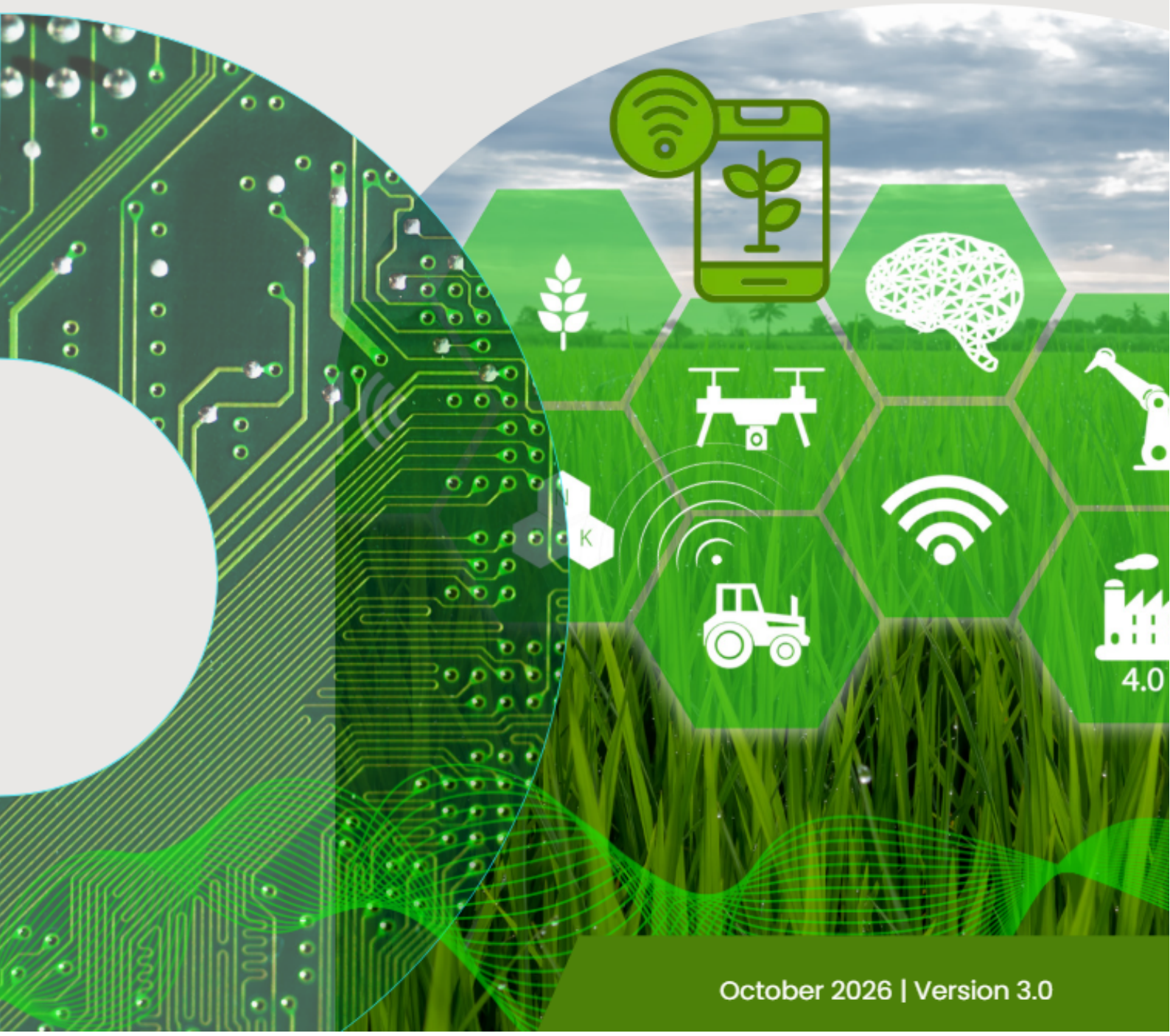
Bharat6G Alliance

Bharat 6G Alliance Whitepaper

SUSTAINABLE 6G:

DESIGNING NETWORKS FOR A CARBON NET ZERO FUTURE



October 2026 | Version 3.0

Bharat6G Alliance

SUSTAINABLE 6G

Designing Networks for a Carbon Net Zero Future

Bharat 6G Alliance
Green and Sustainability Working Group
White Paper · October 2026 · Version 3.0

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Executive Summary

This whitepaper assesses sustainability across a telecom network and technology lifecycle, encompassing infrastructure, computing, artificial intelligence, energy sources, materials and electronic waste, while preserving coverage, affordability, resilience, security and quality of service. The objective is a reduction in absolute lifecycle carbon and material impact, rather than an improvement in bits per joule alone.

The paper proposes the telecom tower, rather than the radio unit alone, as the appropriate unit of analysis. India's approximately 0.86 million towers each draw between 3 and 10 kW through individual low-tension connections, and the principal challenge is grid availability rather than consumption: backup power at tower sites consumes an estimated 100 crore litres of diesel annually. Annual electricity consumption and greenhouse gas emissions per subscription are proposed as the headline indicators, supported by the renewable share, backup diesel consumption, embodied emissions and full-scope emission factors. Artificial intelligence is to be assessed on both its own environmental footprint, and the network-level benefits it enables. These directions are consistent with ongoing 3GPP 6G studies and O-RAN work, which treat energy as an end-to-end design requirement, although the corresponding specifications are yet to be finalised.

The paper further argues that network algorithms are likely to become energy- and carbon-aware. Security mechanisms, including post-quantum cryptography and hybrid PQC-QKD schemes, should be optimised jointly with energy, quality of service and reliability, while carbon intelligence treats grid carbon intensity as a real-time control input across radio, transport, edge, core and cooling. On the supply side, Green Energy Open Access represents the most significant near-term lever. Since 2023, connections within the same electricity division may be aggregated to meet the 100-kW eligibility threshold; coordination efforts are needed to scale adoption.

To address the residual dependence on diesel, sodium-ion batteries offer advantages over lithium iron phosphate in safety, temperature tolerance, cycle life and supply diversification, subject to qualification against Indian duty cycles. Hydrogen fuel cells supplied from cluster hubs offer an alternative to diesel provided significant scale and distribution becomes viable. Finally, circularity is treated as an engineering requirement, to be achieved through modular equipment, digital product passports, second-life cascades and material-recovery obligations.

Intended Audience:

- Bharat 6G Alliance working groups and the Department of Telecommunications.
- ITU, 3GPP, TSDSI, ETSI, GSMA, NGMN, O-RAN Alliance, Next Gen Alliance and 6G Smart Networks and Services Industry Association (6G-IA) contributors.
- Network operators, OEMs, semiconductor and component manufacturers.
- Cloud, software, AI, energy management and utility interface providers.
- Test laboratories, certification bodies, academia, startups and SMEs.
- Policymakers responsible for telecom, manufacturing, energy, climate and circular economy.

1 Introduction

Digitalization is increasing worldwide. There is a rapid change ongoing at the same time as there are needs to lower the environmental impact of the Information and Communications Technology (ICT) sector. With 6G there is an opportunity to focus on and incorporate environmentally beneficial solutions from the beginning. India's 6G vision is anchored in affordability, sustainability and ubiquity, and the Bharat 6G Alliance calls for renewable energy, energy-efficient technologies and circular-economy practices to be embedded into next-generation telecommunications.

Radio transmission is by far the largest consumer of energy, with non-RAN components following. Traditionally, the RAN consumes nearly three quarters of the power of a telecom network. However, both RAN and non-RAN components are set to increase their functionality. For example, massive MIMO systems at higher frequencies will mean shorter ranges and an increase in RAN site density; Reconfigurable Intelligent Surfaces will be spread across the network; further applications and edge computing for new use cases (virtual reality, haptic interfaces) will be added to central and local data centers. Inevitably, their energy consumption will increase. It is thus more meaningful to talk about how efficiently and sustainably this energy can be consumed. Efficiency has been discussed in previous publications [27],[39]. Energy efficiency, typically expressed as bits transmitted per joule consumed, has been the dominant sustainability metric across 4G, 5G, and early 6G research [1]. A few examples are in Table 1.

Table 1: Sample energy efficiency KPIs

KPI	Description	Applicability
Energy Efficiency (bits/J)	Ratio of total data traffic delivered to total network energy consumed. Indicates how efficiently electrical energy is converted into carried traffic.	RAN/network design and optimization benchmarking.
Energy per Petabyte (kWh/PB)	Electrical energy required to deliver one petabyte of data. Captures traffic-normalized energy intensity at site or network-segment level.	Operational/site benchmarking and trend monitoring.
Energy per Connection Type	Energy attributable to a connection/service category, such as IoT/MTC, eMBB or URLLC, normalized by the number of active connections or service instances.	Service-level energy attribution and optimization.

However, Sustainability cannot be reduced to radio energy efficiency alone. In the recent past, the outlook for Sustainability in 6G has expanded: it should be assessed across the network and technology lifecycle, including infrastructure, computing, AI, energy use, and associated environmental impacts. AI-native 6G introduces an additional dimension. This paper is also aligned with the relevant ministerial guideline on AI-native network sustainability. Accordingly, it addresses the associated network-level KPIs, as well as circularity across the equipment and energy lifecycles, so that sustainability in AI-native 6G networks can be measured, governed and reported in a consistent and auditable manner. The following design principles are foreseen for sustainability in 6G:

- Sustainability by Design
- Carbon-aware operation by default
- Multi-objective optimization
- Lifecycle-aware decision making

- Circularity-aware infrastructure planning
- Sustainability assurance and auditing.

Sustainability measurements need to use clearly defined lifecycle and assessment boundaries. The ICT sector can be seen as comprising of three main parts; the networks covering mobile and fixed networks as well as access, core and transport networks; data centers from large hyperscalers, to co-location and small local data centers; and finally, the connected devices, being user devices from phones, computers and monitors to all Internet of Things (IoT).

The current publication focuses on sustainability and is arranged as given in Table 2. The background of green and sustainability aspects of Telecom networks is given in Section 2. This section also proposes that the telecom-tower, rather than only its radio units, can be considered as the basic unit of analysis; this model is suited to the idiosyncrasies of Indian telecom networks. Measurement of sustainability and circularity, and of energy efficiency discussed in previous reports, is the bedrock of going green. The current outlook of KPIs and their practical applications are described in Section 3. The global standardization landscape for the same KPIs is discussed in Section 4; this section also shows an architecture of 6G systems, which recognizes energy- and sustainability-aware operations in a closed loop. Sections 5 and 6 peek into the future of how 6G implementations might evolve. Algorithms, and hence, predominantly software solutions are discussed in Section 5. Section 6 explains not only calls for urgent implementation of Green Energy Open Access in India, but also envisages fundamental, potentially disruptive Battery technologies and Hydrogen fuel cells, thereby illuminating a path towards a Net Zero future.

Table 2: Quick guide to sections in this paper

Section	Section heading	Brief Description
2	Background	Information and Communications Technology and Tower as the basic unit of a RAN
3	Measuring Overall Sustainability Performance	Describes the KPIs used to measure energy efficiency, sustainability and circularity.
4	Global Sustainability Standards and Policy Landscape	Summarizes global standards related to sustainability. 3GPP and O-RAN standards are expanded.
5	Energy- and Carbon-aware algorithms for 6G	Revisits security, QoS, and reliability optimization algorithms, including quantum-safe mechanisms, and proposes energy-aware alternatives.
6	Net Zero future: Transition to Green Energy	Open Access recommendations for telecom networks, future greener energy sources such as Sodium Ion Batteries and Hydrogen Fuel Cells.

2 Background

2.1 Information and Communications Technology

The global ICT sector's energy use increases (Figure 1) due to build out of communication infrastructure and increased use [1]. However, the total life cycle greenhouse gas (GHG) emissions of the ICT sector has started to decrease due to an increased use of electricity from renewable energy sources or other non-fossil sources [1].

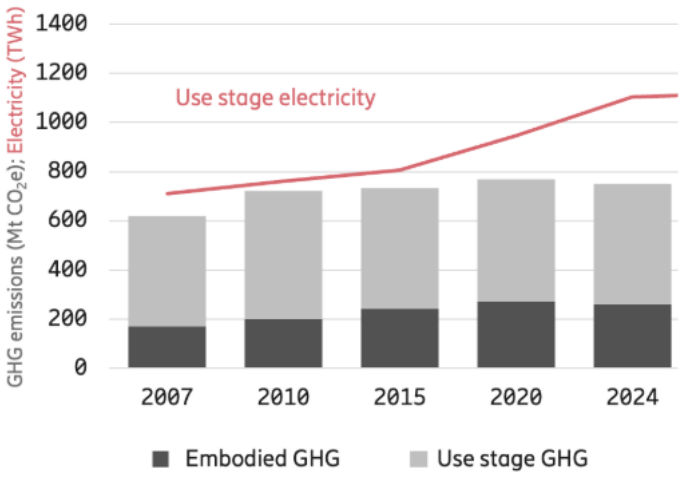

Figure 1: Global ICT sector use stage electricity (TWh) and total life cycle GHG emissions (million metric ton CO2e, Mt) [1]

The life cycle stages of raw material acquisition and production are combined into upstream embodied emissions, while the end-of-life treatment is downstream compared to the use stage leading to operational emissions, see Figure 2. Different KPIs are needed to capture these different parts, where the primary focus is reasonable to be the use stage emissions, as being the primary source of GHG emissions for networks and data centers.

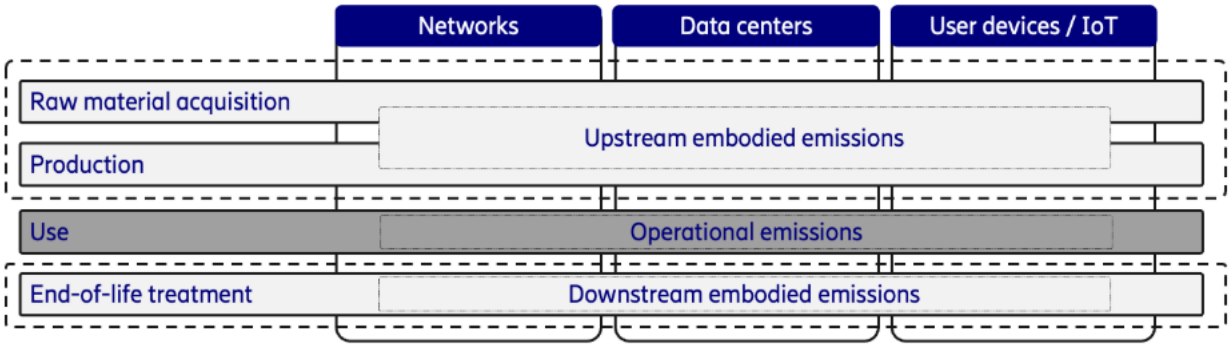

Figure 2: Overview of the life cycle stages and parts of the ecosystem

Focusing on 2024, the global networks used about 330 TWh and the mobile networks represented 205 TWh, while data centers used 315 TWh. For the global ICT sectors GHG emissions, the key contributors apart from user devices and IoT, were related to networks use stage. Mobile networks were responsible for about 60% of the GHG emissions related to networks, see Figure 3.

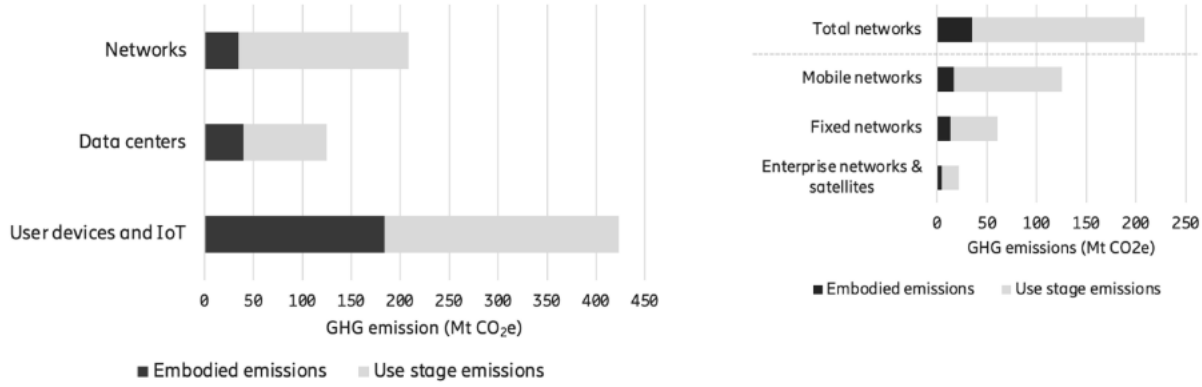

Figure 3: GHG emissions of the global ICT sector in 2024 (left) and in detail for networks (right) [1]

Operational electricity use is the main part of the GHG emissions for networks, over 80%, while the embodied GHG emissions relating to raw material acquisition, production and end of life treatment account for the rest. For data centers, about 30% of the GHG emissions relate to embodied emissions, while it was just above 40% for the user device segment [1]. The embodied GHG emissions largely relate to electricity use in production.

To reduce global warming potential impact the focus points are:

- reducing energy consumption in all parts of the life cycle
- increase the share on non-fossil based sources for electricity
- reduce the amount of material used, leading to less energy needed in production and for transportation
- a switch to low GHG emitting materials, including recycled materials

The impact from the end-of-life treatment stage is very small share of the total lifetime GHG emissions, but more important from a material resource point of view [2].

Focusing on reducing the embodied GHG emissions, a focus on prolonged lifetime, being able to repair and exchange parts of the product before recycling and recovering, hence keeping the product in the closest circle for as long as possible.

2.2 Energy architecture for Indian telecom towers

The telecom tower estate is the single largest distributed critical-power problem in Indian infrastructure, and it is about to get larger: 6G, aligned to the ITU IMT-2030 framework and to the Bharat 6G Vision, implies denser deployment at higher frequencies and AI-native edge compute at the base station [41].

The energy challenge at a tower is not average consumption; it is availability and carbon intensity. Grid electricity drives Scope 2 emissions at an all-India weighted average emission factor of 0.675 t CO_2 per MWh for FY 2025-26 [88]. Diesel backup drives Scope 1 emissions, local air pollution, noise, pilferage, and logistics exposure wherever the grid is inconsistent. Batteries and power electronics carry embodied carbon and end-of-life obligations that no operator has yet fully accounted for.

A potential solution is a single circular energy architecture rather than a collection of isolated green projects. Four levers that address four different time scales of the same problem have been identified. Green Energy Open Access is the dominant Scope 2 lever, and the legal right to use it already exists: since the Second Amendment Rules of 23 May 2023, ten to thirteen

towers within one electricity division constitute an eligible entity. On-site solar is valuable but physically bound, typically around 5 KWP per site. Advanced batteries, including sodium-ion, provide flexibility from seconds to hours. Hydrogen fuel cells address the difficult tail of long, recurrent outages where batteries alone cannot bridge the gap economically.

Figure 4 brings the proposed architecture together on one page. There are five integrated energy pathways. Grid power is progressively decarbonised through Green Energy Open Access. Space-constrained on-site solar supplies part of the load. The battery bank moves from valve-regulated lead-acid to lithium-ion and sodium-ion, with second life and recycling loops. Hydrogen PEM fuel cells displace legacy diesel. AI-enabled energy management coordinates all of them. The pathways converge on the −48 V DC bus through a high-efficiency switched-mode power system. A circular lifecycle surrounds the whole system: design for longevity, a digital product passport, repair and reuse, second life, and material recovery. Together, these deliver lower Scope 1 and Scope 2 emissions, higher resilience, lower diesel and operating costs, stronger supply-chain security from reduced concentration risk, and circular material use. Figure 5 then maps each of the four supply levers to the time scale of the energy problem it addresses.

