Fiber Broadband Networks, a Lower Carbon Alternative to Cable and Fixed Wireless Networks

A CARBON FOOTPRINT ANALYSIS:
FTTH / XGS vs. HFC / DOCSIS 4.0 in Suburban Deployments
and FTTH / XGS vs. FWA in Rural Deployments

AUGUST 2026
Sustainability Working Group

Fiber Broadband ASSOCIATION

When fiber leads, the future follows.

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EXECUTIVE SUMMARY

Communications service providers (CSPs) are pursuing improvements to their sustainability metrics with some aiming for net-zero carbon emission targets. Beyond carbon emissions, reducing electricity consumption will have a lasting impact on operators, consumers and society at large. The Fiber Broadband Association (FBA) Sustainability Working Group published "Fiber Broadband Deployment is Paramount to Achieving Zero Carbon Footprint, A carbon footprint analysis: FTTH vs. HFC/DOCSIS" in July 2024. That comparative study examined the carbon footprint, measured as carbon dioxide equivalent (CO_2e), across the product life cycle of fiber to the home (FTTH) using XGS-PON technology versus Hybrid Fiber Coax (HFC) using DOCSIS 4.0 technology for a suburban use case. This updated release includes this previous study and a new comparison of FTTH / XGS-PON versus fixed wireless access (FWA) for a rural use case.

The approach considers the network component manufacturing (embodied carbon), network builds and installation (installation carbon), and the yearly recurring operational electricity consumption (operational carbon). The operational electricity consumption examines each network technology in the two areas in which each differ: 1) access network segment and 2) customer premises equipment (CPE) segment. The access network segment calculates electricity consumption of the networking equipment used to offer broadband internet services in a serving area, such as a neighborhood. The CPE segment calculates electricity consumption of equipment to connect the home to the broadband internet service. The analysis determined that both HFC / DOCSIS 4.0 and FWA consume substantially more electricity than FTTH / XGS-PON technology. The higher electricity consumption impacts both service provider and consumer with higher reoccurring electricity costs as well as higher electrical grid demands on communities. Considering most of the grid is still fossil- fuel based, this results in higher CO_2e impacting the global environment.

KEY FINDINGS

HFC / DOCSIS 4.0 vs FTTH / XGS-PON technology for suburban [1]:

- network component manufacturing (embodied carbon) is 60% less for FTTH
- network builds and installation carbon is 7% less for FTTH
- operator's access network yearly electricity cost & CO_2e is up to 96% less for FTTH
- consumer's network equipment yearly electricity cost & CO_2e is up to 17% less for FTTH

FWA vs FTTH / XGS-PON technology for rural:

- network builds and installation carbon is 31% less for FTTH
- operator's access network yearly electricity cost & CO_2e is up to 98% less for FTTH
- consumer's network equipment yearly electricity cost & CO_2e is up to 70% less for FTTH

INTRODUCTION

The FBA's Sustainability Working Group studied the environmental impacts of broadband internet services. The specific intent of the working group and this paper was to examine the carbon footprint in the following life cycle stages:

1. Manufacturing Network Infrastructure Components and Systems,
2. Network Infrastructure Deployment and Buildout,
3. Network Operational Use (Electricity), and

The broadband internet technologies under study in this paper include:
- Fiber to the Home (FTTH) Using XGS-PON Technology
- Hybrid Fiber Coax (HFC) Using DOCSIS 4.0 Technology
- Fixed Wireless Access (FWA) Using Purpose-Built or Proprietary Technology

The FTTH internet working technology examined is XGS-PON (10-Gigabit-capable Symmetric Passive Optical Network) standards defined by the International Telecommunication Union (ITU) Telecommunication Standardization Sector, known as the ITU-T. Throughout this paper the terms fiber, FTTH, PON, and XGS-PON will be used to represent fiber broadband internet services.

The HFC internetworking technology examined is DOCSIS 4.0 (Data Over Cable System Interface Specification version 4.0) using Extended Spectrum DOCSIS (ESD) defined by CableLabs. The terms HFC and DOCSIS will be used to represent the typical approach for Cable broadband internet services. Though ITU-T 50 Gigabit-capable PON technologies will emerge about the same time as DOCSIS 4.0, the working group chose to examine the current XGS-PON technology as this will be used in most cases. Cable Operators have used PON for over two decades, initially for business services, then new build (green field) to residential consumers, FTTH, and in some cases cable operators have overbuilt HFC with FTTH. However, in most cases Cable broadband internet services are delivered via HFC and DOCSIS networks as of the date of this publication. The use of FTTH has been widely embraced by incumbent telecommunications (Telco) broadband internet providers with many overbuilding substantial portions of their existing copper twisted pair telephone network that once used digital subscriber line (DSL) for broadband internet services. Of course, beyond Cable and Telco operators, over 1,100 Fiber Broadband Service Providers have deployed FTTH and PON technology for many years, and these deployments continue to grow rapidly.

