FIXED NETWORKS ENERGY EFFICIENCY TOOLKIT

WORLD BROADBAND ASSOCIATION

This toolkit is the third installment in the World Broadband Association's Sustainability White Paper series. It aims to deepen the understanding of the available technologies and solutions that can help improve the energy efficiency of fixed broadband networks.

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EXECUTIVE SUMMARY

Energy efficiency is a core element of environmental sustainability policies introduced in the last few years. It is a part of the public policies of the EU, the US, and China and is essential to the achievement of net-zero goals. For the telecom and broadband industry in particular, reducing energy consumption has become an important aspect in carbon footprint reduction as well as a key performance indicator used to showcase successful network operations and a useful tool for vendor selection.

This toolkit highlights five key areas where the broadband industry should focus its efforts to achieve better energy efficiency in fixed networks:

- **Migration of legacy, primarily copper, networks to full fiber:** Fiber-optic networks are the most energy efficient of existing broadband access technologies. By decommissioning legacy copper and cable co-axial infrastructure, telecom operators can achieve significant energy consumption improvements.

- **Network innovation using simplified network architecture and artificial intelligence (AI) solutions:** Simplified all-optical network architecture has the least pass-through traffic and the fewest redundant nodes and equipment, and therefore its implementation results in overall energy consumption reduction. Moreover, use of AI and innovative AI-powered solutions can also be introduced to optimize power consumption by monitoring traffic changes and managing transmission route paths, traffic volumes, and allocation policies.

- **Creation of energy-efficient facilities:** Investing capital in energy-efficient buildings and network facilities can make a real difference. Site facilities such as air conditioning and power supply often consume as much energy as the main equipment on the site. Therefore, service providers must improve the efficiency of cooling and power supply systems in their sites.

- **A focus on the energy efficiency of customer premises equipment (CPE):** CPE is responsible for over three-quarters of the total power consumption of fixed broadband networks, depending on the access technology. Therefore, CPE plays a big role in the creation of a sustainable home network and the driving down of overall energy consumption. There are several ways in which this can be achieved, including lowering targets for energy consumption per device and increasing the lifespan of products, for example, through the support of future-proof technologies.

- **Adoption of unified, industrywide energy efficiency measurement indicators and methodologies:** A lack of standardized, industrywide measurement indicators is hampering the ability to take unified action to reduce the industry's environmental impact.

The toolkit aims to deepen the understanding of the available technologies and solutions that can help improve the energy efficiency of fixed broadband networks. It is intended to provide food for thought and help stakeholders decide in which direction to focus their attention and resources on their sustainability journey.

INTRODUCTION

As the sustainability working group of the World Broadband Association (WBBA) explored in its two previous white papers ("The Importance of Environmental Sustainability in Telecom Service Providers' Strategy" and "Evaluating the Telecom Industry's Sustainability Potential"), sustainability is increasingly becoming a key focus point for the telecom industry. On the whole, the ICT industry accounts for 5–9% of electricity use and more than 2% of global greenhouse gas (GHG) emissions, equal to the emissions produced by all air traffic. But the ICT industry also commands a sevenfold abatement effect, meaning it can help reduce emissions by 7× more than the amount created by the sector itself, reducing global CO2 emissions by 15%.[1]

In recent years, the telecom industry has demonstrated its commitment to environmental sustainability: all major service providers have set carbon-neutrality goals for 2050, and some have committed to even earlier deadlines. Equally, many leading vendors are developing products and solutions with low carbon footprint and energy efficiency as a key requirement.

As an industry that both breeds and feeds on innovation, the telecom sector is perfectly placed to provide and enable solutions that help tackle climate change. One of the areas that has progressed most significantly so far is broadband.

Though connectivity demands have been growing exponentially since the early 2000s, the telecom industry has managed to keep energy consumption in check thanks to technological innovation and advances. In fact, according to Nokia, while broadband speeds have increased by 64×, broadband power consumption has declined 38% since 2007. That is a massive gain in efficiency for the home and access networks with the evolution from ADSL to XGS-PON.[2]

Improving the energy efficiency of fixed broadband networks is a strategy to minimize the consumption and waste associated with providing broadband connectivity. It is an important component of a broader goal of achieving carbon neutrality, and continued efforts to enhance the energy efficiency of fixed broadband networks are crucial for addressing environmental concerns, reducing operational costs, promoting innovation, and ensuring sustainable growth of the telecom industry in general.

In its latest research, the WBBA's sustainability working group explored the areas on which fixed network operators, service providers, and vendors can focus their efforts to achieve energy efficiency, drawing on leading players' and WBBA members' experiences and best practices. There are costs associated with the presented solutions and practices, but the associated energy efficiencies result in ROI and an overall contribution to companies' net-zero strategies.