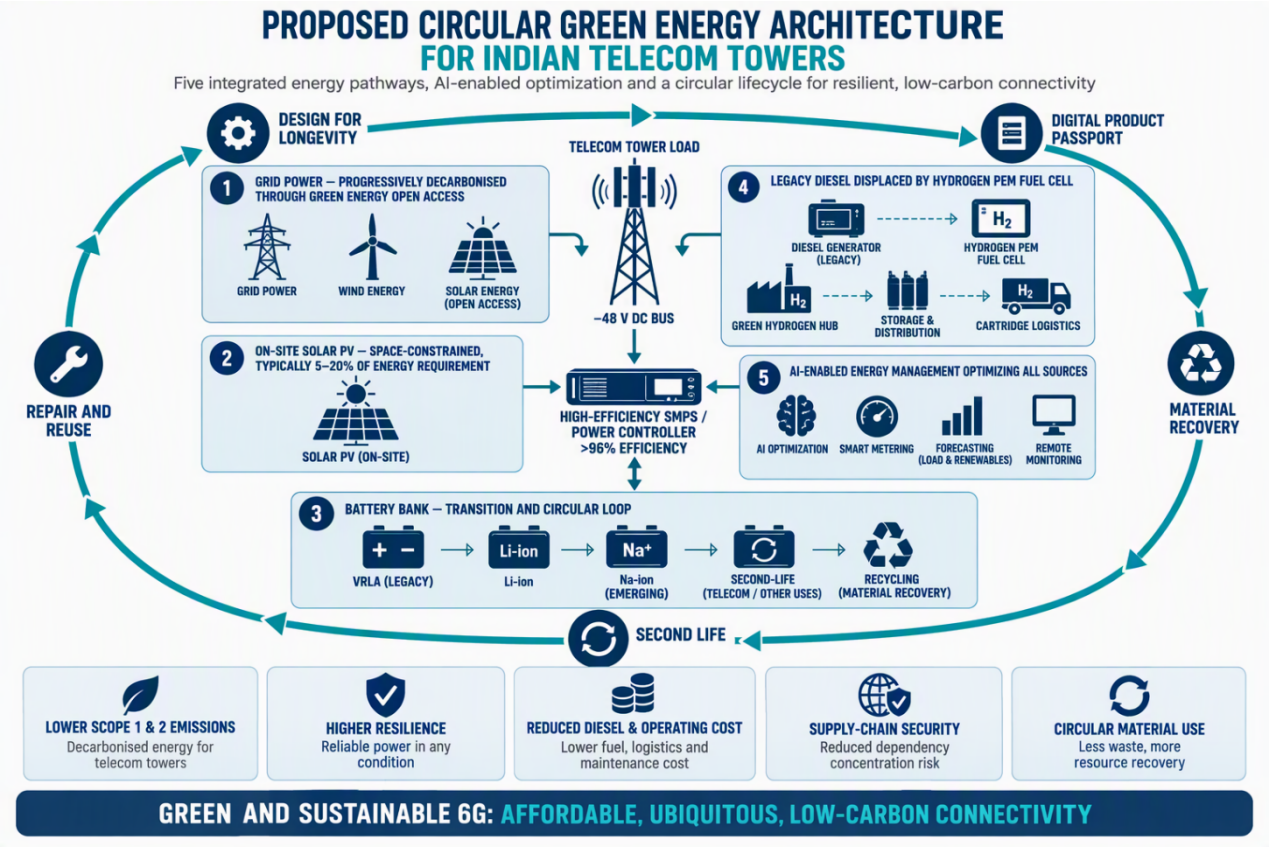

Figure 4: Proposed circular green energy architecture for Indian telecom towers: five integrated energy pathways, AI-enabled optimisation and a circular lifecycle. Analysis by the authors.

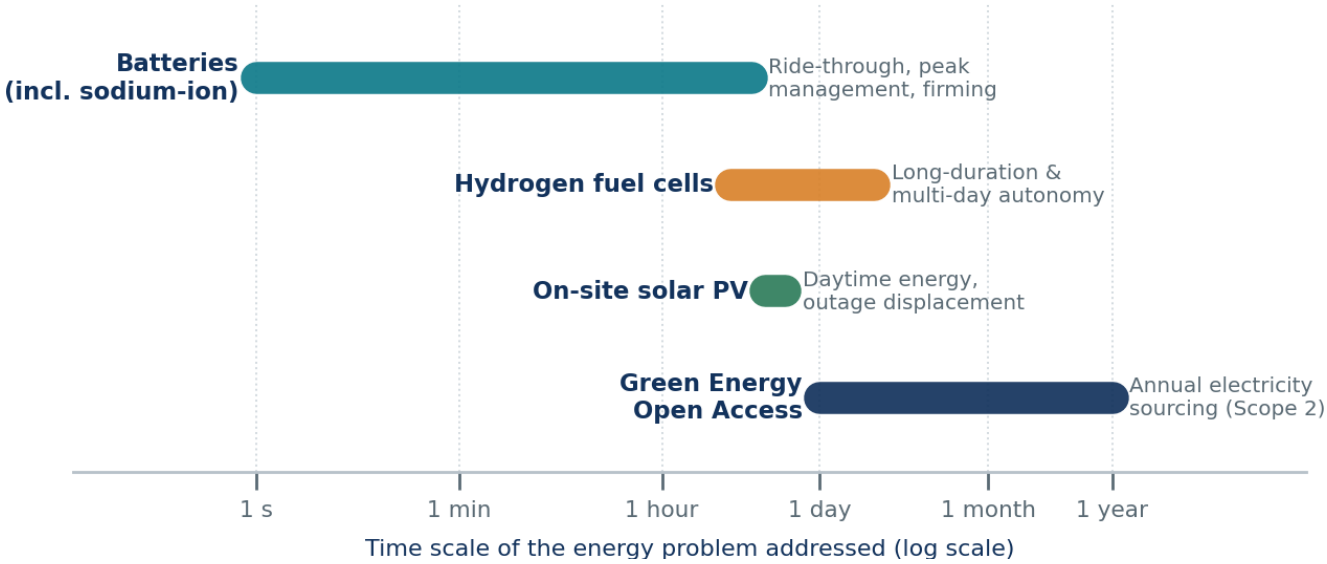

Figure 5: The four levers and the time scales of the energy problem they address. Analysis by the authors.

2.2.1 The Tower as the Unit of Analysis

A mobile service depends on a physical chain of radio access, transport, edge and core compute, power conversion, storage and replacement logistics; carbon, materials and resilience must be managed across the full-service life cycle [40]. The tower is the operational intersection of that challenge.

2.2.2 Why the tower, and not the radio, is the right boundary

The tower is the natural boundary between RAN- and non-RAN subsystems. It is a continuously powered, geographically dispersed asset with a small individual load but a very large portfolio footprint. Network densification and edge computing will increase the number and complexity of powered locations even where energy consumed per transmitted bit improves. The strategic objective is therefore absolute impact reduction, not efficiency gains that are overtaken by traffic growth.

2.2.3 Scale and shape of the load

Telecom assets mapped on the Tarang Sanchar portal included approximately 0.859 million towers carrying 3.297 million base transceiver stations (Department of Telecommunications [41]). The 5G layer has grown rapidly on top of that base, crossing 562,971 installed 5G base transceiver stations by 30 June 2026 [80].

The defining characteristic for energy procurement is the per-site load. The Cellular Operators Association of India has consistently stated that each telecom tower holds an independent electricity connection drawing about three to five kilowatts, rising to approximately ten kilowatts for multi-tenant and 5G-loaded sites [42], [43]. Peer-reviewed analysis of the Indian estate places electricity demand per tower in a range of 1 kW to 8.5 kW depending on configuration, tenancy, tower type, and cooling load [44]. A cluster of 100,000 sites at five kilowatts of average drawn load and a high load factor therefore represents close to 500 MW of contracted demand and of the order of 4 billion units of annual consumption — a profile comparable to a major metals producer but delivered through hundreds of thousands of low-tension service connections spread across every electricity division in the country.

2.2.4 Availability, not consumption, is the hard problem

At the pan-India level, Grid supply differs widely across geographies and seasons. Grid supply is area specific, and varies from about 13.5 hours per day, to more than 20 hours per day. The historical response to those deficits has been diesel backup. DIPA estimates suggest the telecom tower industry consumes approximately 100 crore litres of diesel per annum as backup power, with an estimate of roughly 2.6 million tonnes of CO_2 annually from tower diesel.

The visible fuel bill understates the true cost. An energy manager also pays for the refueling round trip, the security overhead on stored fuel, pilferage from storage, genset overhaul, acoustic enclosure maintenance and, increasingly, compliance. The Telecommunication Engineering Centre observed as far back as 2012 that the single largest hidden cost item at a diesel-backed site is diesel pilferage from the storage area [46]. That observation has not aged.

Because the estate is heterogeneous, this paper models three site archetypes rather than a single national average. They are used consistently in every subsequent section.

Table 3: Three reference site archetypes. Sample illustration.

Parameter	A Grid Availability- Moderate Grid Supply- Reliable	B Grid Availability- Poor Grid Supply- Unreliable	C Off Grid
Average site load	3.0 kW	3.0 kW	3.0 kW
Daily backup hours	2 h	8 h	16 h
Annual backup energy	2,190 kWh	8,760 kWh	17,520 kWh
Diesel consumed at 0.4 L/kWh	876 L/yr	3,504 L/yr	7,008 L/yr
Effective diesel price	₹95/L	₹95/L	₹95/L
Annual diesel-path opex (fuel, O&M, logistics)	₹1.19 lakh	₹3.92 lakh	₹7.37 lakh
Scope 1 CO_2 from backup	2.3 t/yr	9.4 t/yr	18.8 t/yr
Dominant intervention	Open access + Solar + battery	Open access + solar + battery; hydrogen only if economy of scale is established	Hydrogen + solar + battery

3 Measuring Overall Sustainability Performance

3.1 Introduction

Energy use in the operation phase and the GHG emissions leading to global warming are and have been in focus for many years. Reduction of energy use leads to less GHG emissions as well as lower cost.

Only by establishing relevant key performance indicators (KPIs) for the environmental impact of ICT, is it possible to reduce it. KPIs can be, and should be used, on different levels from the design to site level to finally measure and summarize the actual outcome from an overall perspective.

3.2 KPIs for overall development

As mentioned in Section 1, lowering the total environmental impact matters more than just energy efficiency. Optimizing subsystems will lead to a genuine decrease in the total only if the emissions are not shifted to other subsystems. By 6G there is an opportunity to include energy performance and other sustainability aspects from the beginning, but it needs to replace older equipment and not just be added on top. Just as total energy (fuel) consumption and emissions related to any travel and transport activity can be allocated per passenger and transported goods, electricity consumption and emissions for a mobile network can be allocated per user. However, there is a key difference - travel and transports scale with passengers and goods (weight/volume), while mobile networks do not scale with voice and data use or just to a very small degree. Mobile networks and users' mobile devices are "always on" while vehicles are only on when they transport passengers and goods.

Because of this "always on" nature of networks, any KPI that uses voice and data faces problems. To account for daily, weekly, and seasonal differences in the use and operation of mobile networks, electricity consumption data for a whole year is typically used together with the average number of subscriptions served during the same year, typically (and simply) the average between the number of subscriptions at the start and end of the year.

KPIs in the form of emissions per person/capita and year are also used in high level sustainable development discussions in United Nations (UN) or Intergovernmental Panel on Climate Change (IPCC) (e.g. [3],[4]). To be able to express the energy consumption and emissions of any product or service per person or similar, like per household (which easily can be turned into an average per person), is needed to be able to make sound actions or choices to reduce emissions.

Electricity consumption per year and per user or *paying customer (subscriber / subscription)* should be considered as the main sustainability KPI. The unit kilowatt-hour per subscription and year (kWh/subyear). By multiplying this KPI with a corresponding electricity emission factor (given kilogram carbon dioxide equivalents per kilowatt-hour, kg CO_2e/kWh), a closely related KPI with the unit kg CO_2e/subyear can be used to capture the GHG emissions from the use stage. An estimate of the full life cycle GHG emissions, capturing also the embodied emissions, can also be divide by subscriptions to get the total GHG/subyear.

Using these KPIs, the sustainability performance of different networks of different sizes could be compared and their performance development could be followed over time.

Early business models were based on charging mobile subscribers per voice call minute just like with fixed telephony. The addition of mobile data services was seen as a major change for

mobile networks, but it had little impact on the slowly decreasing economic KPI average revenue per user (ARPU) as mobile network operators could not charge much more for additional data. The addition of IoT was also seen as a major change but once again there was little economic gain for mobile operators. So far it is only human subscriptions that matters, although there are around 3.5 billion cellular IoT subscriptions in 2026. More mobile Internet data was transmitted than traditional mobile voice data for the first time at the end of 2009. Mobile data use increased rapidly and passed >100 times mobile voice data 10 years later in 2019 and is currently >500 times (mid-2026). The mobile data growth has slowed down considerably though, and current Compound Annual Growth Rate (CAGR) is about +25%. Subscribers around the world to mobile services that once paid >30 $ per month for voice and SMS services and no additional data on average, now pay in the order of 10$ per month for voice and SMS services, and 20 GB additional data per month. Figure 6 shows how electricity consumption per subyear has developed over time since the 1990s.

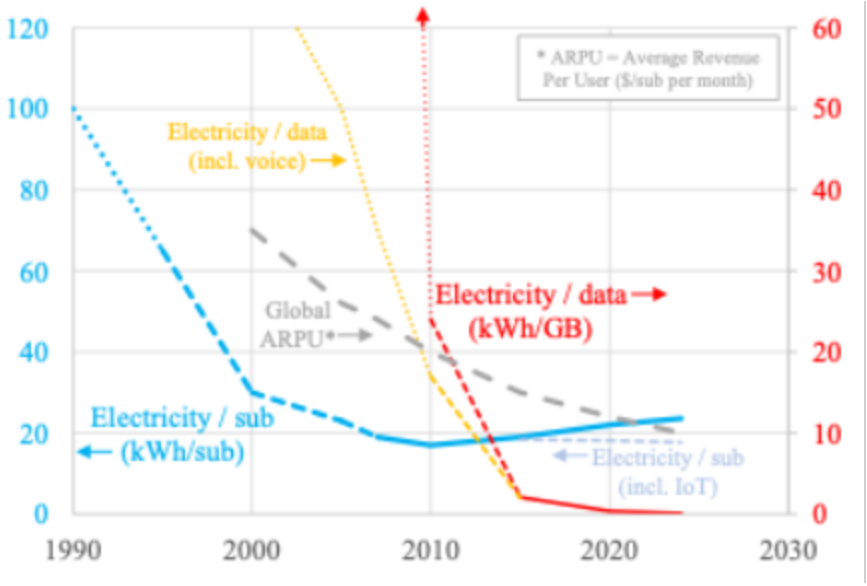

Figure 6: Development since 1990s

3.3 Mobile networks and smart phones

Electricity consumption for mobile networks operation has consistently been the single most important source of GHG emissions. The second key part of a mobile subscriber's total energy and GHG footprint come from the manufacturing of the mobile phone or smartphone. The manufacturing or construction of the network and the electricity consumption of the mobile phone or smartphone have always been of less importance but should also be included to get the full picture. The following shows the electricity and GHG emissions for these parts for one subscription and year 2024 [1].

- Mobile network electricity consumption, 24 kWh, 12.5 kg CO_2e /subyear
- Mobile phone or smartphone manufacturing (embodied), 9 kg CO_2e /subyear
- Mobile network manufacturing / construction (embodied), 2 kg CO_2e /subyear
- Mobile phone or smartphone electricity consumption, 3 kWh, 2 kg CO_2e /subyear

In the early years of mobile phones, the mobile phone battery chargers consumed considerable stand-by power when left plugged in, but the stand-by power is nowadays low. Figure 7 shows the development since 1995 for mobile networks and mobile phones/smartphones.

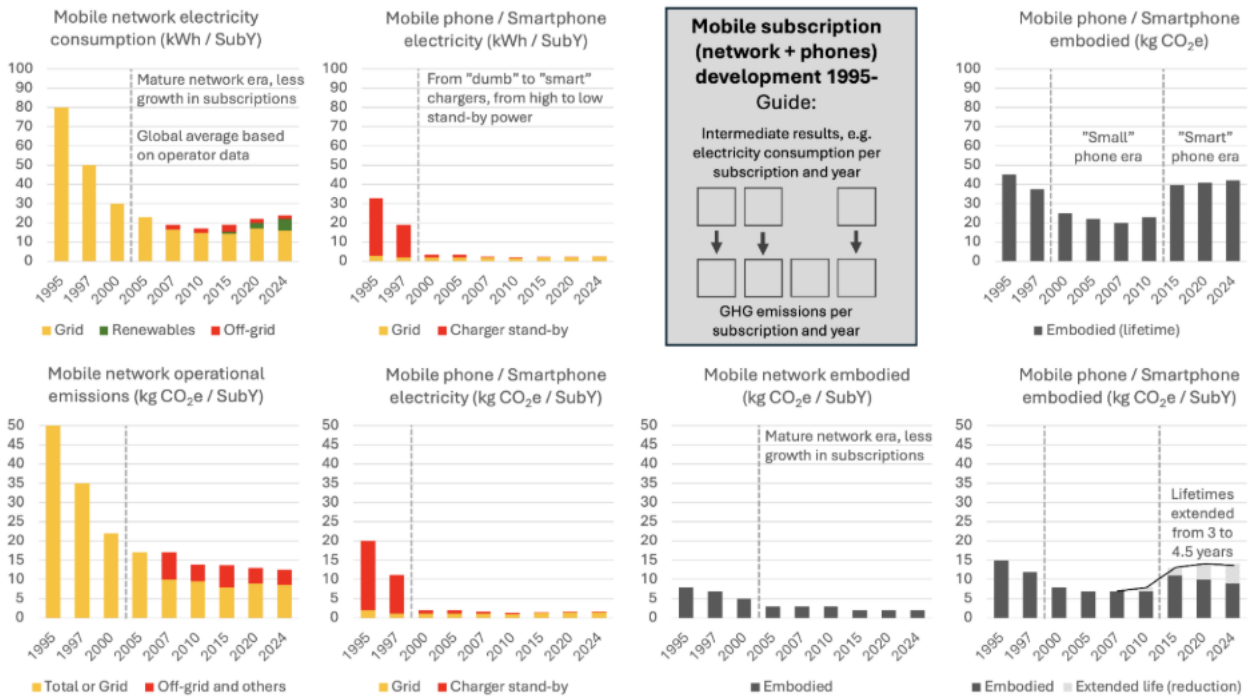

Figure 7: Development of electricity and use stage GHG emissions for mobile networks and mobile phones/smart phones (left part) and the embodied GHG emissions (right part) [1], [5]

The embodied part of mobile networks, hence the manufacturing and construction, has decreased significantly. These figures are influenced by the growth in number of subscriptions sharing the burden of the embodied emissions. 6G will be used in parallel to previous networks, the overall target and thereby the main KPIs is to decrease the total GHG emission and to be able to compare and understand the development useful KPIs are electricity per subscription and GHG emissions per subscription.