Fixed wireless access (FWA) provides high-speed internet connectivity to homes and businesses as a last mile solution using radio waves instead of wired connections. These radio waves carry data that is transmitted between equipment at the provider's tower and subscriber's home. FWA has several network technology options as well as spectrum or frequency band choices. FWA can use cellular-based broadband technologies such as 4G LTE and 5G, Wi-Fi 6E / Wi-Fi 7, or purpose-built proprietary technologies. The FWA internetworking technology examined in this paper is based on purpose-built or proprietary networking hardware and software that may use 3 GHz, 5 GHz or 6 GHz spectrum. Wireless internet service providers (WISPs) frequently use unlicensed, shared and exclusive-use licensed spectrum at low-band, mid-band and high-band frequencies, predominantly in rural, unserved, and underserved areas [13]. There are an estimated 2,000 WISPs across the United States extending broadband to underserved, mainly rural areas in recent years [14]. There are pockets of the country where FWA is the only viable broadband technology due to the costs to build, deploy, and maintain a network in some remote rural areas [14]. Traditional mobile operators may use 5G cellular-based broadband technologies with licensed and unlicensed spectrum to offer FWA services in urban, suburban and rural markets [15]. The use of FWA has expanded beyond WISPs and mobile operators in recent years to include rural telephone, cable and electric cooperatives, however many of these providers have adopted a fiber first strategy using FWA as a last resort or temporary solution until FTTH is deployed.

The carbon footprint calculations are based on current sources; however, continuous improvements are taking place across both ecosystems, thus these findings will continue to evolve. For example, companies in these ecosystems are working to reduce materials, packaging, and power usage, and there will be an increase in the use of recycled materials and renewable electricity sources, all of which will reduce carbon footprint. Some businesses are embracing the concept of a circular economy, where materials are recycled to reduce waste. While a 100% circular economy is impractical with current and near-term technologies, adoption of such philosophies will result in continued reduction of carbon footprint.

OVERVIEW

Fiber deployments are gaining momentum around the world. Optical fiber satisfies the bandwidth demand of today and will best satisfy future demand because of its ability to support virtually unlimited symmetric bandwidth. The latest fiber networks for home users can deliver 2,000 times higher bandwidth and over 7 times longer distances for the same number of users vs. legacy ADSL networks, making fiber the best choice [2].

Shutting down legacy ADSL copper networks and migrating to all-fiber solutions has become a priority for Telcos, since it enables them to reduce cost and drastically lower yearly carbon emissions while delivering far superior services in terms of broadband speed, latency, and overall reliability. In 2023, altafiber stated that its legacy copper network contributed to 39% of its greenhouse gas emissions, making it a prime target for replacement [3]. When looking at the raw materials and manufacturing of optical fiber and copper, Corning calculated that a twisted copper pair used in ADSL networks has a carbon footprint that is 6 times higher than that of an optical fiber of the same length [2].

Fiber to the home (FTTH) with passive optical network (PON) technology and fixed wireless access (FWA) technology are the newest types of access networking technologies providing data communication services to both residential consumers and businesses. These technologies are used across the telecommunications industry to include the large traditional Cable and Telco service providers to smaller regional and municipal service providers.

Many service providers that were traditional telephone operators that used twisted pair copper cables for both telephone and internet services have been overbuilding those legacy networks with FTTH and in some cases using FWA. It should be noted that the cable industry has, for the most part, adopted a “fiber first” strategy for greenfield and expansion builds to deliver more competitive broadband performance, while benefiting from the installation, operational cost and performance advantages of fiber networks. Some cable operators have selected areas to overbuild HFC with FTTH using PON technology with no, or dramatically fewer, active components [powered devices] than HFC networks. Cable operators have also been deploying FWA in some areas as well.

METHODOLOGY

The Greenhouse Gas (GHG) Protocol is a globally recognized standard for measuring and managing greenhouse gas emissions[4]. This document leverages the Life Cycle Assessment (LCA) methodology and calculations methods established by the GHG protocol to compare the carbon footprint of two different networks: an all-fiber network and an equivalent HFC network serving the same number of households. Different life cycle stages are evaluated, from raw material extraction and manufacturing to network installation and operation, to end-of-life.