The WBBA energy efficiency toolkit presents five key areas that have been identified as having the most impact on the reduction of power consumption in the short and medium term:

- Migration of legacy, primarily copper, networks to full fiber
- Network innovation using simplified network architecture and AI solutions
- Creation of energy-efficient facilities such as buildings and central offices
- A focus on the energy efficiency of CPE
- Adoption of unified, industrywide energy efficiency measurement indicators and methodologies

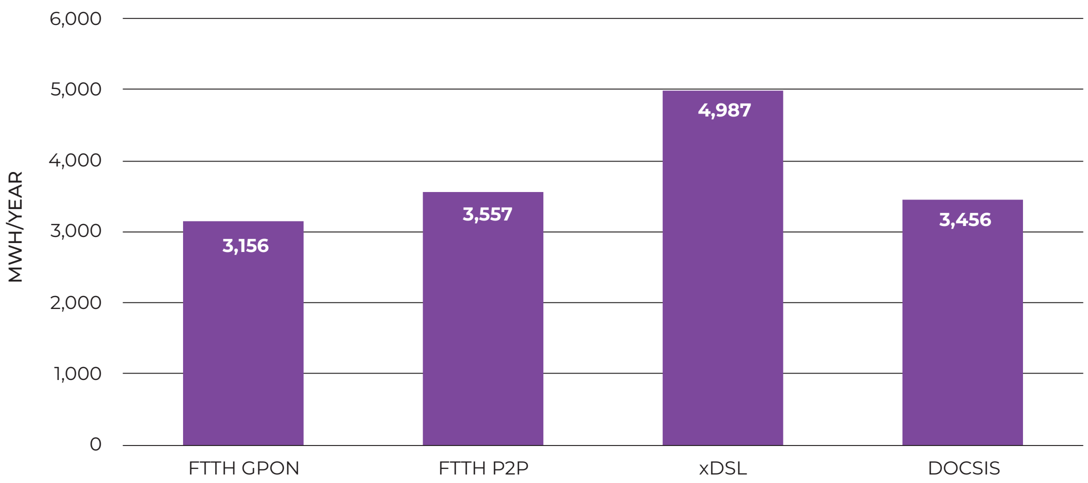
[1] European Commission Factsheet, "Supporting the Green Transition," February 2020

[2] Nokia, "Broadband Zero: Delivering the benefits of broadband while minimizing environmental impact"

MIGRATION FROM COPPER TO FIBER

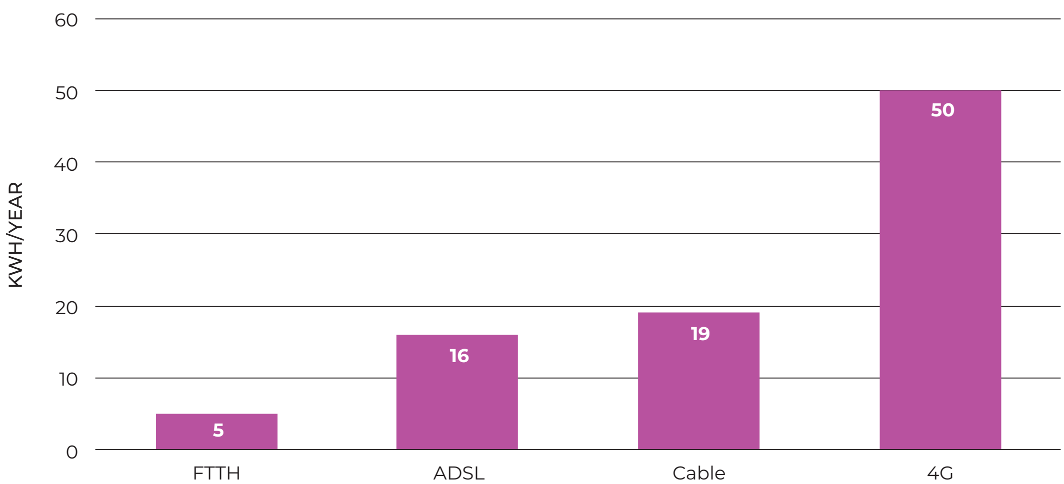
Numerous studies have been published in recent years examining the power consumption of various broadband access network technologies, and all have concluded that the benefits of fiber networks are undeniable. Whether what is measured is power consumption in MWh per year as in a 2018 Europacable study; kWh per line as examined by the French telecoms regulator ARCEP in 2019; or power in watts consumed per subscriber, evaluated in Nokia's 2023 study, fiber-to-the-home (FTTH) Gigabit Passive Optical Network (GPON) networks come out as the most energy efficient.