3.4 Operation is more than electricity

The electricity consumption of a mobile network cannot just be read from the network operator's electricity bill as operators typically have both mobile and fixed networks. There are several other issues when collecting metered electricity consumption and trying to estimate unmetered network equipment and sites.

- Mobile network sites (base stations) with individual electricity meters that are only used for the mobile network under study are straight-forward to include in an estimation of the total use stage emissions.
- Sites may not have individual electricity meters, or the mobile network part is just a share of a larger site hosting many types of network equipment. In that case, common consumers like power and climate systems also need to be shared. Estimates can still be made quite accurately based on internal equipment meters, sites with meters including similar equipment, or specifications, and estimates for additional power conversions, cooling, and other common site consumers.
- A mobile network site may still include co-located equipment owned by other operators renting space which then needs to be excluded, and in that case also a share of common consumers like power and climate systems need to be excluded.

- Electricity consumption for off-grid sites or off grid operation, should also be included but it is recommended to use the same “feed point” as grid electricity, meaning that additional losses should not be accounted for.
- Transmission is partly included already at the mobile sites, but additional transmission and core nodes should also be included.
- In addition to transmission and core nodes, the data traffic that a mobile network generates shares a common core network, which can also be estimated and included.
- In addition to the mobile and core network, an operator has offices, data centers, stores and other sites (e.g. warehouses, repair, service), that also can be included in a total.
- Data centers or part of data centers used for co-location and hosting third party data services should not be included in the mobile network.

From the list above it is obvious that the scope of a mobile network energy and GHG emissions in the use stage can differ. Preferably all points above should be considered.

When multiplying electricity consumption figures with electricity emission factors, it is important to use the same scope, preferably the full scope that consists of three main parts:

- Scope 2: The electricity production emissions at power plants (0.44 kg CO_2e/kWh)
- Scope 1-3: adding fuel supply (e.g. coal and gas) and grid transmission and distribution losses are included (+0.06 kg CO_2e/kWh)
- Scope 1-3: adding embodied emissions for power plants, the grid, and possibly also end-of-life treatment which is very uncertain for nuclear (0.02 kg CO_2e/kWh)

It must be noted that full scope is required to account for the total impact from renewables including the construction of e.g. solar panels and wind turbines. It is also of great importance to know the share of renewables which on its own can be defined as another KPI. The average emission factor for renewables (0.03 kg CO_2e/kWh) is less than 1/10th of the global average electricity grid mix emission factor (0.52 kg CO_2e/kWh). All figures within parenthesis are average emission factors.

The operational electricity consumption and GHG emissions of an average mobile network operator is shown in Table 4 (based on [5]). It includes all possible parts discussed above.

Table 4: Electricity consumption and GHG emissions per subscription year (subyear) for an average mobile network operator and its different parts (based on [5])

	Electricity consumption per subyear	GHG emissions per subyear
Mobile network sites	Grid mix: 20 kWh	Grid mix: 7.8 kg CO_2e
	Off-grid: 2 kWh	Diesel generators: 1.5 kg CO_2e
Core network	Grid mix: 0.75 kWh	Grid mix: 0.7 kg CO_2e Other (travel, transports, other): 2.5 kg CO_2e
Offices, data centers, stores, other sites	Grid mix: 1.25 kWh	
Total	Total: 24 kWh	12.5 kg CO_2e

Mobile network sites grid mix are made up of 18 kWh base stations and 2 kWh core nodes and transmission. The 22-kWh grid mix is made up of 6 kWh renewables and 16 kWh average grid mix.

Allocation to subscriptions

Allocations to subscription can be difficult and might not be clear on how to handle the rising IoT subscriptions.

For the year 2024, as can be seen in the fact box, mobile IoT subscriptions represent a small share of subscription revenues (~2%) and mobile data traffic (~2%), but they have grown in numbers and are estimated to 2.9 billion representing about 25% of all mobile subscriptions. So, should 25% be allocated to IoT based on the subscription share, or should 2% be allocated to IoT based on the share of revenue and data? There are different reasonings. A typical IoT subscription does not move around in the network and has revenue and data traffic less than 1/10th of a typical smartphone subscription on average. However, some IoT like vehicle IoT move around and can sometimes have high data traffic, but the total data traffic is still significantly lower than a smartphone over a year.

FACT BOX

Mobile networks globally in 2024
[1], [6], [7], [8]

Use stage electricity consumption: 205 TWh
Use stage GHG emissions: 108 Mt CO_2e
Embodied GHG emissions: 17 Mt CO_2e
Subscriptions: 11.6 billion incl. 2.9 billion IoT
Revenues: ~1100 billion $
Data traffic: ~2000 to ~4000 ExaByte (EB) *

*Data traffic reported by [6]/[7] and [8] use different definitions

In the simplest allocation of mobile network services, the totals are allocated evenly on all subscriptions, see Table 5. This could be done with or without IoT subscriptions. A first step to a more just allocation is to first allocate 2% to IoT based on revenue and data traffic and then allocate these 2% evenly to IoT subscriptions. Then the remaining 98% is allocated evenly to all “human” subscriptions (including also fixed wireless access, PCs and portable routers).

Table 5: Allocation of mobile networks total

Total network	All subs	“Human” subs	“Human” subs	IoT subs
Allocation	100%	100%	98%	2%
Subscriptions	11.6 billion	8.7 billion	8.7 billion	2.9 billion
Per sub, for…	**All subs**	**“Human” subs**	**“Human” subs**	**IoT subs**
Use stage electricity	17.7 kWh	23.6 kWh	23.1 kWh	1.4 kWh
Use stage GHG emissions (CO_2e)	9.3 kg		12.2 kg	0.74 kg
Embodied GHG emissions (CO_2e)	1.5 kg		1.9 kg	0.12 kg

Allocating by all subscriptions result in 17.7 kWh per subscription but this value neither represents ”human” subscriptions nor IoT subscriptions especially well. To allocate 100% of electricity to only ”human” subscriptions gives in a reasonable result, but to first allocate one part to IoT and another to ”human” subscriptions based on revenue (or data traffic) and then allocate each part on their subscriptions, gives more just results. Currently the revenue and the data traffic are both 2% the same share, which results in the last two columns in Table 5. The approach suggested hitherto to allocate first based on revenue is believed to also work well in the future where it can be assumed that the share of IoT subscriptions increases.

3.5 Geographical differences

The KPIs per subscription make it easier to compare different geographical regions. Any region, country, network, and operator could use the proposed KPIs.

The global data can also be allocated to different regions and countries. An allocation of the global 2024 for the use stage electricity of mobile networks is presented in Table 6. The global

average in Table 6 equals the second column in table 2, where 100% of electricity is split on "human" subscribers, excluding IoT.

Table 6: Electricity per subscriber and year for different regions compared to data per subscriptions and population density.

	kWh / sub year	GB / month	GB / year	People / km^2	Subs billions
USA	53	25	300	**30**	*0.4*
Finland	52	50	600	**17**	*0.007*
Sweden	42	30	360	**23**	*0.012*
China	41	20	240	**145**	*1.7*
EU-30	33	30	360	**110**	*0.61*
Global average	**24**	**20**	**240**	**55**	***8.7***
India	16	30	360	**410**	*1.25*
Bangladesh	9	10	120	**1200**	*0.19*
Rest of World	15.5	10	120	**35**	*4.17*

Finland has been a standout in the mobile communication sector for years, through its high data traffic per user. The impact of the low population density and stringent regulatory requirements on mobile network operators is somewhat countered by high concentration of people living in urban areas. USA has even a slightly higher electricity consumption per subscription than Finland, although the population density is higher and data traffic is lower. USA has a high ARPU and has built out their mobile networks more than e.g. Europe. China also has a high electricity consumption per subscription despite their high population density.

For Europe the electricity per subscription is higher than the global average, but lower than e.g. USA and China. Europe has a higher population density than the global average, but mobile networks have been built to cover a much larger share of the land area.

India has a rather high data traffic per user but due to the high population density, and the high aggregate capacity utilization factor of powered network equipment driven by the massive data volume flowing through the telecommunication networks, electricity consumption is still low per subscription. Bangladesh has one of the highest population densities in the world and one of the lowest electricity consumptions per subscription.

A key observation is that the electricity consumption of mobile networks shows a correlation to population density, but other parameters like area coverage requirements, urban concentration, and geography also matter.

3.6 Optimizing networks on different levels

While high-level KPIs are important indicators, improvements are needed at different levels. Thereby sub-KPIs can be of importance to add and act upon.

In the product design phase, simplified life cycle assessment (LCA) approaches can be used to capture the materials and processes that contribute the more to GHG emissions. The recommendation on LCA or simplified LCA from ITU-T can be used by the manufacturers (ITU-T L.1410 [9] and L.1411 [10]).

Energy performance of radio access networks is constantly improving and with 6G comes new possibilities to optimize energy-use and thereby a possibility to decrease the electricity consumption in the use stage [11].

Site optimization covers the embodied impact of RAN equipment, site equipment like batteries, cables as well as the site itself meaning tower and tower foundation at macro sites. It also covers the use stage impact mainly related to electricity use, but also e.g. the maintenance transport needed and power backup solutions. Environmental impact from all embodied related items can be estimated using LCA approaches and prolonging the lifetime is one possibility to decreasing the annual impact. The operational related environmental impacts can be monitored regularly and more easily optimized and impacted. It makes sense to have sub-KPIs for the operational part, while the embodied impacts are better investigated before installation and when it is time to swap to new equipment.

When constructing a site and equipping it, the future electricity consumption and related GHG emissions can be reduced by choosing the active base station equipment with the lowest power consumption, and power and climate system with the highest efficiency. It is, however, a bit difficult to relate to the network level and use KPIs expressed per subscription. Sites can be built in different ways for different purposes, e.g. capacity vs coverage.

The mobile network total embodied KPI is on average about 2 kg CO_2e per subscription and year. The major embodied part does not typically come from active radio equipment but from infrastructure like antenna towers, housing, batteries, cabling, etc., and roads, if such are needed to be constructed. Embodied KPIs is a lot more uncertain than operational KPIs as they are to a much less degree based on real measurements, and in addition the lifetimes are also uncertain making any embodied KPIs expressed per year rather uncertain.

3.7 Global data centers and data services

What share of global data centers can be allocated to mobile network services? Large consumers of data services like PCs at work and home, and TVs at home, use mainly fixed networks. Many data centers are also used by employees in closed enterprise networks owned by companies and organizations. On the other hand, the most common device used to access the Internet today is a mobile phone or smartphone, about 95% of all Internet users do that compared to about 60% using a PC (in addition to their phone).

One way to estimate global data centers is to use the number of Internet users, about 6 billion, which result in about 53 kWh and about 21 kg CO_2e per Internet user. The “mobile use” part can be estimated based on the mobile web data traffic share, which is currently as high as about 60%, resulting in 32 kWh and about 13 kg CO_2e per mobile Internet user. These figures can further be reduced by subtracting an estimate for the enterprise networks (private company employee usage) part, but such quantification is very difficult.

In addition to the top-down approach described above, a bottom-up approach building on data for individual data services can be used. Meta’s data services (Facebook, Messenger, Instagram, WhatsApp) could be quantified to 5.5 kWh per year and user on average globally. In the same way, Google’s many services can be quantified to 7 kWh in total. Both companies report GHG emissions in the order of about 2 kg CO_2e per user and year, mainly embodied emissions related to constructing data centers. To get to a figure for their mobile part only, a fixed part and other parts need to be excluded which is difficult without further help from Meta/Google.

It is very difficult to build a bottom-up model of the literally millions of data services related to mobile networks. For electricity and GHG emissions the same general principles described for mobile networks also apply to data centers and data services. A data center and a data service total are difficult to assess and interpret at being large or small. However, when the electricity consumption and GHG emissions are related to number of data center and data services users

a given year, the figures can be understood much better. When building new data centers, more site-specific KPIs like Power Usage Effectiveness (PUE) are vital to guide the construction.

3.8 AI Environmental Footprint

The environmental footprint of AI extends beyond inference. It can include data processing, model training, retraining, inference, supporting computation, and model retirement. The measurement approach should reflect the AI workload. Token-based metrics are relevant to generative AI applications such as network agents, digital twins, and service orchestration. Task-based metrics are more suitable for functions such as radio optimization, mobility prediction, resource allocation, and anomaly detection. Table 5 summarizes the mapping between representative 6G AI workload output structures and their applicable metrics.

Table 7: Matching AI workload output structure to metric

Workload output structure	Example 6G AI functions	Applicable metric
Token-sequence output	LLM-based network agents, digital twins, service orchestration	Token-based metrics
Discrete-task output	RF optimization, anomaly detection, mobility management	Task-based metrics

3.8.1 Network Sustainability Benefit and Net Sustainability Impact

AI can provide network-level sustainability benefits through optimization, prediction, automation, and intelligent resource management. These benefits may include reduced network energy consumption, improved resource utilization, reduced carbon emissions, and improved service efficiency. At the same time, AI introduces additional energy and resource requirements for computing, data processing, training, inference, and other lifecycle activities. In addition, particularly in the emerging AI Native paradigm, different levels in the communications, networking, and software stacks may utilize AI processing during operations at different time intervals. AI inference engines operating at smaller time-scales (in the order of several microseconds or milliseconds such as in a lower physical layer) will execute such inference tasks more often during an overall duration for operation of the system, relative to AI inference engines operating at larger time-scales (such as in the order of several seconds or minutes) at an upper network operations and management layer or in a software application layer. The actual energy consumed for each inference talk and the quality of the AI generated output will depend on the size of the AI model for each inference task, and the number of model parameters and the quantization associated with such parameters. As suggested in this paper, the overall cost for operations needs to be considered and compared with the relative benefits of adopting AI for such processing, to determine the overall benefit and impact. The sustainability impact of AI-enabled network functions therefore reflects both the environmental footprint associated with AI and the environmental benefits enabled by its use. The environmental footprint and corresponding network benefits can be considered within the same lifecycle and system boundary to provide a consistent view of the sustainability impact.

3.8.2 Lifecycle and Assessment Boundaries

For AI-enabled 6G functions, the lifecycle may include model development and training, deployment and integration, inference during network operation, retraining and continual learning, and model replacement or retirement. AI functions operate across the RAN, edge, core, cloud, and data-centre environments. The assessment boundary can therefore vary according to the AI workload and network function being evaluated. Task-level boundaries are

suitable for functions such as RF optimization and mobility prediction, while service-level boundaries can be used for analytics, automation, and orchestration functions. Generative AI applications such as network agents and digital twins may additionally require token-level assessment. The assessment boundaries are given in Table 8. The same assessment boundary should be maintained when comparing alternative implementations or evaluating sustainability improvements.

Table 8: 6G domain, AI workload, and assessment boundary

Domain	Typical AI workload	Assessment boundary
RAN / Site	Beam management, mobility prediction, RF optimization	Task-level
Edge Cloud	Local analytics and automation	Task-level and service-level
Core Network	Network copilots, orchestration, digital twins	Task-level and service-level
Data Centres/ Cloud	AI training and inference platforms	Compute-level
AI Lifecycle	Pre-training, continual learning, inference, re-evaluation	Full AI Lifecycle

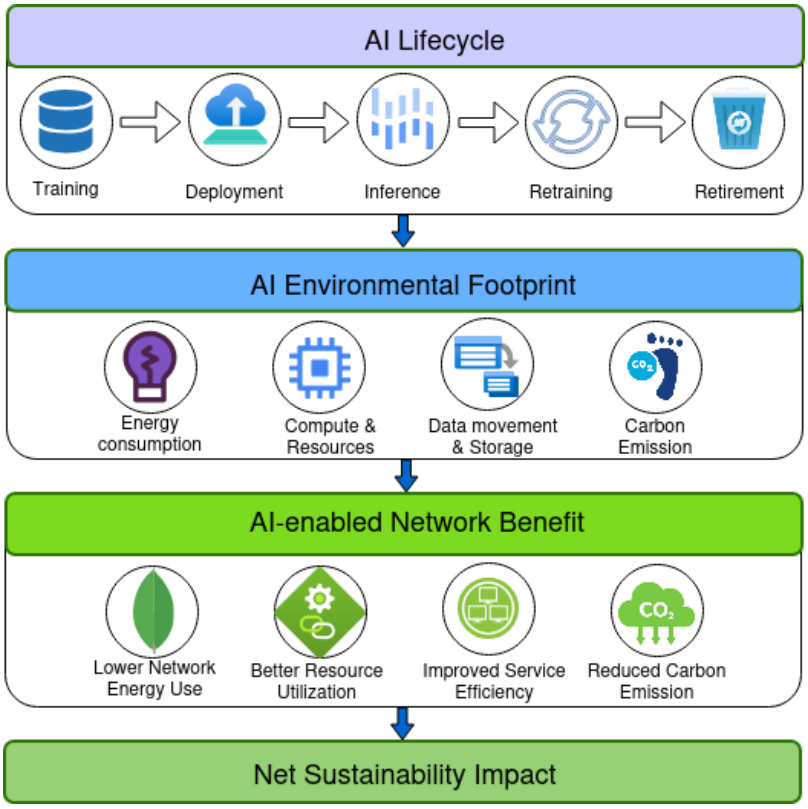

Figure 8: AI lifecycle, environmental footprint, and network sustainability benefit in AI-enabled 6G.

In fact, AI can reduce network energy consumption through optimization, prediction, automation, and intelligent resource management. However, AI itself consumes computing resources and energy. Sustainability assessment should therefore consider both the AI environmental footprint and the network benefits enabled by AI. This could be seen as, provided all terms use the same unit, time horizon and system boundary.

Net Sustainability Impact = Savings in network lifecycle impact – AI lifecycle impact – induced or rebound impact

Figure 8 illustrates the AI lifecycle, the associated environmental footprint, and the environmental benefits enabled through network operation. Existing sustainability methodologies ITU-T L.1410, L.1421 and L.1801 provide relevant foundations for lifecycle,

greenhouse-gas, and AI environmental-impact assessments. Emerging token-based evaluation approaches can complement these methodologies for generative AI workloads.

3.9 Summary

Overall energy and GHG per subscriber are the preferred measures to decrease the environmental impact. Optimizations leading to reduced energy and GHG emissions on different levels are necessary means to achieve a reduced environmental impact per subscriber.

The main KPIs for overall network level are summarized in Table 9. The table also includes additional KPIs at the site-level, which is mirroring the detailed analysis of RAN energy consumption given in Section 2.2.

