency and optimized power and cooling systems. These infrastructure-oriented strategies are the key to complementing network-level orchestration, especially in densely packed areas where energy consumption can become a limiting factor.

In addition, the latest mapping results show that sustainable development is increasingly incorporate hybrid connectivity setups that include non-terrestrial elements, like satellites, UAVs and HAPS. These technologies can provide widespread coverage and boost resilience but they also introduce some sustainability trade-offs related to energy requirements, operational complexity and lifecycle footprint. Therefore, a lot of experts are suggesting energy-aware integration and optimization strategies that combine land-based and non-terrestrial parts together, trying to find the balance. Finally, beyond technical enablers, the literature repeatedly argues for sustainability frameworks that connect engineering decisions with lifecycle assessment methods, principles of circularity and clear indicators for measuring sustainability. Without some agreed-upon definitions and evaluation standards, we risk letting sustainability remain just a nice idea, something that we aspire to but we fail to put into practice.

Diving into the third research question, the comparative review clarifies how the sustainability agenda transforms as we move from 5G to 6G, especially when it comes to goals, strategies and challenges. Thus, in many 5G-oriented works, sustainability mainly pop ups through enhanced energy efficiency and through the enabling role of connectivity in helping sustainability results in other sectors. However, sustainability in 6G is totally different. Sustainability is not just an afterthought but it is a core objective of the system. This shift captured in two main themes that keep coming up in the literature as “Sustainable 6G” which is all about making the network greener and “6G for Sustainability”, highlighting how 6G can drive sustainability changes in fields like mobility, industry, smart cities, health and agriculture.

In comparison with 5G that laid down some solid groundwork with concepts like virtualization, slicing and MEC, 6G really steps things up. It is focusing on AI-driven control loops, spreading edge intelligence more widely and embracing a mix of different architectures including deeper integration of NTN.

At the same time, the third research question highlights that 6G also introduces challenges that are less pronounced in 5G. The pursuit of all those super ambitious performance goals, like ultra-low latency, high reliability, advanced sensing/positioning and new spectrum utilization, can increase total energy consumption due to denser deployments and higher computational intensity. As a result, this brings the key issue for 6G, to find the spot which balances performance and intelligence with the overall energy, carbon and lifecycle footprint of the system. Furthermore, as networks and device ecosystems grow, we cannot overlook lifecycle factors, like what materials we are using, how often devices get replaced, the ease of repairs and the amount of e-waste that accumulates. All of this makes it even more important to think about circular economy strategies and having some standardized ways to evaluate sustainability.

In conclusion, this thesis highlights that sustainability in next-generation communications is evolving from a narrow optimization task into a holistic design, operation and governance challenge. The evidence that we have found shows that there is a solid push towards sustainability by design in 6G, while also indicating that measurable progress depends on consistent metrics, comparable assessment methods and real-world validation.

Looking ahead, future research should prioritize on a few key priorities. Firstly, they need to create common metrics to track environmental impact throughout a network's lifecycle. Secondly, they must develop energy-efficient AI/ML models that keep simultaneously computational load light. Thirdly, it is crucial to move from theory to real-world testing through large-scale experiments. Additionally, future researches need to evaluate how NTN and ground networks can work together under strict sustainability rules. Finally, equally important, stronger collaboration between academia, industry and standardization bodies will be required so that sustainability targets become measurable, enforceable and comparable across future 6G ecosystems.

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