FIGURE 1: TOTAL POWER CONSUMPTION BY ACCESS NETWORK TECHNOLOGY



SOURCE: EUROPACABLE, "ENERGY CONSUMPTION OF TELECOMMUNICATION ACCESS NETWORKS," OCTOBER 2018

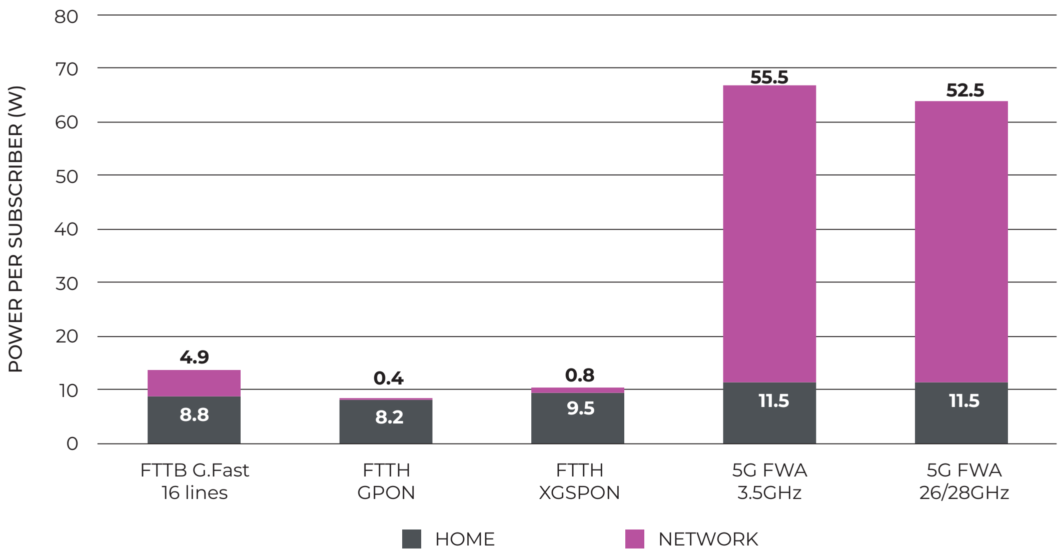
FIGURE 2: YEARLY ENERGY CONSUMPTION IN KWH PER LINE (BASED ON 7GB MONTHLY DATA CONSUMPTION PER LINE)



SOURCE: ARCEP, "RÉSEAUX DU FUTUR : L'EMPREINTE CARBONE DU NUMÉRIQUE," OCTOBER 2019

The bandwidth provided by GPON solutions is 10–12× larger than that provided by xDSL. Moreover, the successive generations of PON further improve the ratio of bits delivered per watt consumed. Even though XGS-PON networks need twice as much energy as PON solutions, they provide 4× downstream and 8× upstream the bandwidth of PON.

FIGURE 3: POWER CONSUMPTION COMPARISON FOR VARIOUS ACCESS TECHNOLOGIES



SOURCE: NOKIA, "BROADBAND ZERO: DELIVERING THE BENEFITS OF BROADBAND WHILE MINIMIZING ENVIRONMENTAL IMPACT," 2023

Successful migration of legacy technologies to fiber can also considerably reduce server space and enable the decommissioning of entire buildings, because fiber networks require so much less server infrastructure. Decommissioning buildings can also contribute to energy optimization by reducing the need for cooling. Because fiber requires less space for servers, cooling demand can drop dramatically, from whole rooms cooled by industrial-grade air conditioning units to a limited number of racks requiring much simpler cooling solutions.

The benefits of migrating legacy networks have been recorded by many operators currently in the process of decommissioning their copper networks. For example, Spanish incumbent Telefónica has seen approximately 60% energy savings after shutting down its copper network. To manage its copper network decommissioning process, Telefónica developed the FARO project to encourage customer migration to fiber and industrialize the shutting down of copper in entire switchboards.

As part of the FARO project, Telefónica focused on optimization of infrastructure and space, which resulted in a smaller cross-section but greater capacity. For example, a 2,400-pair copper harness provides service to 2,400 customers, while a 256-wire fiber cable provides service to 16,384 customers. In addition, a fiber switchboard can service the same number of accesses as four copper switchboards, but fiber access technology only occupies 15% of the space occupied by copper access.[3]

Belgian incumbent Proximus has also recorded impressive energy savings of 75% since starting its large-scale fiber deployment project.

In Asia, China Telecom has seen energy consumption per unit of information traffic reduced by 60% in 2020 compared with 2015, and energy consumption per unit of information traffic in 2021 was 8.3% lower than in 2020. The company is currently migrating all legacy copper services onto a mix of GPON and XGS-PON fiber network. At a central-office level, China Telecom has recorded an approximately 60–80% decrease in energy consumption and expects further energy efficiencies from consolidation of central offices as a result of greater reach from fiber.

[3]https://www.telefonica.com/en/communication-room/press-room/telefonica-will-shut-down-one-copper-switchboard-a-day-until-2020/

New Zealand wholesale operator Chorus has deployed fiber networks to more than 300 cities, towns, and communities and has announced its plan to shut down its copper network by 2033. The company notes that active withdrawal of copper technology is now necessary to eliminate the energy costs of running a parallel, legacy network.

However, fiber network deployment can still be a costly and lengthy endeavor. In many countries legacy copper networks continue to be protected by regulation, and migration to fiber has been primarily based on customer opt-in. Therefore, it is essential that regulatory policies setting up clear, fair, and timely conditions for copper decommissioning be established. Network operators also need to define a clear roadmap for decommissioning of legacy networks that is tailored to their specific market conditions.