Table 9: Proposed KPIs for network level

KPI	Description
Total grid electricity consumption (GWh)	Includes base station sites, transmission and core network, non-network sites (offices, stores, etc.) Preferable include and transparently report all parts described previously. For base station sites colocation needs to be handled carefully.
Renewable grid electricity actively purchased (% of total grid, GWh)	Actively purchased renewables, not the average renewables in the country electricity mix
Additional electricity consumption own-generated (backup, off grid) (GWh)	Estimate the electricity for the base station
Intensity factors, grid and renewables emission factors (kg CO_2e/kWh)	Make sure to include the embodied emissions of the generated energy and T&D losses
Additional diesel consumption for backup power (kg CO_2e)	Amount of diesel x emission factor
Additional operator GHG emissions (kg CO_2e)	Sites, vehicle fleet, travel
Network embodied GHG (kg CO_2e)	Estimate based on typical base station sites, includes large uncertainties
Number of paying subscriptions	
Electricity per subscription (kWh/sub)	Can be calculated from above parameters
GHG/subscription (CO_2e/sub)	Can be calculated from above parameters

4 Global Sustainability Standards and Policy Landscape

This section provides a snapshot of ongoing 6G standardization activities in 3GPP and O-RAN addressing energy efficiency and the broader objective of sustainability across services, system architecture, radio access, media, management and orchestration. The material reflects the standardization status and technical directions available at the time of writing; it should not be interpreted as representing final 6G specifications or settled industry conclusions. Only subsequent 6G standardization decisions will determine which study outcomes are carried into normative work and ultimately incorporated into Technical Specifications. Accordingly, the definitive conclusions and the solutions that will form part of the 6G specifications will become clear only over time.

4.1 3GPP

4.1.1 SA1 – Services and Use cases

SA1 as part of Release 20 has published TR 22.870 [16] Study on 6G Use Cases and Service Requirements during the first quarter of 2026. The study includes use cases related to energy, carbon and sustainability and emphasis on 6G must be better than 5G on joint network and UE energy, expose energy/CO_2e, steer sensing/AI/computing on energy, support slice energy credits, cooperating UEs, and task offload. Also, it includes requirements on energy related to NTN, data and AI, such as Energy efficiency consideration of one-to-many services based on TN vs NTN access, Mobility between TN/NTN/HAPS during energy shortage, restricted data collection at UE (e.g., to save battery), continuation to provide AI Service & enable cross-operator cooperation including during disasters with limited resources (e.g., limited energy). Those are now in draft TS 22.270 [15] clause 5.1.5 (6G-REQ, ~40% done). Rel-20 SA1 energy work is a separate 5G-A track (Energy as a Service Criterion in TS 22.261 [25] 6.15 / 6.15a), which 6G explicitly treats as necessary but not sufficient. SA1 sets the service bar for the 3GPP WGs have to meet for a sustainable 6G and 6G for sustainability.

Moreover, SA1 3GPP TR 22.870 [16] clause 13.2 on considerations on sustainability is a section that goes into topic of sustainability beyond only the energy consumption. Additionally, several use cases in SA1 TR 22870 include potential sustainability impact in terms of environmental sustainability and socio-economic sustainability of those use cases. Environmental sustainability and socio-economic sustainability are mapped to the UN SDG's environmental, social and economic goals.

SA1 as part of Release 21 has been actively defining the TS 22.270 [15] 6G Service Requirements. Clause 5.1.5, Energy-related aspects describe requirements such as energy-saving methods, network and UE energy efficiency, energy-aware & carbon-aware service delivery; energy efficiency across various access network technologies, energy management policies etc. Additionally, below requirements enable sustainability beyond energy.

- Requirements related to security; privacy is described clause 5.1.3
- Resilience in clause 5.1.4 specify requirements related to emergency service continuity, on-demand network-service provisioning; minimisation of communication service degradation during disasters, autonomous operations.

- Clause 5.4 specifies requirements for seamless integration of terrestrial and non-terrestrial networks which aid to bridge social gap, digital access and digital inclusion and can unlock new economic opportunities.
- Clause 5.2 connected intelligent of network and devices.

4.1.2 SA2 - 6G System Architecture: Energy Efficiency and Sustainability

Architectural Requirements state that the 6G System should follow design principles including cloud nativeness, improved sustainability and energy efficiency, robustness and resiliency and that these apply to every task. In the TR [17], energy is therefore not a side KPI: it appears as UE battery awareness, RAN sleep, core-network policy, slice admission, computing-site selection and Massive IoT small-data transfer. The architecture is a closed loop (Figure 9). The UE exposes energy intent and traffic shape; KI#6 (policy) and KI#5 (QoS collaboration) translate that into PCC rules, DRX/sleep windows and slice/compute placement; the UE then updates preference as battery, thermal or demand changes.

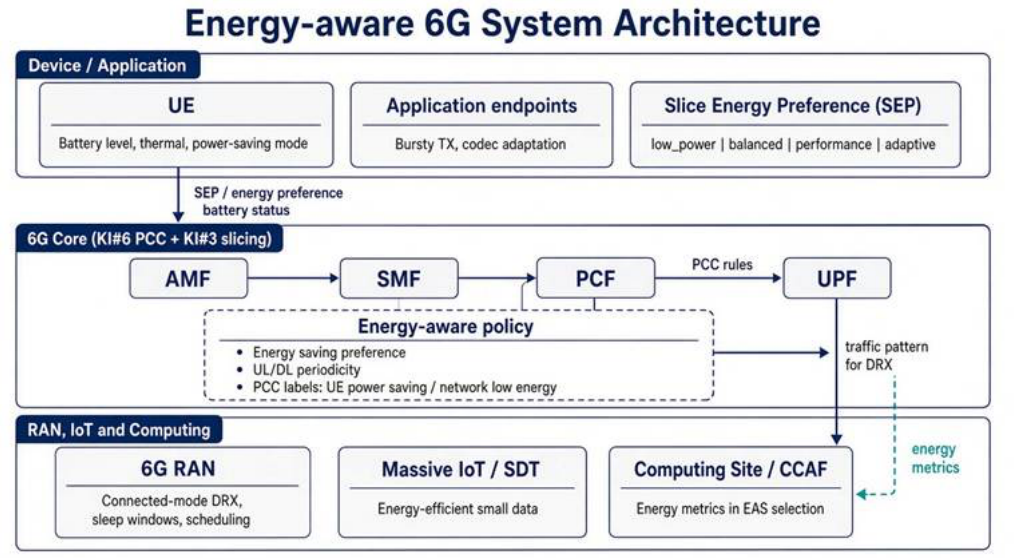

Figure 9: Energy-aware 6G architecture (TR 23.801-01)

KI#6 starts from the 5G SM/UE/AM policy split and asks how 6G should simplify associations, take UE input into PCC, and use energy information when it is available. NOTE 10 of clause 5.6 is explicit: if energy-related information exists (5G or 6G mechanisms), this key issue studies how to take energy efficiency and consumption into account for policy decisions.

- **Energy-saving preference.** The UE may provide an Energy Saving preference indication as non-QoS PCC input, authorized by 6GC (PCF, SMF or an NW-Agent) against subscription and operator policy, for ongoing or future PDU sessions.
- **Live device status.** Battery level, memory and thermal status sit in the same input set. Policy should not treat every UE as equally powered.
- **Periodicity for radio sleep.** UL/DL periodicity, already used as AF input in TS 23.501 clause 5.37.8, is reused as UE input so connected-mode DRX and similar RAN techniques can sleep.
- **Policy labels the UE can choose.** SMF (via PCF) can offer labels such as “UE power saving”, “Support network low energy consumption”, “Acceptable low service quality” and “High throttle”. The UE selects one; PCF returns matching PCC rules; coupling device battery and network watts in a single choice.

UE input is authorized, may be overridden, and does not replace AF input. Users' express preference; the operator still decides the slice, QoS flow and charging key.

KI#6 bullet 5 states that UE QoS-related PCC input follows KI#5. Clause 6.5.6 (collaboration layer) is where energy is earned in the user plane, not only declared in policy.

- **Bursty transfer preference.** PCF/SMF/UPF can tell application endpoints to send larger chunks followed by silent periods. The TR states this lets devices and network equipment maximize sleep modes and significantly reduce energy consumption.
- **Traffic pattern to RAN for DRX.** The UE/application may provide UL/DL periodicity and burst descriptors. The 6G UPF can pass that pattern to RAN for connected-mode DRX and scheduling and may request a QoS configuration that RAN applies or further adjusts.
- **Predicted network status.** When UPF exposes predicted bitrate or delay, the application can drop XR resolution or codec rate before packets are wasted — battery and RAN-energy savings written as a QoS function.

Adjacent key issues that complete the energy story

Energy does not live only in QoS and PCC. The same TR places complementary mechanisms in slicing, computing, IoT and data storage.

Key issue / clause	Energy-related mechanism	What it saves
KI#3 — slicing	SEP IE (low power, balanced, performance, adaptive) on NAS Registration / PDU session / UE policy. AMF, SMF and PCF may be used for slice selection and admission. Non-binding; network retains override (e.g. emergencies).	Avoid high-demand slices the UE cannot sustain; prefer energy-efficient slices for low power; fallback instead of mid-session battery drop.
KI#22 — computing	Computing Service Provider collects energy metrics. CCAF/CCCE selects EAS or computing sites using network, compute, infrastructure and energy metrics; secondary target may be minimizing energy consumption.	Place the workload where communication plus computing energy is lower, not only where latency is lowest.
KI#24 — Massive IoT	Optimized SDT for Massive IoT: low-latency, energy-efficient MO/MT transfer (RAN-led; CN buffering / RRC Inactive aligned with KI#1).	Avoid full CONNECTED-mode cost for tiny payloads — the dominant drain for massive MTC fleets.
KI#10 FWA / KI#21 DSF	FWA-CPE has less/no energy constraints, so CONNECTED–IDLE timers should not be copied from handsets. Storage energy calculation is flagged for SA5 coordination.	Do not apply handset power-saving timers to mains-powered FWA; do account for storage/collection energy.

Architectural takeaways

The TR does not invent a new "energy NF". It threads energy through existing control points — NAS, PCF, SMF/UPF, RAN, slice selection and compute coordination — and treats sustainability as an end-to-end 6G property rather than a radio sleep feature.

- **One loop, many enforcement points.** KI#5 shapes traffic so sleep is possible; KI#6 maps preference to PCC; KI#3 selects an energy-appropriate slice; KI#22 places compute; KI#24 keeps IoT payloads cheap.
- **Preference is first-class, not binding.** SEP, energy-saving indication and PCC labels are UE/user inputs. Emergency, SLA and subscription still win — the right split for a multi-vendor, operator-controlled system.

- **Device battery and network watts are coupled.** Labels such as “UE power saving” versus “support network low energy consumption” make the trade-off visible. Burstiness and DRX convert it into joules saved on both sides of the air interface.
- **Reuse before redesigning.** SEP rides existing NAS; periodicity reuses TS 23.501 AF input; collaboration-layer metadata extends Rel-19 MRI-like information. Signalling cost of energy awareness stays low — itself an energy requirement.

4.1.3 SA4 Energy efficiency activity

In the 6G media study (TR 26.870 clauses 6.3.2.1.1 / 6.3.2.1.4.2) energy is only a reason to treat better video codecs as a network-efficiency tool.

SA4’s real energy work was in 5GA and is media energy exposure which highlights the need for a well-defined, media-aware, and policy-controlled approach to expose and utilize energy consumption information, both within the 5G System and across the broader media delivery architecture: Rel-19/20 TR 26.942 [18], now turning into TS 23.367 (Energy Information AF that bridges SA2 EIF and the Media/RTC AS) and instantiations in TS 26.501 / 26.506.

4.1.4 SA5 energy efficiency activity

SA5 study on 6G [19] includes focus on energy saving and energy efficiency. The study builds on the use cases already supported in 5G and extends the use cases for 6G. The key issue use cases being studied are the following:

Centralized energy saving scenario – configuring the Network Elements and/or Network Functions (e.g., Cell, Core NF etc) to enter or exit energy saving state directly (e.g., by modifying the energy saving state of the Network Element or Network Function) based on other configured control parameters (e.g., traffic load thresholds).

Distributed energy saving scenario – configuring the Network Element or Network Function (e.g., NG-RAN Node) with load thresholds, ES policy, etc, to be utilized by Distributed energy saving functionality within the Network Element to achieve energy saving.

Energy Saving and Energy Efficiency optimization scenario - improving energy savings across multiple Network Elements and Network Functions (e.g., RAN nodes, cells, Core Network Functions etc), and which can be used to support optimizing the configuration used in the Centralized energy saving scenario and Distributed energy saving scenario (e.g., by collecting and analyzing the performance of the Network Elements and/or Network Functions such as traffic loads, identifying a group of cells with coverage overlaps for energy saving, and identifying the sequence in which these Network Elements or Network Function should enter or exit energy saving state etc).

Agent-driven Energy Saving Optimization scenario: bridging high-level reasoning with low-level network parameter modification and investigating how agents autonomously decide to utilize corresponding network services to modify ES parameters based on e.g., traffic load performance measurements.

In 6G the study includes defining an architectural framework for energy efficiency management to support and extend the use cases for energy saving and energy efficiency management and optimization (including reduction of carbon equivalent emissions).

4.1.5 RAN 6G energy efficiency

6G RAN has made energy a first-class design requirement, but it is still in study. RAN plenary froze the requirement as per clause 5.1.15 in [20]: 6GR must be energy-efficient at zero and

low load, for both network and device, with saving features that do not break user experience, and with a RAN architecture that consumes less energy than today's networks (clause 5.2). SA1 is converting that into 6G service requirements in its TS in clause 5.1.5 [16]; joint NW+UE efficiency is better than 5G, user preference, slice energy credits, and energy-aware sensing/AI/computing.

On the radio, RAN1 is building DL wake-up signalling plus "EE processing" so the UE can monitor and measure while staying in deep sleep, with a dedicated evaluation framework clauses 6.1, 9.5, A.6 of [21]. RAN2 is trying to collapse 5G's many DRX/WUS/DCP options into one discontinuous-monitoring framework and to specify network sleep / CELL DTX-DRX clause 14.2 and annex A.2.3.3 of [22]. Specify solutions focusing on reducing always-on network transmissions, including cell DTX/DRX, clustering of common signals, PRACH and paging adaptation. RAN3 is treating area-wide AI/ML cell on/off as a 6G NES use case in clause 7.2.1.1 of [23]. Nothing here is a finished 6G RAN energy specification yet; the study item FS_6G_Radio is about halfway done.

4.2 O-RAN

4.2.1 Energy Savings and sustainability in O-RAN

Sustainability Focus Group (SuFG) of O-RAN monitors, tracks and supports continuously all ORAN activities in the domain of sustainability (including energy efficiency) by working closely with the ORAN WGs (e.g., establishing joint meetings per WG with volunteer peers and jointly providing some outputs such as "Technical Status Report" and "Survey on prioritized list of operator requirements"). It provided so far a set of white papers, TRs and recommendations to O-RAN WGs. SuFG includes the four following task groups (TGs):

TG1(Accelerate software energy optimization) TG2(Specification of energy measurements) TG3(Improve Hardware Energy Efficiency) TG4(Circularity on network equipment)

4.2.2 O-Cloud Energy Savings and sustainability in O-RAN

Energy management of Open RAN (O-RAN) is considered as an important sustainability goal. It requires a standardized approach not only for reducing energy consumption, but also for analysing, measuring, and monitoring energy consumption of O-RAN Cloud deployments. WG6 of O-RAN works on O-Cloud and there is a dedicated sub-team for energy saving and sustainability of O-RAN O-cloud. Several energy techniques and use cases that can be utilized within the O-Cloud for improving energy consumption and sustainability in O-RAN Cloud have been introduced in O-RAN WG6 ES TR [24].

O-Cloud Node Shutdown in Idle Mode use case presents an approach to perform O-Cloud Energy Saving by shutting down O-Cloud Node(s) in idle times through Non-RT RIC provided guidance. Where an O-Cloud Node as defined in O-RAN.WG6.CADS is the basic computational resource designator and can be commonly considered as a server.

To save energy, another Use Case considers CPU core frequency and pinning changes for O-Cloud platform based on energy saving policy which is generated by non-RT RIC or Cloud Operator (especially for the CPU allocated to VNF/CNF in idle or low CPU utilization/load to save energy). In other words, if the service performance or the number of UEs are low, also CPU utilization or load of VNF/CNF is low, the CPU frequency mode given to dedicated VNF/CNF can be modified for the goal of energy saving, or several CPU cores for dedicated VNF/CNF can be released.

Another use case presents concept of Mode (e.g., energy saving or Eco mode) and aims to select a specific Mode, for instance, Eco Mode, to achieve energy savings on an O-Cloud Node Cluster. It presents the processing of a request to select a specific Mode for energy saving.

In addition to use cases for energy savings of O-Cloud in O-RAN, a set of measurements and KPIs related to energy consumption and energy efficiency are presented. Several power consumption measurements at the O-Cloud Resource level have been introduced in O-RAN WG6 ES TR. In addition, several energy consumption measurements at the O-Cloud node resource level have been presented in the same document. Power, energy consumption metrics of containers, Cloudified NF and NF deployment have been also discussed in O-RAN WG6 and mentioned in O-RAN WG6 ES TR [24].

5 Energy- and Carbon-aware algorithms for 6G

In 6G, it is possible that several algorithms will be adapted to optimize for energy. This is an inherent optimization at all layers of the software as against an energy saving mechanism that operates in an “outer loop”, such as for RAN sites.

Referring to mobile phone technologies, battery-capacity constraints has given power-consumption-optimization paramount importance in cell phones, laptops, and certainly, IoT devices. For example, a smartphone’s modem is clocked at lower frequencies or switched off, when the phone is in idle mode or in flight-mode. Network infrastructure cannot follow the same procedure because they need to be available all the time, unless deliberately turned off. Instead, it is envisaged that several network functions will include the energy consumption as a parameter in their algorithms. Typical RAN functions may may use traditional ML rather than LLM-based implementations. Some functions are, which are covered by the standardization activities describe in Section 4 and can use a decision matrix such as the one given in Table 10.

- Cell Sleep
- Dynamic cell switch-off
- Deep sleep
- Symbol shutdown
- Beam Optimization
- AI beam prediction
- Reduced retransmissions
- Traffic Steering
- Carbon-aware load balancing
- Coverage Adaptation
- Energy-aware mobility

Table 10: Carbon Optimization Decision Matrix

Action	Energy Impact	Carbon Impact	Complexity
Sleep modes	Medium	Medium	Low
Workload shifting	Low	High	Medium
Storage optimization	Medium	High	Medium
Renewable matching	Low	Very High	Medium
Hardware refresh	High	Mixed	High

Some future AI-driven examples are given in Section 5.1. It is also possible that, as a next step, the outer loop is enhanced to use carbon-aware approaches, again using AI, such as envisioned in Section 5.2.

5.1 AI-Driven Energy-Efficient Security and QoS Management for 6G

5.1.1 Joint Energy-Security-QoS Optimization

IMT-2030 treats sustainability, security and resilience, and ubiquitous intelligence as core 6G principles [26]. Because authentication, key establishment, encryption, signatures, monitoring, AI/ML and quantum-safe security consume processing, memory, signalling and energy, 6G energy management should optimize energy, security, QoS and reliability together, extending earlier Bharat 6G Alliance work on energy-efficient operation [27].

The network can minimize energy and security overhead subject to application-specific security, latency, throughput and reliability constraints. AI/ML can adapt the operating point as conditions change, consistent with 3GPP Release 20 studies on energy efficiency and AI/ML management [28][29]. The aim is not weaker security; instead, it is to enable minimum total resource consumption subject to non-negotiable security and service constraints.

Referring to Figure 10, the AI/ML orchestrator monitors channel, traffic/QoS, security, device and energy states, then selects energy-aware cryptography, adaptive security, or quantum-safe mechanisms. Feedback enables continuous re-optimization across energy, QoS, security and reliability.

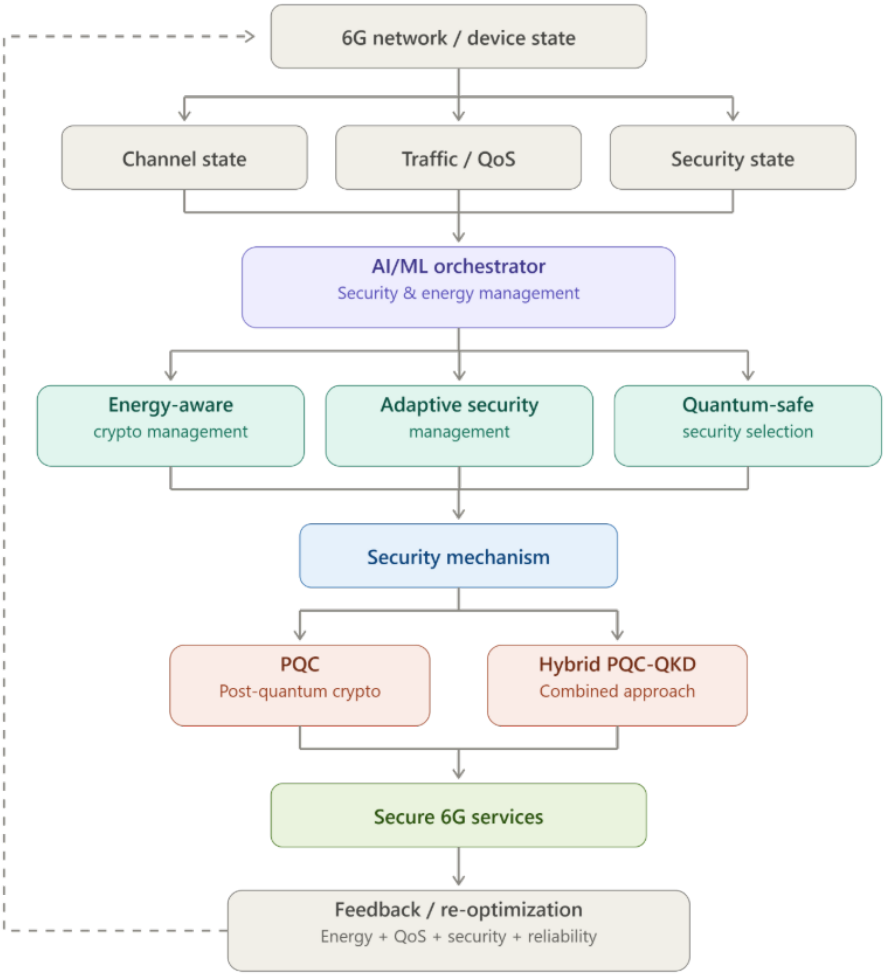

Figure 10: Conceptual architecture for AI-driven energy-efficient security management in 6G networks

5.1.2 AI/ML-Based Adaptive Security Management

Heterogeneous devices and services should not use one fixed security configuration. An AI/ML controller can select mechanisms using traffic, channel, application criticality, threat level, device capability, available energy, compute, latency and congestion while maintaining required security and QoS.

- RL/DRL can model changing security and resource decisions as a sequential process with outcome-based feedback.
- Federated or distributed learning can move intelligence closer to devices and edges, but its computation, communication and model-management cost must be included [26].
- AI-based control is sustainable only when optimization gains exceed the intelligence layer's own overhead; higher threats may trigger stronger controls, while constrained devices may use compliant lower-overhead options.

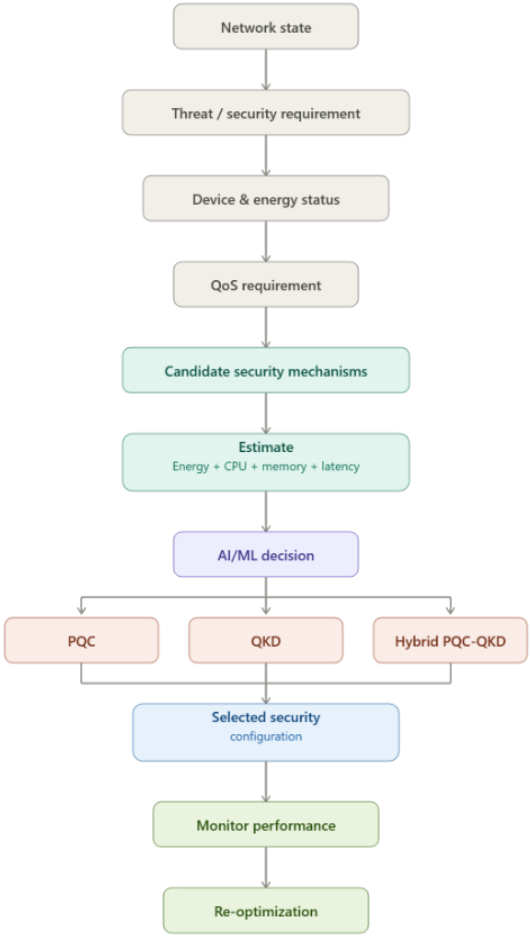

Figure 11: AI-assisted adaptive security decision process

Figure 11 presents the proposed adaptive decision process, in which network state, threat level, security requirements, device capabilities, energy availability, and QoS requirements are jointly considered before selecting a security mechanism. The selected configuration is continuously monitored, and the decision is re-evaluated when network conditions, threat levels, or resource availability change.

5.1.3 Energy-Aware Cryptographic Management

Cryptographic operations add processing, memory, communication and signalling cost, especially at scale. Energy-aware management should choose or configure mechanisms by security level, application criticality, device capability, energy, latency and network conditions, without weakening required protection.

Candidate mechanisms can be compared by processing latency, memory, communication overhead and estimated energy. Processing may be distributed across device, edge and network resources. This security-resource-aware approach also supports cryptographic agility as requirements and capabilities evolve. IEEE work demonstrates direct PQC energy measurement on constrained IoT nodes and links results to battery life [30].

5.1.4 Energy-Efficient Post-Quantum Security for 6G

Long-lived 6G systems must consider quantum-enabled threats. NIST standardized ML-KEM (FIPS 203), ML-DSA (FIPS 204) and SLH-DSA (FIPS 205) [31]-[33] ML-KEM-512, -768 and -1024, are positioned in order of security strength vs performance[31].

PQC selection should account for security strength, computation, memory, latency, communication and energy across constrained devices, edge nodes and infrastructure. Suitable implementations may use hardware/software co-design, acceleration or edge assistance. Evaluation should report latency, CPU, memory, throughput and energy per operation or secured bit under defined security levels and workloads [30].

5.1.5 AI-Assisted Hybrid PQC-QKD Security

PQC offers software-based quantum-safe protection over conventional infrastructure, while QKD distributes quantum-generated keys where quantum links exist. ETSI TS 104 146 defines authenticated hybrid key establishment and QKD-integration requirements [34].

An AI-assisted orchestrator can choose PQC, QKD-assisted or hybrid operation using application criticality, QKD key availability, QBER, secret-key rate, link conditions, latency, traffic, compute and energy. Hybrid operation can serve stringent applications where QKD is available; PQC remains the quantum-safe option elsewhere. AI coordinates, rather than replaces, the underlying mechanisms, consistent with IMT-2030 integration of communication, computing, AI and security [26].

5.1.6 Sustainability Metrics and Standardization Considerations

Security sustainability requires measurable indicators that quantify the resource cost of a defined security level. Measurements should cover the complete security path under specified workloads, device configurations and network conditions; shifting computation to communication or edge processing may not reduce total energy.

Table 11: Sustainability Metrics and Standardization Considerations

Metric	Purpose
Energy per secured bit/transaction	Energy required per protected communication unit
Energy per cryptographic operation	Comparison of cryptographic implementations
Security processing latency	Security impact on QoS
CPU utilization	Computational overhead
Memory consumption	Suitability for constrained devices
Communication/signalling overhead	Network-level security overhead
Security-energy trade-off	Security level versus energy requirement

Metric	Purpose
Security-QoS trade-off	Security processing versus service performance

These are proposed evaluation indicators, not existing standardized 6G KPIs. They can complement 3GPP TR 23.700-67 on energy efficiency and energy saving and TR 28.882 on AI/ML management [28][29]. ITU-T SG17 is also studying IMT-2030 security with liaison to ITU-T SG13, ITU-R WP5D and 3GPP SA3 [35].

- Include security-related computation and communication overhead in energy studies.
- Define common energy-measurement methods for cryptographic and quantum-safe functions.
- Account for device energy and resources when evaluating PQC.
- Evaluate AI/ML orchestration together with the energy cost of AI/ML itself.
- Standardize security-energy-QoS trade-off metrics.
- Investigate adaptive PQC-QKD coordination.

The overall objective is to move from energy-efficient networking to energy-efficient secure networking within the 6G sustainability framework.

5.2 Carbon Intelligence for Sustainable AI-Native 6G Infrastructure

6G combines communication, sensing, computing, and embedded AI across the RAN, transport, edge, and core. These capabilities can improve network efficiency, but densification, massive MIMO, edge infrastructure, and AI training/inference also increase operational and embodied carbon. The resulting challenge is to use AI not only for performance, but also for continuous carbon-aware control [26],[36]-[38].

Energy efficiency alone is incomplete because it is carbon-blind, workload-blind, and scope-blind. Equal energy consumption can have different emissions depending on grid intensity; AI workloads can shift across time and location; and joules-per-bit metrics often omit hardware lifecycle emissions. Carbon intelligence therefore adds temporal foresight, geographic choice, and system-level accounting without replacing energy efficiency.

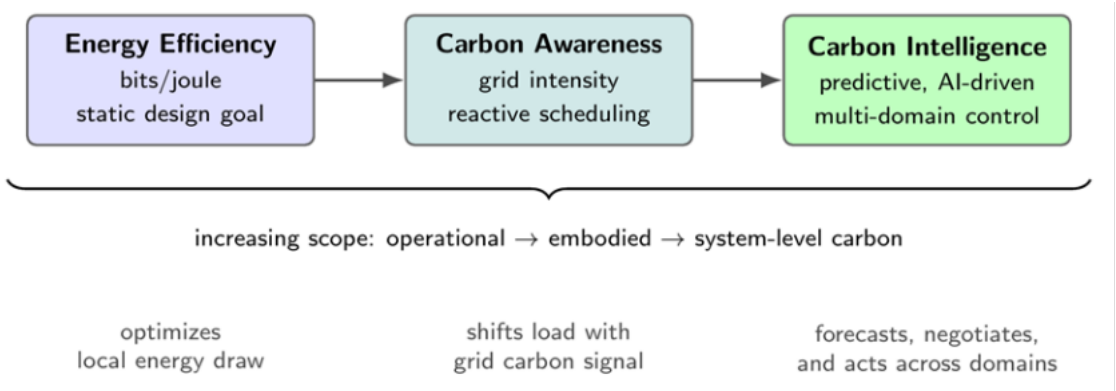

Figure 12: Evolution from energy efficiency to carbon intelligence. Each layer subsumes rather than replaces the previous one, with increasing temporal foresight, spatial scope, and carbon accounting scope (operational to embodied).

5.2.1 Carbon as an Operational Parameter

Carbon intensity, expressed as instantaneous and forecast gCO2eq/kWh, should be exposed to the AI-native control plane alongside throughput, latency, energy, queue state, and channel

information. This enables RIC and orchestration functions to optimize performance and carbon together, rather than calculating emissions only after operation.

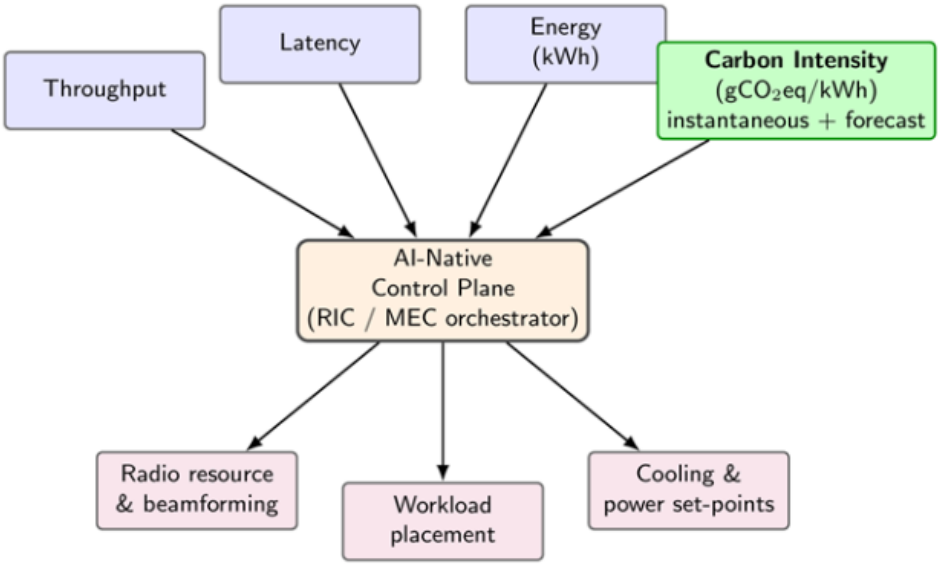

Figure 13: Carbon intensity treated as a first-class input to the AI-native control plane, alongside throughput, latency, and energy, driving joint actuation of radio, compute placement, and cooling.

5.2.2 Methodology

The framework uses a conceptual system-architecture method. It defines functions, interfaces, telemetry, and control flows, then uses representative published values to illustrate relative outcomes. Quantitative validation is reserved for operator-scale traces, carbon-intensity time series, simulations, and controlled testbeds.

Typical interfaces required for AI controlled carbon management are as follows.

- Energy telemetry interface
- Grid-carbon signal interface
- Renewable-availability forecast
- workload-flexibility descriptor
- SLA and resilience constraint interface
- decision/audit log, measurement and verification interface.

5.2.2.1 AI-Driven Carbon-Aware Control

- **Sense:** Collect network KPIs, equipment states, grid carbon signals, renewable forecasts, and environmental telemetry.
- **Model:** Forecast traffic and grid intensity, and use digital-twin models to estimate the energy and carbon impact of candidate configurations.
- **Decide:** Select actions through constrained reinforcement learning, model-predictive control, or rule-based fallback, while enforcing coverage, reliability, latency, throughput, and emergency-service requirements.
- **Actuate:** Apply decisions through RIC xApps/rApps, MEC or cloud orchestrators, and cooling or power-management systems.

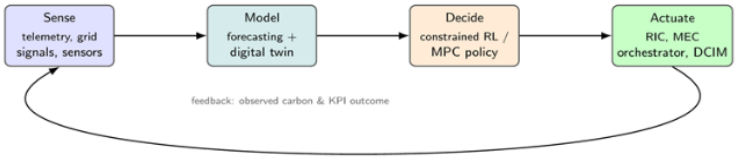

Figure 14: Sense-model-decide-actuate loop for AI-driven carbon-aware decision making in AI-native 6G infrastructure.

Control is hierarchical: fast loops manage beamforming and sleep modes using local telemetry, while slower loops manage workload placement and cooling using forecast carbon signals, consistent with near-real-time and non-real-time RIC structures [36].

5.2.3 System-Level Carbon Management

Local optimization can shift emissions rather than reduce them. For example, offloading inference may lower RAN energy while increasing transport energy or using a higher-carbon destination grid. Carbon management must therefore coordinate five coupled domains: radio access, transport, edge, core/cloud, and physical infrastructure.

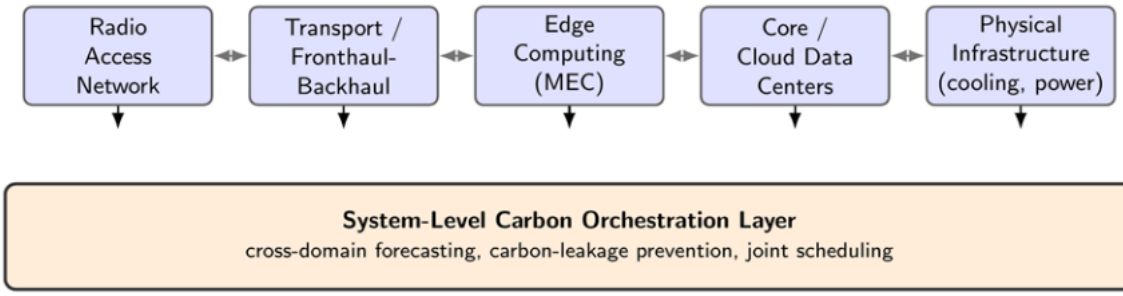

Figure 15: Carbon management as a system-level problem: five coupled infrastructure domains report telemetry to a shared carbon-orchestration layer, which prevents carbon from being displaced ("leaked") from one domain to another.

5.2.4 From Measurement to Management

Retrospective inventories support reporting but too coarse for operational control. Carbon intelligence requires a four-stage maturity pipeline:

- Monitor: fine-grained energy and carbon telemetry per network function.
- Attribute: emissions by service, slice, and tenant.
- Forecast: short-horizon grid intensity and network demand.
- Actuate and verify: automated actions followed by confirmation of realized reductions and model feedback.

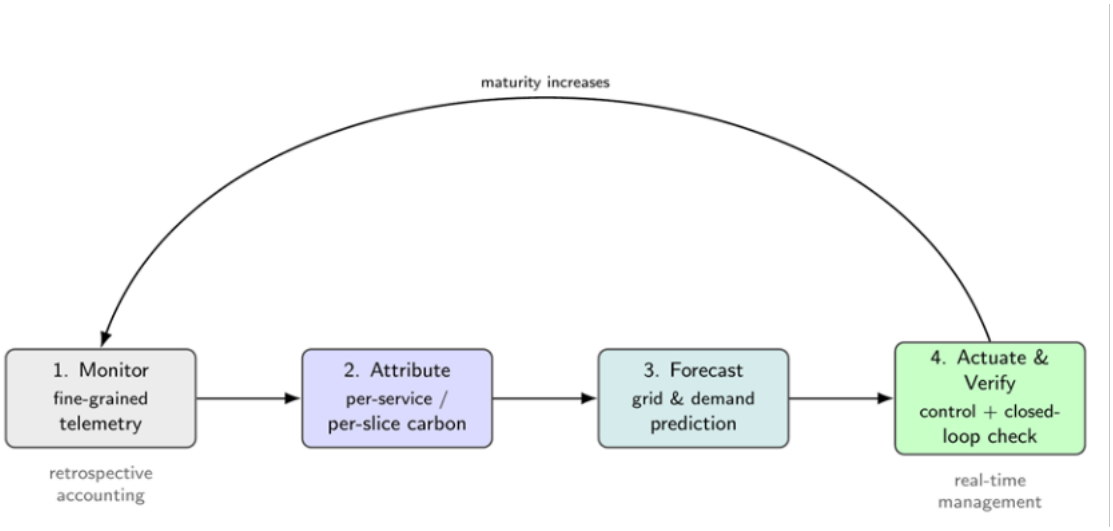

Figure 16: Maturity pipeline from carbon measurement to carbon management: monitor, attribute, forecast, actuate and verify.

5.2.5 Illustrative Results and Extensions

The scenario compares three strategies over a representative 24-hour period: energy-only control, carbon-aware time-shifting, and carbon-intelligent joint control of radio sleep modes, edge/core placement, and cooling. Results are illustrative and normalized to an energy-only baseline of 100; they show relative ordering, not deployment guarantees.