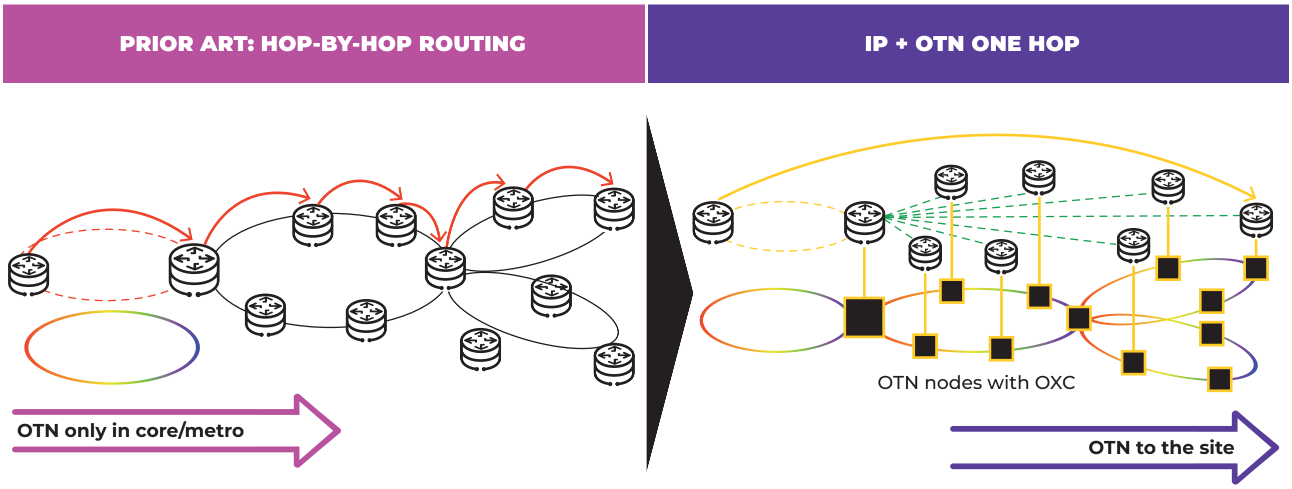
NETWORK EVOLUTION TOWARD HIGHER EFFICIENCY

Simplified all-optical network architecture can also effectively reduce overall energy consumption, for example, converged metro and converged backbone for those fixed and mobile services and planes in addition to spine-leaf-based fabric architecture. Simplified architecture has the least pass-through traffic and the fewest redundant nodes and equipment.

Legacy optical networks use ring architecture featuring multilayer aggregation, which results in low efficiency in long-haul transmission. The simplified network architecture implements one-hop transmission at the electrical layer, greatly improving transmission efficiency, reducing network latency and power consumption, and simplifying network maintenance. In general, network operators agree that simplifying their network architecture is essential.

One of the solutions utilized in network simplification is optical cross-connect (OXC). OXC offers a more flexible solution with an all-optical cross-connection grooming mode. Unlike traditional ROADM based on separate boards, OXC's optical backplane implements full-mesh interconnection, integrates many optical fibers on a single optical backplane, and supports high integration of service boards. One slot corresponds to one direction. OXC uses integrated interconnections to build an all-optical switching resource pool, achieving highly integrated, fiber-free, and all-optical cross-connections, in turn significantly improving the efficiency of switching large-granularity services. As illustrated in **Figure 4**, using the latest OXC technology to replace the traditional ROADM can reduce the equipment room footprint by up to 90% and the power consumption by up to 60%.

FIGURE 4: OXC POWERED ONE-HOP OPTICAL NETWORK



SOURCE: HUAWEI

OXC was successfully deployed by e& in the UAE (Etisalat UAE) in 2023. E& has used this Huawei-developed solution to upgrade 24 traditional ROADM sites on its live network, reducing power consumption by 36% and improving network energy efficiency by 56% without changing service capabilities. Moreover, e& employs end-to-end advanced technologies, such as 1.2T high-speed transmission technology, to build an all-optical, highly energy-efficient, and eco-friendly transport network.

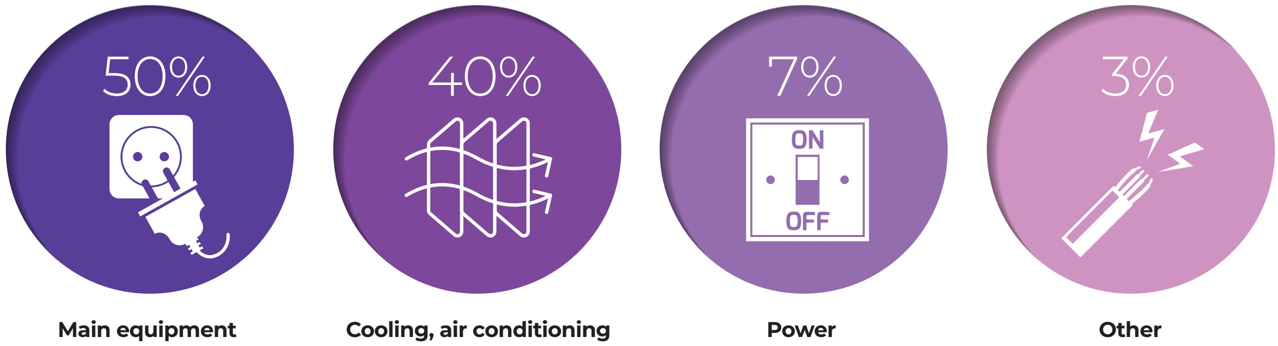
Innovative AI-powered solutions can also be introduced to optimize power consumption by monitoring traffic changes and managing transmission route paths, traffic volumes, and allocation policies. For example, idle-resource sleep and dynamic frequency adjustment can adaptively allocate network resources according to the network load and traffic volume. AI can be used to develop a power consumption visualization and management system that will allow service providers to fully understand the energy consumption profile of their networks, identify low-efficiency links in a timely and accurate manner, and perform targeted optimization by replacing equipment and rerouting traffic.

EFFICIENCY OF FACILITIES

Investing capital in energy-efficient buildings and network facilities can make a real difference. Site facilities such as air conditioning and power supply often consume as much energy as the main equipment on the site. Therefore, service providers must improve the efficiency of cooling and power supply systems in their sites. Advanced solutions such as smart ventilation, heat exchangers, heat piping, liquid cooling, and thermotanks have been considered to ease the strain on air conditioners and reduce energy consumption.

Advanced power supply solutions, such as high-voltage power transmission, DC module dormancy, and power harmonic treatment, can improve power modules' efficiency, improving the overall energy efficiency of a telecom site. Replacing diesel generators with battery backups powered by renewable energy (e.g., solar or wind) can be one way to improve energy efficiency.

FIGURE 5: EXAMPLE OF POWER CONSUMPTION CONTRIBUTORS IN A BROADBAND NETWORK SITE



SOURCE: OMDIA

Fiber-optical networking greatly reduces the need for equipment room footprint. Further migration of a synchronous digital hierarchy (SDH) network to an optical transport network (OTN) can lead to additional savings. For example, Orange France replaced legacy SDH equipment with OTN equipment for 150 network elements at 110 sites, reducing the total power consumption by 67%, equipment room footprint by 58%, and maintenance costs by 62%.[4]

[4] https://www.etsi.org/images/files/ETSIWhitePapers/ETSI-WP-60-All_Optical_Network_facilitates_the_Carbon_Shift.pdf

The power consumption of a network site has two components:

- Power consumption of main equipment, such as electrical-layer equipment and optical-layer equipment
- Power consumption of auxiliary devices, such as the air conditioner and power supply in the equipment room

Each component accounts for approximately half of the site's power consumption. The reduction of power consumption by the auxiliary equipment focuses on the application of advanced power supply, heat dissipation, and air conditioner energy-saving technologies, thereby maximizing the energy efficiency of the site.

Optimizing energy usage of main equipment improves site energy efficiency in two ways. First, the energy efficiency of the main equipment improves along with a reduction in power consumption, contributing to overall network energy efficiency. Second, the amount of heat dissipated by the main equipment will fall, and this contributes to a reduction in the energy consumption of the auxiliary devices (e.g., air conditioning).

There are several potential approaches to optimize energy consumption main equipment:

- **General and dynamic fan speed adjustment:** The fan speed of main equipment can be dynamically adjusted according to the energy consumption of the main equipment, so the fan always uses optimal speed with minimum energy consumption.
- **Differential and dynamic fan speed adjustment:** This approach may further adjust one or more fans individually to account for the fact that temperature is not consistent across the equipment (e.g., some slots may be spare, and the fans for them may run at lower speed to save energy).
- **Powering down line cards that are not provisioned for service:** This practice eliminates unnecessary energy use by devices that are not in service.
- **Shutting down line cards or ports:** When equipment is not in service or when there are no users connected or no traffic, it can be switched off.
- **Dynamic adjustment of hardware running clock:** When the traffic is low, the running clock of the hardware can be slowed to reduce energy consumption.

To enable the abovementioned approaches, AI may be used to increase agility and efficiency.

The use of auxiliary equipment such as air conditioners can be reduced through site architecture innovations, such as DC-based equipment deployment, isolation of cold and hot air channels, and liquid cooling. Use of advanced silicone coating in air conditioning for the chillers' radiators can also improve energy efficiency.

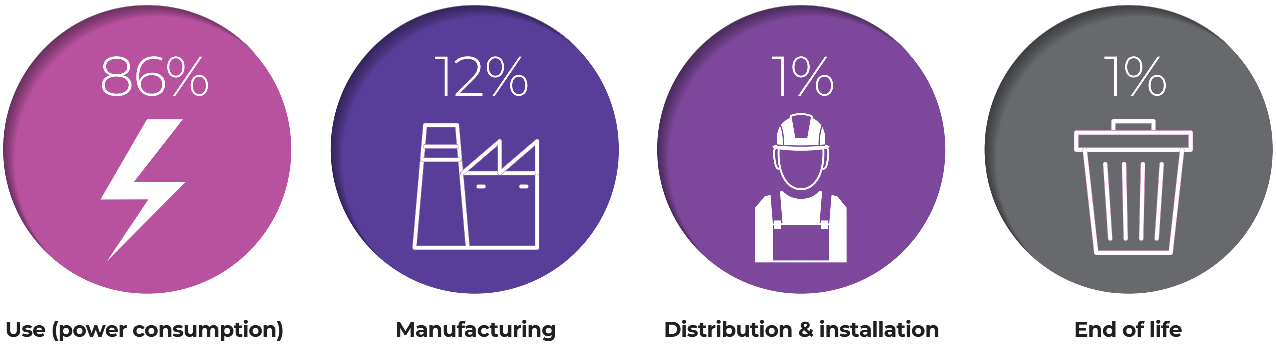
China Telecom, for example, introduced a combination of AI, big data analytics, and Internet of Things (IoT) to create energy consumption scenarios in server rooms. The company also developed a nationally unified intelligent energy-saving system for server rooms, improving the energy-saving rate of cooling of the intelligent energy-saving system in the machine room by more than 15%.