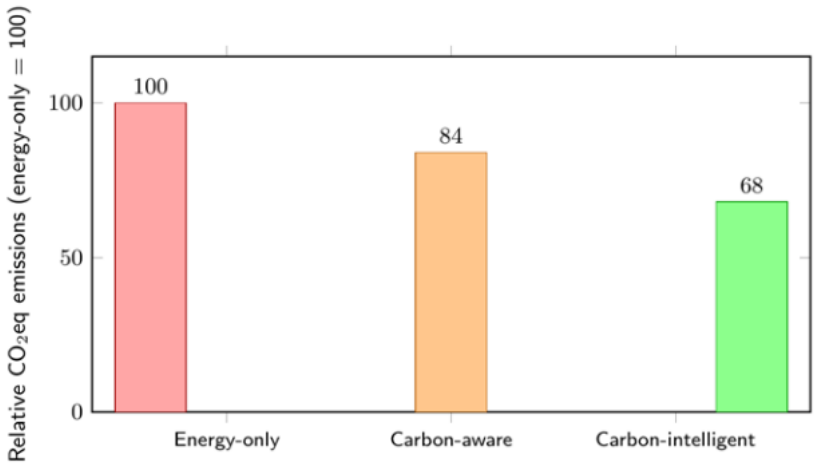

Figure 17: Illustrative relative CO_2eq emissions for three operating strategies over a representative 24-hour period, normalized to the energy-only baseline (100). Values are indicative, derived from representative published carbon-intensity variability and shiftable-workload fractions, and are intended to show relative ordering rather than absolute magnitude.

The illustrative ordering in Figure 17 is consistent with the underlying mechanism: carbon-aware time-shifting alone captures a meaningful share of the available benefit by exploiting temporal variation in grid carbon intensity, while carbon-intelligent joint control captures additional benefit by also exploiting spatial variation (routing shiftable workload to lower-carbon regions) and by coordinating cooling and radio sleep-mode scheduling with workload placement rather than optimizing each domain independently.

5.2.5.1 Environmental Intelligence Beyond Carbon

A sustainable 6G control plane should also consider water, land and biodiversity, materials and e-waste, and local air quality or noise. These parameters can share the same telemetry, modelling, optimization, and policy-generation infrastructure used for carbon management.

Table 12: Environmental parameters beyond carbon: representative sources and primary control uses

Parameter	Representative source	Primary control use
Carbon intensity	Grid operator or carbon API	Workload timing and placement
Water use	Cooling flow meters; water-stress indices	Cooling set-points
Land / biodiversity	Siting databases; protected-area registries	Site selection; renewable co-location
Material / e-waste	Lifecycle and procurement records	Hardware refresh scheduling
Air quality / noise	Environmental sensors; generator logs	Backup-power policy

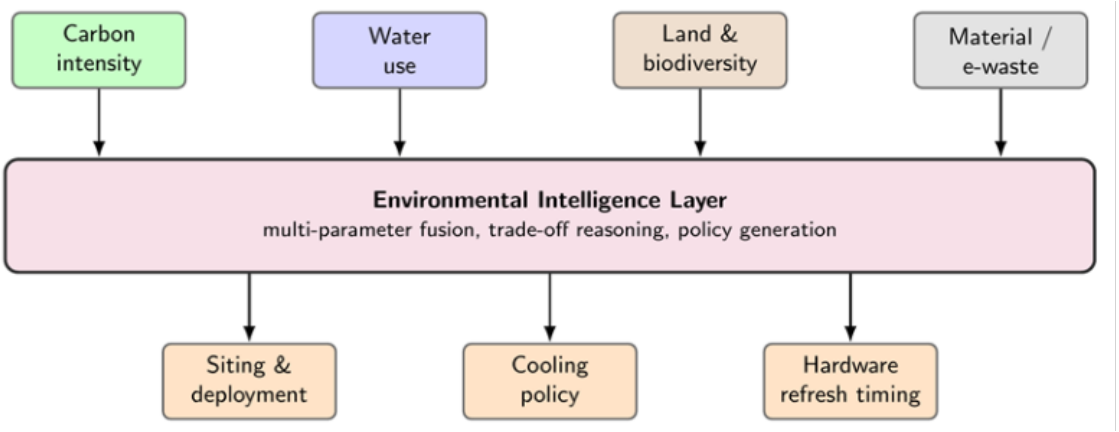

Figure 18: Environmental intelligence extends the carbon-intelligence loop to water, land/biodiversity, and material footprints, producing siting, cooling, and hardware-refresh policies alongside carbon-driven radio and compute decisions.

5.2.6 AI-Controlled Biological Carbon Management

A speculative extension couples digital infrastructure with co-located biological sinks. Potential approaches include algal photobioreactors using waste heat and backup-generator CO2, biochar production from biomass supported by waste heat, and AI-scheduled irrigation or soil monitoring for green roofs and wetlands. The controller can regulate light, nutrients, irrigation, and harvesting using the same sense-model-decide-actuate pattern.

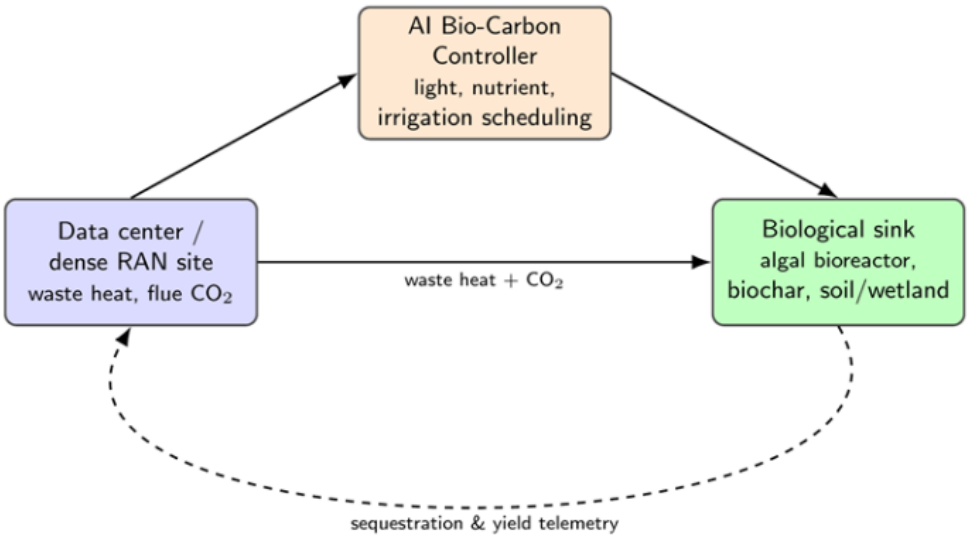

Figure 19: AI-controlled biological carbon management: waste heat and flue CO_2 from digital infrastructure feed a co-located biological sink, with an AI controller closing the loop using the same sense-model-decide-actuate pattern used for radio and compute carbon management.

5.2.7 Roadmap

- **Standardized carbon interfaces:** Expose telemetry and forecasts to xApps, rApps, and orchestrators using interoperable interfaces aligned with network and sustainability standards [36]-[38]. (Section 5.2.2.)
- **Cross-domain data sharing:** Establish common attribution and exchange mechanisms across operators, infrastructure partners, and cloud providers to prevent carbon leakage.
- **Regulatory and market alignment:** Improve the availability and granularity of grid signals and connect flexible network workloads with demand-response mechanisms.
- **Verification and trust:** Use auditable, tamper-resistant logs to support compliance and customer-facing claims.

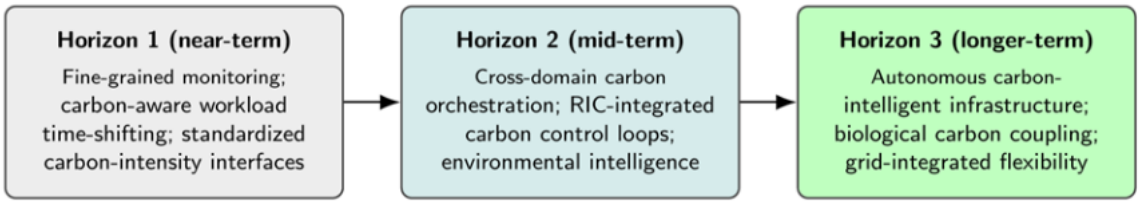

Figure 20: Three-horizon roadmap towards carbon-aware AI-native 6G infrastructure.

5.2.8 Recommendations

Although the framework is architectural and conceptual, and the scenarios are illustrative rather than empirically validated, and biological approaches require site-specific lifecycle assessment, the initial recommendation remains consistent with those in Section 3.8.1: The Net sustainability Impact (NSI) = Sustainability Benefit from AI - AI footprint on energy and space. Alternatively, a Sustainability benefit Ratio (SBR) of AI Sustainability Benefit to the Sustainability Cost can be used. Only AI functions with SBR > 1 should be considered sustainable.

6 Net Zero future: Transition to Green Energy

6.1 The Target Architecture

6.1.1 A design hierarchy for sustainable tower power

Green Energy Open Access, on-site solar, advanced batteries and hydrogen fuel cells are not competing answers. They address different time scales of the same energy problem. Figure 21 shows the sequence in which they are applied; the ordering matters more than the individual technology choice, because supply-side assets deployed before demand-side reduction are permanently oversized. Lean radio design, deep sleep modes, reduced always-on signalling, high-efficiency rectifiers, free cooling and AI-based source scheduling must therefore be exhausted before any supply asset is added [78], [79].

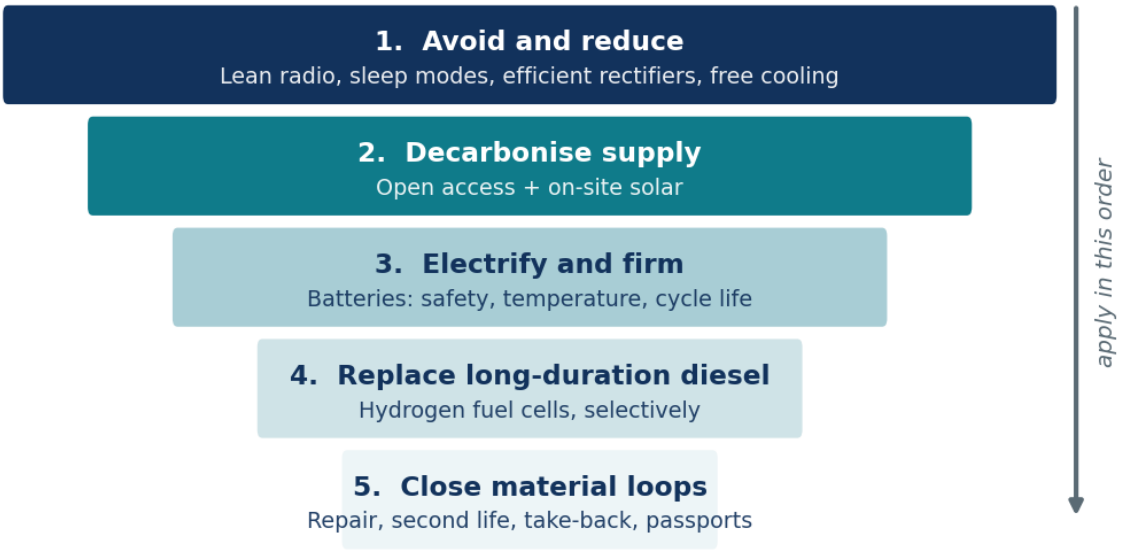

Figure 21: Design hierarchy for tower power. Interventions applied out of sequence permanently oversize the assets above them. Analysis by the authors.

6.1.2 The DC power plane as the integration backbone

The −48 V DC bus and the switched-mode power system form the integration backbone of the site (Figure 22). Grid supply, solar, batteries and fuel cells should converge through efficient, monitored conversion stages rather than through isolated parallel systems. DC-coupled paths remove avoidable conversion steps: a fuel cell produces unregulated DC and integrates through a DC–DC converter straight onto the existing bus, deleting the AC rectifier stage that a diesel genset requires and recovering conversion loss that comparisons based on AC generation understate [44]. Modular rectifiers let capacity track tenancy and radio growth rather than being sized once for a hypothetical end state.

The power controller becomes the enforcement point for the entire architecture: source priority, state-of-charge limits, black-start logic, fault isolation and carbon-aware scheduling all resolve there. Priority logic in the target design runs solar, then grid, then battery, and then fuel cell, with the battery always present to absorb transients.

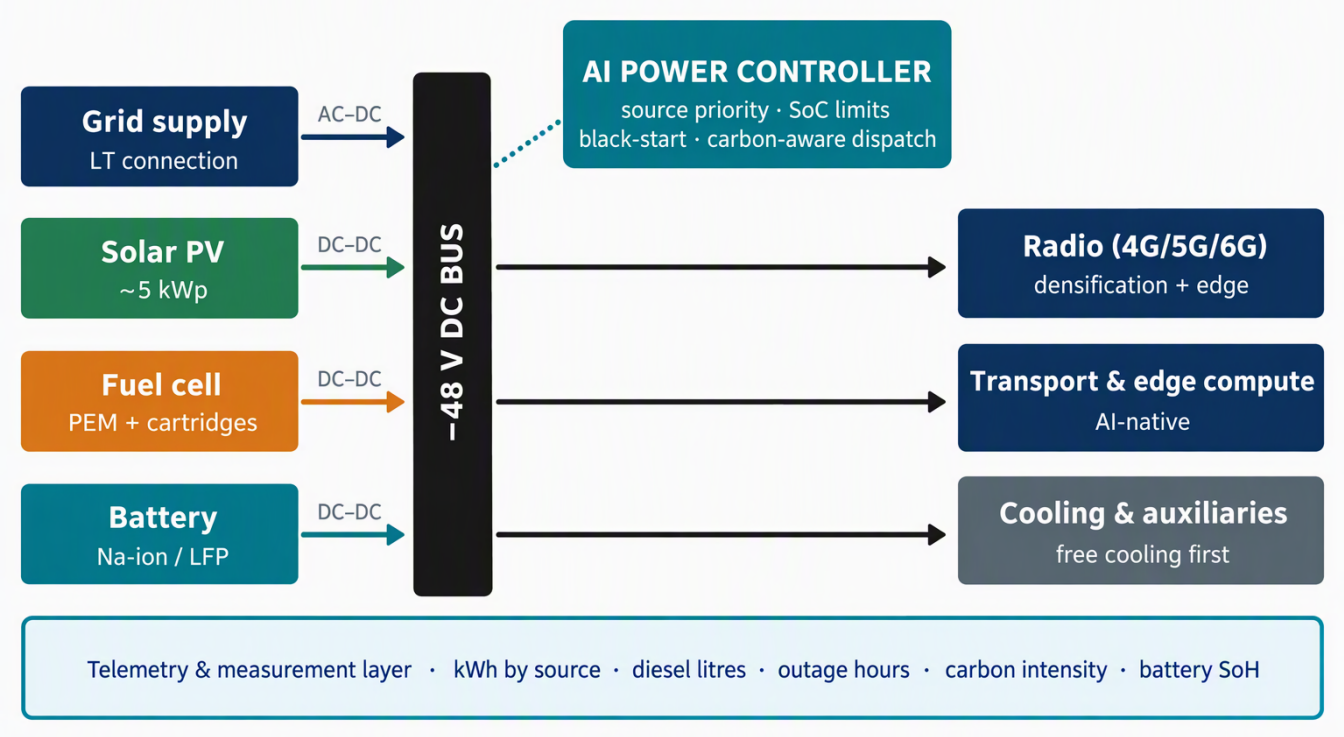

Figure 22: Reference architecture for the 6G-ready tower power plane. Analysis by the authors.

6.1.3 On-site solar: valuable, but physically bounded

Solar PV at the tower directly reduces imported electricity and reduces diesel runtime during daylight outages. Its contribution is constrained by compound area, rooftop rights, shading from the tower and equipment sheds, structural loading, vandalism risk, soiling and the mismatch between daytime output and a 24-hour load. Typical installations are of the order of 5 kWp and commonly address five to twenty per cent of site consumption across diverse load portfolios of telecom sites.

Hybrid-system research for Indian towers supports combining solar, grid, storage and backup rather than treating any single source as sufficient: solar photovoltaics combined with grid electricity and diesel generators in hybrid mode delivered significant emission reductions in modelled Indian tower configurations [45]. The correct architecture is therefore complementary rather than substitutive.

6.2 Green Energy Open Access: The Portfolio-Scale Electricity Lever

6.2.1 The statutory and regulatory architecture

Open access is defined in the Electricity Act, 2003 as the non-discriminatory provision for the use of transmission lines or the distribution system by any licensee, consumer or generator, in accordance with regulations specified by the Appropriate Commission. Section 42(2) requires State Commissions to introduce open access in the distribution system and to specify conditions and surcharges; Section 86 assigns to them the regulation of intra-state wheeling and the promotion of renewable sources. The design of access therefore sits with regulators, not with government — a point of considerable practical consequence [47].

On 6 June 2022 the Ministry of Power notified the Electricity Rules, 2022 [48]. Four changes mattered most: the eligibility threshold was reduced from 1 MW of contracted demand to 100

kW, with no minimum for captive consumers; applications were routed through a single national portal, with Grid Controller of India designated Central Nodal Agency and an approval process to be completed in approximately fifteen working days with deemed approval on delay; the leviable charges were standardised as transmission, wheeling, cross-subsidy surcharge and standby charges; and consumers were given an entitlement to demand green power from distribution licensees [50], [48], [51].

The Second Amendment Rules of 23 May 2023 made the change that matters most to telecommunications. The definition of an 'entity' was revised so that the 100 kW threshold may be met through a single connection or through multiple connections aggregating 100 kW or more located in the same electricity division of a distribution licensee [49], [52].

6.2.2 The aggregation arithmetic, and what still blocks it

For a portfolio of sites with individual sanctioned loads of eight to ten kilowatts, as few as ten to thirteen sites within one electricity division constitute an eligible open access entity. That arithmetic is why the mechanism is transformative rather than marginal. A tower company does not need to concentrate load; it needs only to map its existing connections to distribution divisions and cluster them. In a dense urban circle, a single division may contain several hundred sites, representing two to five megawatts of aggregated load — enough to support a dedicated intra-state renewable plant. In sparse rural divisions the cluster may sit just above the threshold, which is precisely the case the amendment was drafted to enable.

6.2.3 Anatomy of the landed cost

The landed cost of open access power is the power purchase agreement tariff plus a stack of regulated charges. Because these charges are set by State Commissions and revised through annual tariff orders, they — not the generation tariff — are the dominant source of commercial uncertainty for a multi-state telecom portfolio.

Table 13: The open access charge stack. Compiled from [48], [53], [47].