EFFICIENCY OF CPE

As shown in **Figure 6**, CPE can be responsible for over three-quarters of the total power consumption of fixed broadband networks, depending on the access technology. That being the case, CPE can play a big role in creating a sustainable home network and driving down the overall energy consumption.

Data from Liberty Global shows that in a typical dual-band Wi-Fi 6 gateway, power consumption accounts for approximately 86% of the CPE's lifetime CO2 impact. A lot of progress has been made in recent years in improving overall CPE sustainability through the use of recycled plastic materials, environmentally friendly packaging, or old equipment refurbishment, but there is even bigger potential in reducing the in-life power usage of CPE.

FIGURE 6: CO2 IMPACT OF A TYPICAL DUAL-BAND WI-FI 6 GATEWAY LIFETIME



SOURCE: LIBERTY GLOBAL

There are several ways in which this can be achieved, including setting lower targets for energy consumption per device and increasing product lifespan, for example, through the support of future-proof technologies. One key area where CPE energy consumption can be reduced is the home gateway's idle-time power consumption, which can be better managed by implementing efficient sleep modes, leveraging AI for energy management.

For their part, equipment vendors are developing innovative designs and solutions to improve the energy efficiency of the home network. For example, ZTE's optical network units (ONUs) are equipped with in-house ONU chips, which have gone through several development stages from separation of GPON MAC and 10G PON MAC to full-mode MAC and then to programmable full-mode MAC. Consequently, the power consumption of ZTE's GPON ONUs is currently 20% lower than the CoC V7 standard. Nokia's WiFi 6 Beacons allow power-saving modes with scheduled sleep/wake times for longer battery life and up to 67% lower power consumption for end devices.

Edge-deployed AI (eAI) helps ONUs to dynamically monitor data traffic usage over PON interface and Wi-Fi interface and enable corresponding energy-saving mode automatically (e.g., scale down speed to save energy in case of light traffic load, go to doze or sleep mode, or even shut down some parts of the CPE). Data shows that Huawei's latest series of gigabit optical network terminals (ONTs) which are powered by eAI, can save each customer 38kWh of electricity per year thanks to the smart hibernation technology that takes its energy consumption levels down to 30% less than that of similar products and 20% lower than the level set out by the EU's Code of Conduct on Energy Consumption Broadband Equipment Version 7.

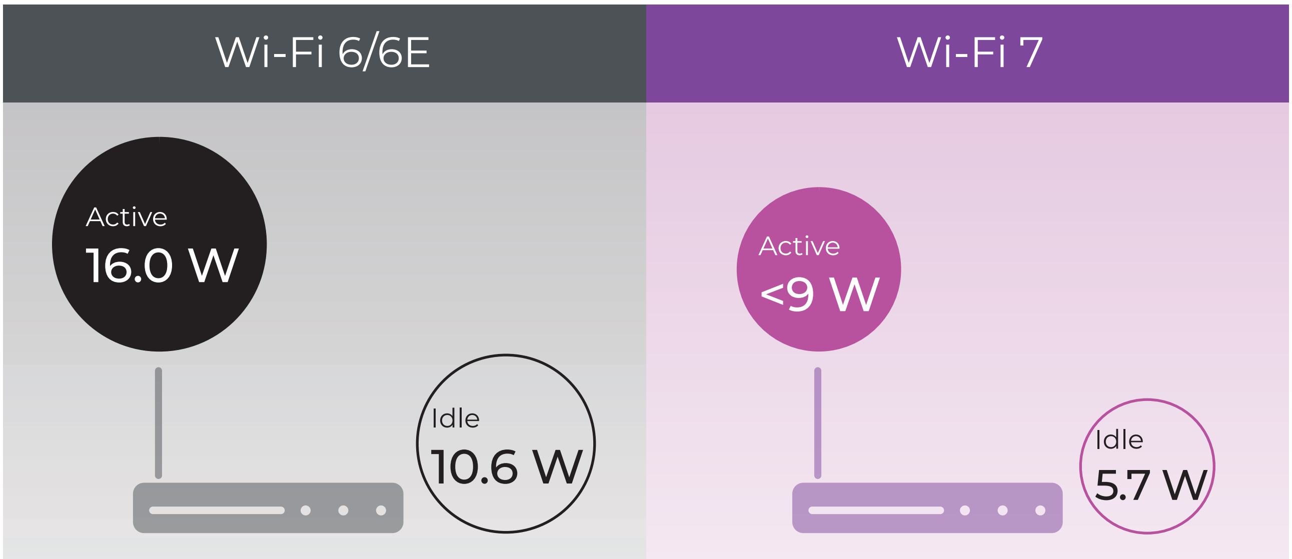
Another solution aimed at improving home broadband network performance, pioneered by Huawei, is fiber-to-the-room (FTTR) technology. In the FTTR architecture, a primary ONU is connected to multiple edge ONUs placed in each room in the home. The primary ONU is located between the optical line terminal (OLT) and the edge ONUs at the end-user premises and serves as the main control center of the home network, enabling unified management and configuration. FTTR can also improve network energy efficiency by 10× in comparison with traditional FTTH connections.

In particular, when it is powered by the latest C-WAN architecture and Wi-Fi 6 standard, the solution can ensure 2Gbps Wi-Fi coverage in every room, and an AI-driven adjustment of Wi-Fi coverage can lead to energy savings through monitoring of energy consumption across the FTTR connection. The energy-saving determination is made in the controller of primary ONU and includes sleeping periods for each access point according to the quality-of-service requirements of the secondary ONUs placed in each room and temporarily disabling/enabling a specific access point of the associated ONU stations depending on actual data transmission needs.

Additionally, the new Wi-Fi 7 hardware standard shows promising advances in gateway power consumption per bit of traffic. In addition to providing higher bandwidth (46.1Gbps vs. the 9.6Gbps provided by Wi-Fi 6/6E), lower latency of less than 10ms, and other innovative features, it also offers advanced energy-saving features that help extend the battery life of connected devices and reduce overall power consumption.

Wi-Fi 7 is expected to be widely available in mid-2024, but early demonstrations have shown that the platform consumes no more than 5.7W when idling and less than 7.4–9W in typical usage scenarios (see **Figure 7**).

FIGURE 7: CPE POWER CONSUMPTION IN IDLE AND ACTIVE MODE, WI-FI 6/6E VS. WI-FI 7



SOURCE: WLAN APPLICATION ALLIANCE

ENERGY CONSUMPTION MEASUREMENT INDICATORS AND METHODOLOGIES

One of the key challenges for the telecom industry in measuring energy efficiency effectively is the lack of unified and widely adopted measurement indicators and integrated methodologies.

Currently, network operators and service providers are developing their own studies on end-to-end energy consumption for services provided using different access technologies; some have installed energy-monitoring devices at central-office level. However, in order for the industry to tackle energy efficiency there needs to be standardization of energy consumption monitoring and development of telco-specific power usage effectiveness targets.

In Europe, the European Commission has set out a series of guidelines for self-regulation, which are regularly updated because of the fast-moving nature of this market and the increased demand for data transmission. The EU Code of Conduct on Energy Consumption of Broadband

Equipment describes the principles to be adhered to by all parties involved in broadband equipment operating in the European Community concerning energy-efficient equipment without affecting service levels and technology advances. It also sets the (maximum) electricity consumption for broadband equipment sold in the EU and manufactured or procured by participating companies. The energy and technical characteristics of the device in idle state and on state are set out for each type of device, including home gateways.

In the US, vendors and service providers adopt the Voluntary Agreement for Ongoing Improvement to the Energy Efficiency of Small Network Equipment (first established in 2015), under which they agree to prioritize energy efficiency improvements but also not to hold back technology advances. The equipment covered includes local network equipment, broadband modems, and integrated access devices. The service provider signatories served nearly 95 million residential US internet subscribers at the end of 2022, accounting for 87% of the wireline internet access market.

Several standards to measure energy efficiency have also already been developed by various standards organizations. For example, the energy efficiency rating (EER) for telecommunications devices, which is defined in ITU-T L.1310, is expressed as a functional unit divided by the energy used. Various types of equipment have their own EER definitions. ATIS-0600015.2013 and ETSI EN 303 215 have provided detailed discussion on energy efficiency at equipment level.

These initiatives lead to great industrywide improvements in energy efficiency (e.g., in the US the weighted average power consumption of new small network equipment fell by 87% between 2015 and 2022, according to the “2022 Annual Report: Voluntary Agreement for Ongoing Improvement to the Energy Efficiency of Small Network Equipment”), but they also remain limited to only one area of concern for service providers.

However, examining the energy efficiency of the whole network is essential because it provides a way to determine the energy efficiency of transmitting information bits through an end-to-end network rather than per piece of equipment. Currently, this type of information cannot be derived from a simple superposition or average of the energy efficiency of individual equipment or system. It is therefore necessary to develop methods aimed at measuring network energy efficiency (NEE) on an end-to-end network level, considering both the end-user side (whether that is enterprise, home, or base station component) and the network side of NEE. Using this approach provides a comprehensive view of the whole network and enables measurement and evaluation of any improvements achieved by network architecture optimization in addition to those brought by new devices.

There are currently several ongoing standards projects focusing on determining network-level energy efficiency definition and measurement methodologies. In the fixed network domain, the fixed network energy efficiency (FNEE) standard is under discussion in both ITU-T and ETSI. FNEE considers multiple performance dimensions such as data traffic, transmission distance, network protection, network scalability, and other factors. The ***Appendix*** contains a detailed description of the suggested definition and calculation.