Charge head	Basis	Position under the GEOA framework
Cross-subsidy surcharge	Compensates the licensee for loss of cross-subsidising revenue when a consumer migrates.	The GEOA Rules cap escalation at 50 per cent of the surcharge applicable at grant, for twelve years. Adoption across states is uneven.
Additional surcharge	Compensates for stranded fixed cost of tied-up generation capacity.	Waived where the consumer maintains contracted demand and pays fixed charges; to be phased out within four years of open access approval.
Wheeling and transmission	Use of the distribution and transmission networks.	Determined by the State Commission. Intra-state sourcing avoids inter-state transmission charges entirely.
Banking charges	Compensates the licensee for storing surplus injection for later drawal.	Monthly banking period under the Rules; the Forum of Regulators model recommends 8 per cent in kind of energy banked. State practice varies materially [53].
Standby charges	Compensates for capacity kept available when the open access source fails.	Capped at 10 per cent of energy charges for the consumer category under the Rules; several states operate multi-tier frameworks.

6.2.4 The load-shape problem: a tower draws power all night

A telecom tower is an unusually attractive offtaker from a generator's perspective. The load is close to flat across the day, has a very high load factor, exhibits almost no seasonality relative

to industrial process loads, is highly creditworthy when contracted at the tower-company level, and is growing. What it is not is coincident with solar generation.

This creates a structural dependence on banking, and banking is the provision with the widest state-to-state variation. Most State Commissions specify a monthly banking period, but some states specify a period of a quarter or year.

For a twenty-four-hour load, banking rules are the business case

A state that prohibits peak-slot drawal of banked energy converts a solar power purchase agreement from a 24-hour supply into a daylight-hours supply, roughly halving the addressable volume. Three design responses follow: introduce permissive banking; structure wind–solar hybrid rather than solar-only portfolios to broaden the generation window; and plan for battery energy storage co-location from the outset, since storage-firmed round-the-clock supply removes dependence on a banking regime whose charges are widely expected to move toward cost-reflectivity.

6.2.5 Why open access outperforms on-site solar for this load class

Table 14: On-site solar compared with green open access for distributed telecom loads. Analysis by the authors, drawing on [45], [47].

Dimension	On-site solar at the tower	Green energy open access
Capacity achievable	Typically, around 5 kWp, constrained by compound area, shadowing and structural loading.	Unconstrained at the site; sized against the aggregated load of the cluster and located where the resource is best.
Share of consumption addressable	Commonly 5–20 per cent, Replaces Grid + Diesel basis the availability during solar hours.	Up to the green-attributable share permitted by state regulation and the banking framework; directly displaces grid energy.
Capacity utilisation factor	Low; unoptimized tilt, orientation and soiling regimes at large numbers of uncontrolled sites.	High; utility-grade site selection, tracking and operations and maintenance.
Cost per unit generated	High, because of distributed installation, small-lot procurement and per-site O&M mobilisation.	Low, because of utility-scale procurement economics and a single O&M contract.
Balance-sheet impact	Capital expenditure on the tower operator, at every site.	Can be off-balance-sheet under a third-party PPA, or partially on-balance-sheet under group captive to avoid surcharges.
Scope 2 accounting	Reduces purchased electricity; strong but small in absolute terms.	Contracted renewable electricity enters market-based Scope 2 accounting at a zero-emission factor for the physical volume consumed.

6.2.6 Bridging the adoption gap

Between June 2022 and September 2026, the legal right to aggregate distributed telecom load into an eligible open access entity was created, confirmed by amendment, and replicated into state regulations — twenty-seven states had notified GEOA regulations as of April 2025, with one in draft [47]. Adoption by the telecom sector nevertheless remains far below the sector's share of eligible load. Six process changes suggested below can bridge the gap.

1. Disaggregated applications and fees. The aggregation right is defined at the level of the entity, but the application process is operated at the level of the connection. A cluster of thirteen sites reaching 100 kW may require thirteen applications, thirteen fees, thirteen no-objection certificates and thirteen wheeling agreements. Formats suited to telecom tower usage can be introduced; available formats are suited to high-tension industrial consumers.

2. Undefined or unstable low-tension charges. Open access charge schedules were historically constructed for consumers at 11 kV and above. States need to publish a low-tension schedule to price the transaction. Where it has, annual tariff orders can reprice a twenty-five-year power purchase agreement every twelve months.
3. Duplicate metering — now substantially resolved. The Central Electricity Authority notified the Central Electricity Authority (Installation and Operation of Meters) Amendment Regulations, 2026 on 1 April 2026, providing that smart meters of the relevant Indian Standard with an accuracy class of 1.0/0.5S [54]. The residual task is state adoption and approved-vendor notification.
4. Billing systems built around the connection. Distribution licensee billing systems treat the connection as the unit of account. An aggregated entity requires composite billing across connections, with green-attributable energy netted against each connection's consumption and the residual billed at retail tariff.
5. Division-level settlement. Where green energy settlement is performed at division level, a national estate must reconcile against dozens of division-level pools with independent timelines and dispute processes. Settlement pooling at state level, with division-level allocation performed downstream as an accounting step, resolves this without altering any substantive entitlement.
6. Day-ahead scheduling at fifteen-minute granularity per connection. A thousand-site portfolio generates 96,000 schedule values per day for a load that is among the most predictable in the system. One of the state's regulations already extend the option of smart meters to consumers below 11 kV on mixed feeders who opt for exemption from the deviation settlement mechanism — this is a precedent for proportionate treatment [47].

6.2.7 Market concentration and deployment sequencing

Deployment of open access renewables has concentrated sharply. Cumulative installed solar open access capacity stood at 32.9 GW as of March 2026 and approximately 36 GW by June 2026, with the top five states accounting for most of the cumulative installed capacity and of recent additions [56], [57]. For a telecom portfolio, three groupings emerge. States combining charge certainty with workable banking are natural first-wave clusters, because the business case survives without storage. States with deep markets but restrictive banking or volatile charges are second-wave and should be approached through group captive or storage-firmed structures. States that have recently notified or amended warrant early engagement because detailed procedures, formats and metering specifications are being written at that moment [55], [58].

6.3 Storage: Chemistry Selection for the Tower Duty Cycle

6.3.1 The battery as resilience asset and material bank

The battery bank performs transient support, outage ride-through, peak shaving, and renewable firming. The progression from valve-regulated lead-acid to lithium-ion and, prospectively, sodium-ion should be treated as a portfolio segmentation decision rather than a single technology migration. Telecom duty is stationary: mass and volume are secondary, while thermal safety, temperature tolerance, cycle life, and supply security are primary.

6.3.2 Why sodium-ion is relevant to towers specifically

A sodium-ion cell shares the four-component architecture of a lithium-ion cell and operates on the same intercalation principle, with Na^+ substituting for Li^+ as the mobile charge carrier [59], [60]. The single most consequential architectural difference is that sodium does not alloy with aluminum at low potentials, so aluminum foil can serve as the current collector at both electrodes; lithium-ion cells require copper at the anode, and copper is roughly three times denser and considerably more expensive and energy-intensive to produce [59]. That one substitution drives much of the cost, weight, and recyclability advantage, and it simplifies end-of-life separation because both electrodes carry the same non-magnetic scrap metal.

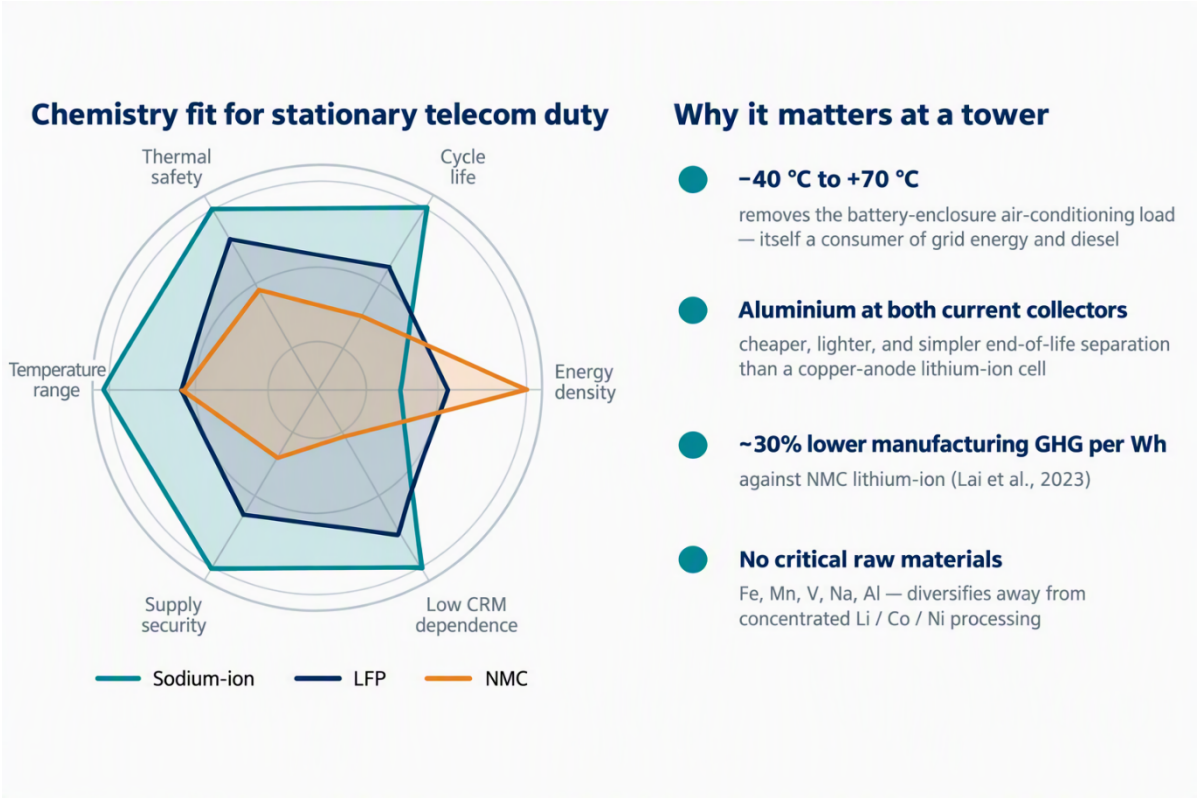

Figure 23: Chemistry fit for stationary telecom duty, and why the differences matter at an unmanned tower. Qualitative scoring by the authors from the sources at Table 15.

Table 15: Indicative comparison of stationary storage chemistries. Compiled from [59], [60], [61]; manufacturer platform disclosures as reported by [62].

Parameter	Sodium-ion (SIB)	LFP
Cell energy density	100–175 Wh/kg (CATL Naxtra platform claim: 175 Wh/kg)	140–190 Wh/kg
Cycle life	Manufacturer claims exceed 10,000 cycles; Prussian-blue-analogue industrial cells rated beyond 50,000	3,000–6,000
Operating temperature	−40 °C to +70 °C	−20 °C to +60 °C (with significant derating at sub-zero temperatures)
Thermal runaway risk	Very low	Low
Anode current collector	Aluminum	Copper
Critical raw materials	Low (Fe, Mn, Na, Al)	High (Li)

6.3.3 Sodium-ion versus LFP: sustainability

Because telecom backup is already migrating from valve-regulated lead-acid to lithium iron phosphate, the relevant sustainability question is not whether sodium-ion outperforms nickel- or cobalt-based lithium-ion chemistries, but whether it improves on LFP, the chemistry it would displace at the tower. LFP already avoids nickel and cobalt and accounts for around 90 per cent of the cost-sensitive stationary storage market [63]. The comparison therefore turns on two questions: raw-material criticality, and manufacturing carbon.

Raw materials. The material difference between the two chemistries lies in lithium, graphite and copper. An LFP cell draws on lithium carbonate or hydroxide, a graphite anode and a copper anode current collector; lithium, graphite, and copper all appear on India's list of thirty critical minerals, and lithium is fully import-dependent [68]. Refining of lithium and battery-grade graphite is also highly concentrated in a single country [64], [65]. A sodium-ion cell replaces lithium with sodium — approximately 23,000 ppm of the Earth's crust against roughly 20 ppm for lithium, and obtainable from salt and soda ash on every populated continent — replaces graphite with hard carbon and uses aluminum rather than copper at both electrodes [59], [66]. The advantage is chemistry-specific: iron- and manganese-based layered oxides, and Prussian blue analogues avoid listed critical minerals, whereas vanadium-based polyanionic cathodes reintroduce one and some layered oxides contain nickel [67], [68]. Feedstock diversification also does not, by itself, eliminate concentration risk: sodium-ion cell and precursor manufacturing capacity, and much of the intellectual property base remain geographically concentrated, so the risk moves one tier up the value chain rather than disappearing.

Manufacturing carbon. The evidence is not yet settled, and results depend on data source, cell design and the electricity mix of the factory. A 2026 Chinese cradle-to-gate assessment based on inventory data from gigawatt-hour-scale manufacturers placed a layered-oxide sodium-ion pack at 56.8 kg CO_2e per kWh against 75.5 kg CO_2e per kWh for an LFP pack, 24.9 per cent lower [69]. A European study, also based on primary production data, reached the opposite ranking at cell level: layered-oxide sodium-ion cells emitted 75–87 kg CO_2e per kWh, and LFP cells required the least production energy of all chemistries assessed [70]. An earlier multi-chemistry comparison found most environmental indicators of sodium-ion batteries lower than those of lithium-ion batteries at the manufacturing stage, with the gap widening as the electricity mix decarbonizes [71]. The prudent position for procurement is that a manufacturing-carbon advantage for sodium-ion over LFP is plausible but not assured, and should be demonstrated through supplier-specific, third party-verified carbon footprint declarations rather than assumed.

6.3.4 Qualification protocol for Indian tower duty

Sodium-ion is not yet a drop-in replacement, and the absence of format and chemistry standardization across suppliers means procurement cannot rely on a generic specification. A structured qualification programme should be run against representative Indian tower duty cycles before any estate-scale commitment.

- Abuse tolerance and thermal behaviour verified at pack level, not cell level, under Indian ambient extremes including sustained 45 °C-plus enclosure temperatures.
- Cycle life measured under a representative partial-state-of-charge duty cycle with rapid recharge after outage, rather than under a laboratory full-depth cycle.
- Weak-grid fluctuation tolerance, including repeated deep discharge and brown-out recharge behaviour.

- Remote telemetry and state-of-health estimation accuracy since condition-based replacement is the mechanism by which long cycle life converts into avoided site visits.
- Take-back, second-life routing and recovery obligations written into the purchase order at the point of first procurement, not renegotiated later.

6.4 Hydrogen Fuel Cells: The Long-Duration Diesel Replacement

6.4.1 Where hydrogen belongs, and where it does not

Solar plus battery storage has already taken the easy wins — sites with modest outage hours, available area, and moderate ambient temperature. What remains is the hard tail: sites needing eight to sixteen hours of daily autonomy, sites in space-constrained or high-shading locations, and sites in cyclone-prone or flood-prone geographies where multi-day autonomy is a network-resilience requirement rather than an energy-cost question.

The structural advantage of hydrogen at those sites is modularity. A battery stores energy in proportion to its mass and cost, whereas a fuel-cell system separates power rating from energy storage: longer autonomy is added by increasing the number of fuel cartridges rather than by oversizing the stack. Each 1.8 kg cartridge supplies approximately 30 kWh net electrical energy, equivalent to roughly ten hours at a 3 kW site load, so four cartridges provide a forty-hour outage ride-through.

6.4.2 Technology selection and site architecture

For stationary telecom backup in the 0.5–10 kW band, the technology choice is effectively settled. Alkaline fuel cells need pure oxygen or CO_2-scrubbed air, because atmospheric CO_2 reacts with the alkaline electrolyte to form carbonates that degrade performance; the scrubber becomes an additional consumable and failure point at an unattended air-breathing field asset. Phosphoric acid systems warm up too slowly for intermittent backup. Solid oxide systems are excellent for continuous prime power but are destroyed by the thermal cycling of a backup duty. Direct methanol eases logistics but forfeits both efficiency and green-hydrogen policy support. Proton exchange membrane is the answer, and the only real decision is air-cooling below about 3 kW versus liquid-cooling above it and in high-ambient circles [46], [72], [73].

Four design points follow from the telecom context and are where naïve designs fail in the field.

- A hydrogen site is always a hybrid site. PEM stacks have finite dynamic response, and voltage undershoot under sudden load steps degrades stack life [73]. A modest lithium-iron-phosphate battery at 48 V absorbs transients, covers start-up, and lets the stack run at a stable, life-preserving operating point.
- Air quality is a consumable, not an accessory. Roadside and industrial-belt air carries SO_x, NH_3, salt aerosol and dust, all of them cathode catalyst poisons. Cathode air filtration must be scheduled with a defined replacement interval.
- Hydrogen purity is a contractual term. PEM anodes are poisoned by carbon monoxide at sub-ppm levels. The purity and impurity limits of ISO 14687:2025 Grade E (Category 3), the specification for stationary PEM fuel-cell applications, must be written into the fuel supply agreement with a right of audit, particularly where hydrogen is sourced as an industrial by-product [74].
- Size the stack to average load, not peak; size storage to the worst credible outage, not the average; and size the battery to ride through start-up plus the largest single load

step. Larger batteries simply shift cost back to the technology hydrogen was chosen to displace.

6.4.3 The economics, and the scale that governs them

Any credible case for hydrogen at the tower has to begin with an honest benchmark of what diesel backup actually costs. The levelized cost of diesel-based backup power comprises three components: fuel expenditure; operations, maintenance and logistics costs; and the annualised capital expenditure on the diesel generator itself. Fuel is the most visible of the three and the one most often quoted, but on its own it understates the true cost of keeping a site alive through an outage. Using a diesel consumption rate of 0.4 L/kWh and an effective diesel price of ₹95/L, the fuel and O&M use component varies from ₹45/kWh to ₹55/kWh depending on usage across all archetypes. The spread is not incidental. At sites with few backup hours, the genset runs for short, inefficient bursts and fixed costs are recovered over very little energy; at sites with long daily outages, the same costs are spread across far more kilowatt-hours. The cost of a delivered unit of backup energy is therefore a function of how, and how often, the site draws on its generator, not merely of the pump price of diesel.

The complete diesel benchmark must also include the annualised cost of the **₹2.5 lakh** genset. That capital is committed whether the generator runs for a few minutes a day or for most of the night, and it must be recovered over the energy the genset delivers across its service life. To it must be added the recurring costs that rarely appear in a fuel invoice: periodic overhauls, lubricant and filter changes, battery-charger and control-panel faults, acoustic enclosure upkeep, refuelling trips to remote locations, security of stored fuel and losses from pilferage. Taken together, these items define the fully loaded cost that any alternative must beat. Comparing hydrogen against fuel cost alone would flatter diesel; comparing it against the fully loaded figure is the only basis on which an operator can take an investment decision.

The hydrogen pathway carries a parallel but differently weighted cost stack. It includes the capital recovery of the fuel-cell system, the hybrid battery and the cartridge storage at the site; the cost of the hydrogen itself; the operations and maintenance of the stack, including cathode air filtration and periodic inspection; and the logistics of moving filled cartridges out to towers and empties back to the hub. Of these, the delivered price of hydrogen per kilogram at the tower is the variable that governs the outcome. Production cost at the hub, compression, cartridge filling, transport distance, route density and cartridge turnaround all collapse into this single figure. Small movements in it change the levelized cost of hydrogen backup far more than comparable movements in any other input, which is why Table 3 frames hydrogen at the unreliable-grid archetype as conditional on a delivered hydrogen commercial suitability rather than as a default recommendation.