APPENDIX

DEFINITION OF NEE FOR FIXED NETWORKS

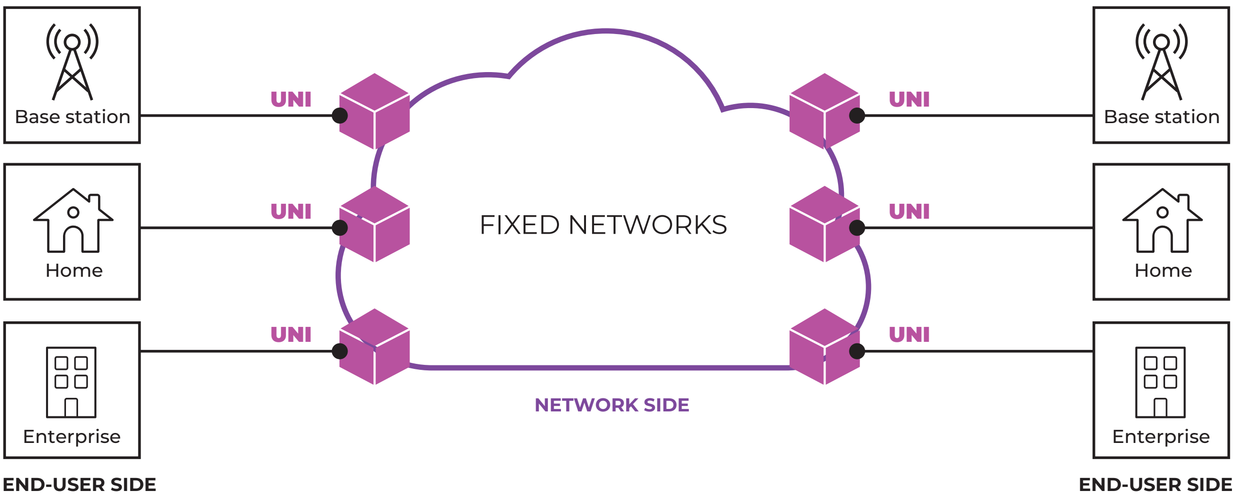
There are currently several ongoing standards projects focusing on determining a definition of and methodologies for measuring network-level energy efficiency. In the fixed network domain, the FNEE standard is under discussion in both ITU-T and ETSI.

A standardized definition of NEE is suggested to better evaluate the energy efficiency of the entire fixed network:

$$NEE_{network} = \frac{\sum \text{base station related UNI bitrate} + \sum \text{home related UNI bitrate} + \sum \text{enterprise related UNI bitrate}}{\sum \text{E2E network energy consumption}}$$

As suggested, the definition includes all components of the fixed network (see **Figure 8**).

FIGURE 8: FIXED NETWORK COMPONENTS TO BE INCLUDED IN NEE MEASUREMENT



SOURCE: HUAWEI

THE WAY FORWARD

An initial concept of FNEE also considers several performance dimensions, such as data traffic, transmission distance, network protection, network scalability, and other factors as outlined below.

Considering multiple dimensional performance, the EER of the fixed network is defined as follows:

$$NEE_{multi} = \frac{f(\text{data traffic, service protection, transmission distance ...})}{\sum \text{E2E network energy consumption}}$$

DATA TRAFFIC

A fixed network works as the fundamental infrastructure that is located at the bottom layer of ICT networks; it aims to ensure high-speed, long-distance, and large-capacity transmission. Moreover, it is employed to provide deterministic bandwidth for end users and provide the maximum pipe capability of the basic network during the specific planning period. Therefore, user network interface (UNI) bandwidth (BW) is selected to represent the data traffic of the fixed network, which is usually the bandwidth of the port on the service board, for example, the bandwidth of a wavelength-division multiplexing (WDM) tributary port, the line rate of a router port, and the rate of a PON port. The data traffic is represented as follows:

$$\textbf{data traffic} = \sum BS\ UNI\ BW + \sum home\ UNI\ BW + \sum enterprise\ UNI\ BW \ldots$$

SERVICE PROTECTION

More service protection in a fixed network means better performance of the network, but it introduces more ports and devices, which increases power consumption. Therefore, with the same UNI bandwidth, a fixed network with service protection has worse energy efficiency.

To compensate for the extra power consumption cost of service protection capacity, the protection factor A_{sp} ($A_{sp} \geq 1$) is proposed. The protection factor A_{sp} is proportional to the protection capacity.

TRANSMISSION DISTANCE

Long transmission distance means more relay devices and consumes more power, which leads to worse energy efficiency. A transmission distance factor A_{td} ($A_{td} \geq 1$) is considered to tolerate the power consumption caused by long-distance transmission. Longer transmission distance means bigger A_{td}.

NETWORK SCALABILITY

The network expansion capability can reflect the scalability of the network. Stronger expansion capability fulfills the service development requirements but can mean a large number of idle resources exist during the current period. This leads to indicators such as slot utilization, channel utilization, and bandwidth utilization being low, further influencing the energy efficiency of the fixed network. A network expansion capability factor A_{ec} ($A_{ec} \geq 1$) is introduced to balance the power consumption of idle resources.

OTHER FACTORS

There are other factors that affect the energy efficiency of fixed networks, such as network coverage, service-level agreements, and more.

ENERGY-EFFICIENCY METRIC

The energy efficiency of the fixed network based on multidimensional performance could be represented as follows:

$$\textbf{NEE}_{\textbf{network}} = \frac{\sum BS\ UNI\ BW + \sum home\ UNI\ BW + \sum enterprise\ UNI\ BW}{\sum\ network\ energy\ consumption} \times A_{sp} \times A_{td} \times A_{ec} \ldots$$

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