The hydrogen fuel-cell pathway becomes commercially attractive only when its fully loaded levelized cost delivers a sustainable cost advantage over diesel, after accounting for capital recovery, hydrogen supply, storage, O&M, logistics, and the risk-adjusted return expected by the operator. A marginal or temporary advantage is not sufficient. An operator replacing a proven technology with a newer one at an unmanned site will price in performance risk, supply-chain risk and regulatory uncertainty, and will expect the saving to hold across fuel-price cycles and over the full life of the asset. Where hydrogen clears that bar, typically at sites with long and recurrent outages and good access to a supply hub, it can displace diesel on cost as well as on carbon. Where it does not, open access, solar and advanced batteries remain the better-value intervention. This is why the economics of hydrogen cannot be separated from the supply model discussed in the next section: the price at which hydrogen can be delivered to the tower is determined by how, and at what scale, it is produced and distributed.

6.4.4 Supply model: why the cluster hub, and not the on-site electrolyzer

At first glance, the idea of placing a small electrolyzer and a modest solar array at the tower, so that each site produces its own hydrogen and does away with fuel logistics altogether, is an attractive one. It promises energy self-sufficiency, removes the dependence on delivery vehicles, and appears to fit neatly with the green-hydrogen ambition. At current technology costs, however, the proposition does not stand up to scrutiny. A typical site (~3kW) running on hydrogen for 8 hours backup needs only approximately 526 kg of hydrogen a year, or about 1.44 kg a day. The electrolyzer alone is not enough. The site would also need a demineralized-water supply, a compressor to raise electrolyzer output to storage pressure, a dryer to condition the gas, buffer storage to hold it, and a second, separate set of statutory obligations to be met at a location where no one is present. In practice, the actual annualized hydrogen requirement at a site may be only 10% to 50% of this reference figure, depending on the grid availability across seasons. Annualizing the full capital cost of this production chain across 526 kg a year, and in most cases considerably less, is what undermines the business case: the asset spends most of its life idle, and its utilization remains far too low to recover the investment.

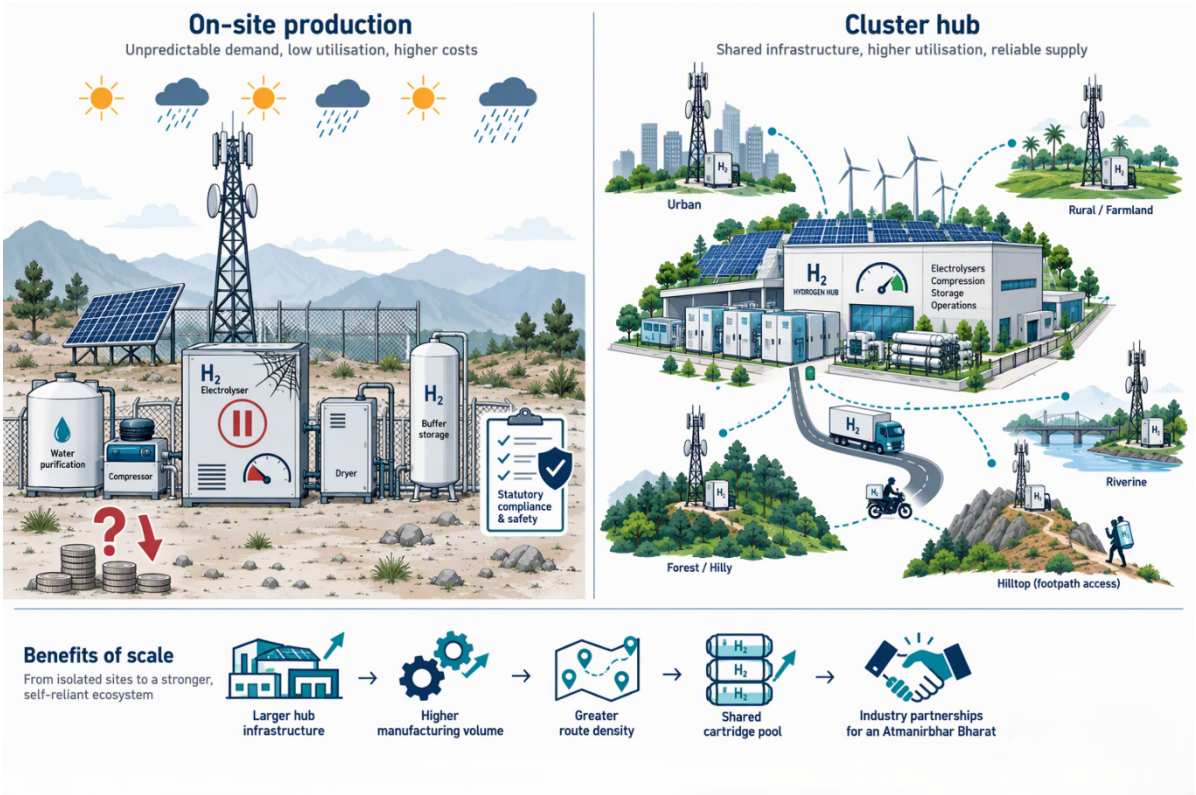

Figure 24: Hydrogen Fuel Cell Production and Distribution

The central difficulty is that hydrogen demand at an individual site is small, unpredictable, and highly heterogeneous. On a day with favorable weather and steady grid supply, the site may need 0 hours of backup; on a day at the height of the monsoon, the same site may need 16 hours. Demand therefore swings between nothing and most of a day's operation with little warning, and it differs markedly from one site to the next depending on location, grid quality, and season. An electrolyzer sized for the worst day sits largely unused on a typical day, while one sized for a typical day cannot meet the worst. Either way, such a demand profile makes it very difficult to achieve economic utilization of the electrolyzer or to recover its capital cost within a commercially acceptable payback period. The challenge is compounded by the balance of plant that on-site production brings with it: demineralized-water treatment,

compression, drying, buffer storage, safety systems and statutory compliance, each of which must be installed, maintained, inspected and secured at an unmanned location that may be visited only occasionally.

None of these rules out on-site production permanently. Research and development aimed at building smaller, cost-effective, and indigenously manufactured electrolysis systems, such as compact, integrated units that combine water treatment, generation, conditioning and storage in a single type-approved package, could reduce the capital requirement drastically. This is a potential area of genuine interest, for industry and for academia, because a substantial fall in the cost of small-scale production equipment could shift the utilization arithmetic enough to make the distributed model viable for at least some categories of site.

In the meantime, a cluster-hub model offers a more practical and economical route by pooling the hydrogen demand of many telecom sites. The unpredictable demand of any one tower becomes considerably smoother when it is aggregated across a cluster, because sites rarely reach their peak requirement at exactly the same time. Centralized production therefore improves electrolyzer utilization and spreads the fixed costs of production, compression, storage, safety, and compliance across a much larger volume of hydrogen. It also concentrates the specialized skills, statutory licensing and quality control needed for safe hydrogen handling at one supervised facility, rather than replicating them at every tower. Although transport to individual sites remains necessary, these economies of scale make the cluster-hub model, in principle, more commercially feasible and more scalable than installing separate production infrastructure at each site.

Distribution, however, is the next problem to solve. Moving hydrogen from the hub to the tower requires specialized logistics partners with the expertise, equipment, and certification to transport gas stored at high pressure, safely and reliably, to the remotest corners of the country. The geography of the telecom estate adds a further layer of difficulty. Towers are located wherever coverage is needed, not wherever access is convenient, and many do not have direct access to a motorable road that can carry four-wheelers. Sites on hilltops, in forested terrain, across rivers or in narrow urban lanes may be reachable only on foot, by two-wheeler or by small utility vehicle. Innovation in hydrogen logistics is therefore needed: lighter and more portable cartridge formats [81], handling equipment suited to last-mile delivery, and route planning that can serve a highly diverse range of locations. At the same time, the regulatory framework governing hydrogen distribution will need to evolve towards the scale and maturity of today's LPG distribution system, under which cylinders are routinely delivered door to door, before an equivalent doorstep delivery model for hydrogen can work.

Ultimately, the adoption of hydrogen as an alternative to fossil-fuel generators rests on two factors: first, the capital investment required for fuel cells and electrolyzers; and second, the cost and practical feasibility of distribution. Both are strongly driven by scale. Hydrogen production cost falls as hub size increases; fuel-cell system cost falls as manufacturing volume grows; distribution cost per kilogram falls sharply as route density rises [82],[83] and cartridge asset utilization improves as the shared cartridge pool expands. Because each of these curves improves with volume, the case for hydrogen is not static; it strengthens as deployment grows. This makes a compelling argument for coordinated action on several fronts at once: continued improvement in technology, indigenous manufacturing of fuel cells, electrolyzers and cartridges, performance-linked incentives that reward delivered outcomes, and industry-wide partnerships that aggregate demand across telecom and other sectors. Together, these measures can turn today's promising but sub-scale proposition into a scalable and commercially workable model.

The capacity factor is doing all the work

Telecom demand is spiky and seasonal, concentrated in monsoon months and grid-stressed periods. Banking and ATM backup, railway signalling, hospital UPS, defence forward posts and material-handling equipment all have different and partly counter-cyclical profiles. The adoption will become much smoother with supporting industry's hydrogen infrastructure — refining, fertiliser or steel, with telecom being the anchor tenant rather than a greenfield developer of its own.

6.4.5 The regulatory gap is the critical path

Hydrogen in India is regulated under the Explosives Act, 1884, administered by the Petroleum and Explosives Safety Organization, principally through the Gas Cylinders Rules, 2016, the Static and Mobile Pressure Vessels (Unfired) Rules, 2016, and the Gas Cylinders (Amendment) Rules, 2024 (Hydrogen), which introduce compressed-hydrogen and green-hydrogen definitions [84]-[86]. The green-hydrogen threshold of well-to-gate emissions not exceeding 2 kg CO_2e per kg H_2 is established by the Green Hydrogen Standard for India [76]. That stack was written for a world in which hydrogen sits in large quantities at a small number of manned, licensed, fenced industrial premises. A national telecom programme reverses those assumptions: small quantities at a very large number of unmanned sites.

Table 16: Regulatory gaps for distributed stationary hydrogen and proposed remedies. Authors' proposal: thresholds are indicative and should be validated by quantitative risk assessment before adoption.

Gap	Problem	Proposed remedy
No de-minimis threshold	A site holding four cartridges contains roughly 7 kg of hydrogen — comparable in stored energy to a quantity of diesel that attracts no license at all. Full storage licensing for each of a hundred thousand such sites are administratively impossible.	A Tier-1 exemption below 10 kg stored on site: no license, but portal registration, a type-approved packaged system, mandatory hydrogen detection with alarm and automatic isolation, and annual self-certification by a recognized competent person.
No type-approval route	Every site is treated as a bespoke installation.	Certify the packaged cabinet — cylinder rack, detection, ventilation, shut-off, Ex-rated components — once as a design, as is done for LPG appliances and CNG kits. Site compliance then becomes a short installation checklist.
No portable-cartridge regime	The rules contemplate cylinders filled at a licensed plant and delivered to licensed premises, not a rapidly circulating pool of small, user-swappable, digitally tracked cartridges.	A registered cartridge scheme: approved manufacturer (for example, to ISO 11119-3 for composite cylinders [75], unique digital identity, mandatory five-year re-qualification, national online register, custody transfer logged at every hand-off — using the existing CNG cylinder testing-station portal as the operational template.
Ambiguity on unmanned premises	Storage licenses generally presume a responsible person on site. A tower has none.	Recognize remote supervision — continuous telemetry, remote isolation, automated emergency shut-off and a defined field response-time commitment — as an equivalent control.

Why this matters more than the technology

India already has a national demonstration of hydrogen fuel cells for uninterrupted power supply to telecom towers, reported by the Department of Science and Technology in March 2025 [77]. The technology question is substantially answered. Moving from a demonstration to estate-scale deployment needs licensing to be defined.

6.5 Circularity as an Engineering Requirement

A circular tower-energy programme begins with architecture and procurement, not with end-of-life. Modular rectifiers, replaceable power modules, interoperable battery racks, standardized telemetry, and vendor-neutral interfaces extend asset life and reduce stranded equipment. Digital product passports then preserve identity, chemistry, ownership, service history, state of health and recycling route — the data that make safe second-life deployment, condition-based maintenance and auditable custody transfer possible at all.

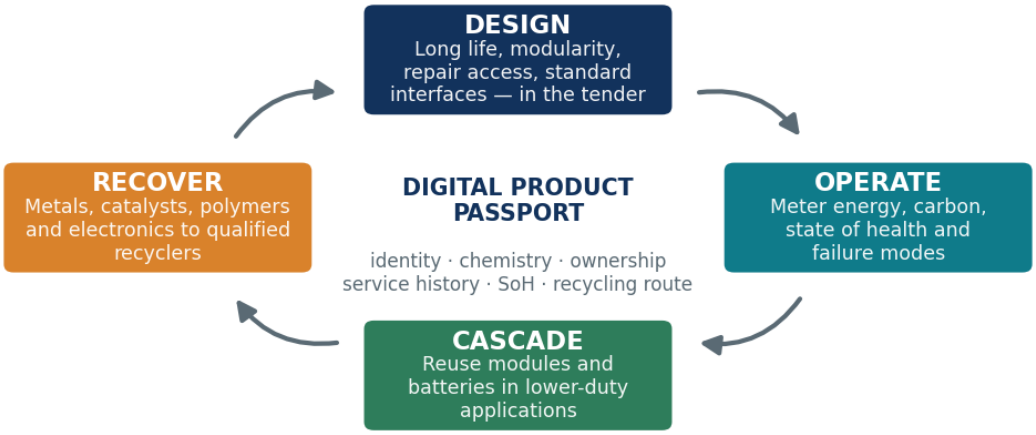

Figure 25: The four stages of a circular tower-energy programme, bound together by the digital product passport.

6.5.1 Four decisions that make the loop real

- Material recovery contracted at purchase. Platinum-group metals in fuel-cell stacks, graphite or coated stainless steel in bipolar plates, carbon fiber and HDPE in cartridge construction, aluminium in sodium-ion current collectors and copper in legacy lithium packs are all recoverable. A mass-recovery target should be an extended producer responsibility clause in the original purchase order, not subsequent negotiation. At end of life a diesel engine is scrap metal, whereas a fuel-cell stack is a concentrated deposit of high-value metals in a known location, owned by a single entity, with a known service history — an advantage no genset can match.
- Second-life cascades in both directions. Stacks and batteries retired from more demanding duty cycles frequently retain adequate life for the steadier duty of telecom backup; conversely, telecom batteries retired from site duty can be adequate for hub-level or depot-level buffer storage. Both cascades lower effective capital cost and defer material extraction.
- Statutory testing reframed as designed refurbishment. The five-yearly cylinder re-qualification required under Rule 35 of the Gas Cylinders Rules is usually treated as a cost. Treated instead as a planned refurbishment point supported by a national re-

qualification network, it is what makes cylinder capital per kilogram delivered small enough to matter.

- Recycling economics addressed by policy where the market will not. This is the central circularity risk in the sodium-ion pathway, and it must be stated plainly: technical recyclability does not produce actual recovery when the recovered material is cheap. Policy instruments — extended producer responsibility, recycling mandates, or deposit schemes — are likely to be necessary [59].

6.5.2 Global practice to consider for adoption

- European 6G industry frames sustainability around universal energy and carbon metrics, integrated measurement, and optimization across the full-service chain rather than the radio interface alone [40].
- NGMN and leading equipment vendors emphasize lean networks, deeper sleep states, reduced always-on signalling, automated energy management and transparent AC and DC metering as continuing design priorities for 5G-Advanced and 6G [78], [79]).
- Global tower strategies increasingly combine renewable procurement for grid-connected portfolios with solar-battery hybrids for weak-grid or off-grid sites. The common lesson is segmentation by load, grid quality, logistics, space, and climate rather than adoption of one standard energy kit.
- Circular practice in digital infrastructure is moving from waste handling to product design: repairability, refurbishment, component harvesting, traceability, and supplier take-back are becoming commercial requirements rather than reporting categories [87].

6.6 Summary

The technology options presented hitherto are for energy choices to meet energy demand in telecom considering green attributes and commercial viability. These are summarized in Table 17. Note that Hydrogen as a scalable option is subject to distribution network establishment, storage standardization and establishment of economy of scale.

Table 17: Technology for energy choices to meet energy demand in telecom considering green attributes and commercial viability

Condition	GEOA	Solar	Battery	Hydrogen
Reliable grid	High	Medium	High	Low
Weak grid	High	High	High	Medium
Remote	High	High	High	High
Disaster recovery	High	Medium	High	High
Border sites	High	High	High	High

7 Conclusion

India's ambition of Green and Sustainable 6G needs a circular energy architecture for its telecom networks, not a collection of isolated green projects. The draft National Telecom Policy 2025 sets a 2030 horizon for powering 30 per cent of telecom towers from renewable energy. Densification will begin adding sites around 2030 — sites that will be connected to whatever energy architecture exists at that moment. A network provisioned into a green, storage-firmed, circular framework from the outset is decarbonized by design; one retrofit afterwards is decarbonized by expensive exception.

Carbon intelligence reframes sustainability as an active 6G control capability. By treating carbon intensity as a first-class operational input, applying a sense-model-decide-actuate loop, and coordinating radio, transport, compute, cooling, and hardware lifecycles, AI-native networks can move from retrospective accounting toward predictive and verifiable carbon management. The same architecture can later extend to water, biodiversity, materials, and carefully validated biological carbon sinks. Standardization work on the sustainability aspects of 6G is already under way internationally.

Solutions to a sustainable 6G are already becoming visible. Green Energy Open Access can decarbonize the dominant grid share and is already available at the 100 kW aggregated threshold. On-site solar can remove a site-specific portion of demand, bounded by physics rather than by policy. Advanced batteries, including sodium-ion where safety, temperature tolerance, cycle life and supply diversification outrank energy density, can provide safe short- and medium-duration flexibility. Hydrogen fuel cells can address the remote, long-duration diesel tail where batteries alone cannot bridge the gap economically. AI-enabled control coordinates the system and, equally importantly, measures it credibly. Circular design closes the loop by extending asset life, enabling second use, and recovering materials.

With the technology becoming available, a standardized industry process will be needed very soon. For open access, the requirement is immediate: applications and fees are assessed per connection rather than per entity, low-tension charge schedules need changes, billing systems need to issue a composite invoice, settlement occurs at division level, and scheduling obligations designed for megawatt consumers are applied to eight-kilowatt sites. For hydrogen, a national demonstration already exists and needs a licensing framework for hundreds of thousands of small, unmanned installations.

The immediate recommendation of this paper is therefore, even as sustainability is standardized globally, to classify the estate, close the first open access clusters where the mechanism demonstrably works, qualify sodium-ion against Indian duty cycles, commit one circle and one hub to a hydrogen pilot under a sandbox, and mandate recovery obligations.

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9.2 Co-authors

Table 2, lists in alphabetical order of the organization-names, Co-authors and their contributions.

Table 18: Co-authors and their contributions

Organization	Co-author names	Primary Contribution
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Symbiosis Institute of Technology, Pune Campus, Symbiosis International (Deemed University)	Dr. Bhavna Ambudkar, Dr. Mangal Singh	Section 5.2
Tata Consultancy Services Limited	Dr. Garima Mishra, Dr. Hemant Rath, Mr. Ranjit Dora Ganguly, Mr. Uday Ramesh, Mr. Radhakant Das.	Sections 3.1, 3.8, Additions to Sections 1, 5, 7

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