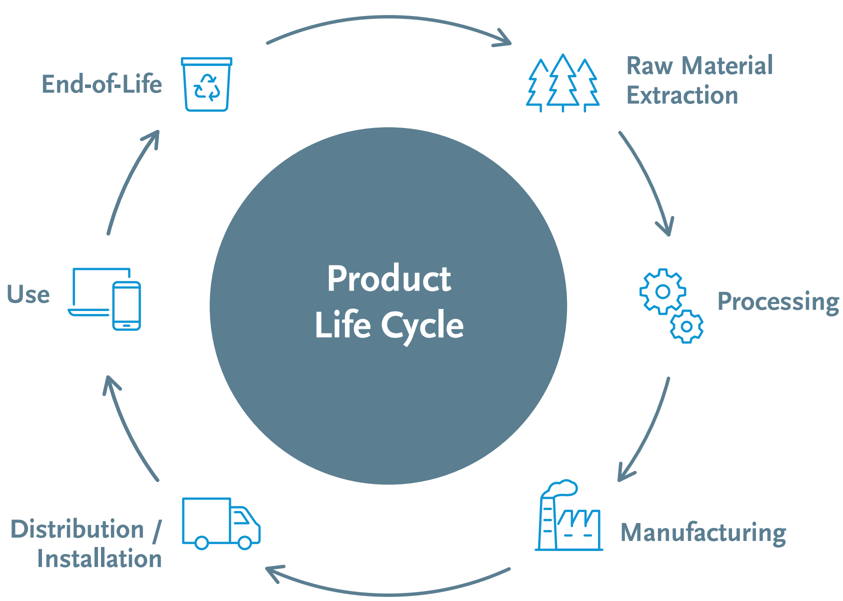

Figure 1: Stages of a Product Life Cycle

For each life cycle stage analyzed, carbon footprint is stated in kgs of carbon dioxide equivalents (CO_2e), and for ease of comparability, is normalized to a per homes passed (HP), and per homes connected (HC) basis. We then apply a subscriber penetration to assess the carbon on a per subscriber basis. Figures 2 and 3 illustrate the outside plant (OSP) network architectures used for this analysis. However as shown further in the paper the data networking systems examine several FTTH XGS-PON and HFC DOCSIS architectures.

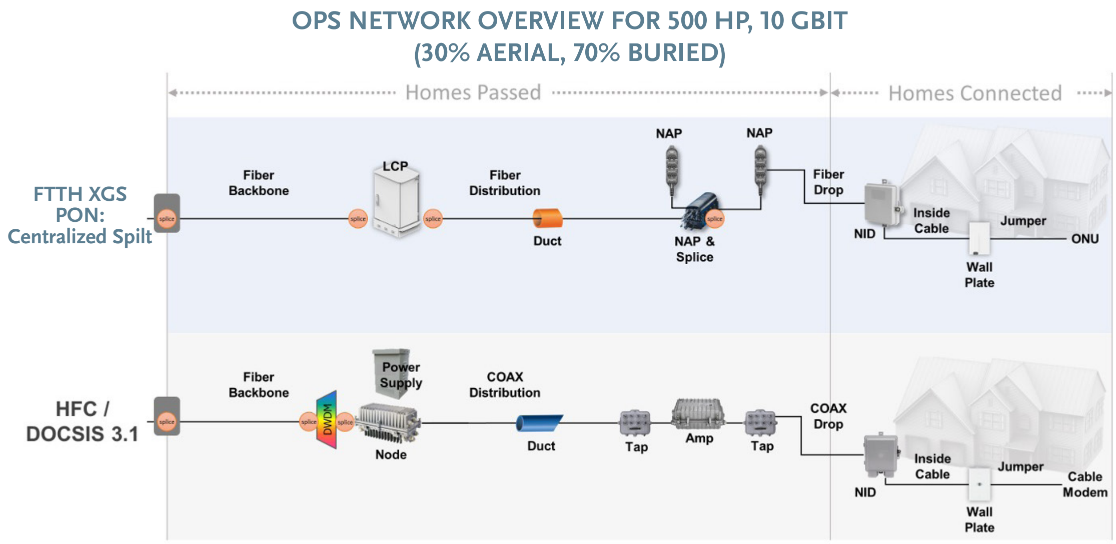

Figure 2: Outside Plant Network Overview of FTTH vs. HFC

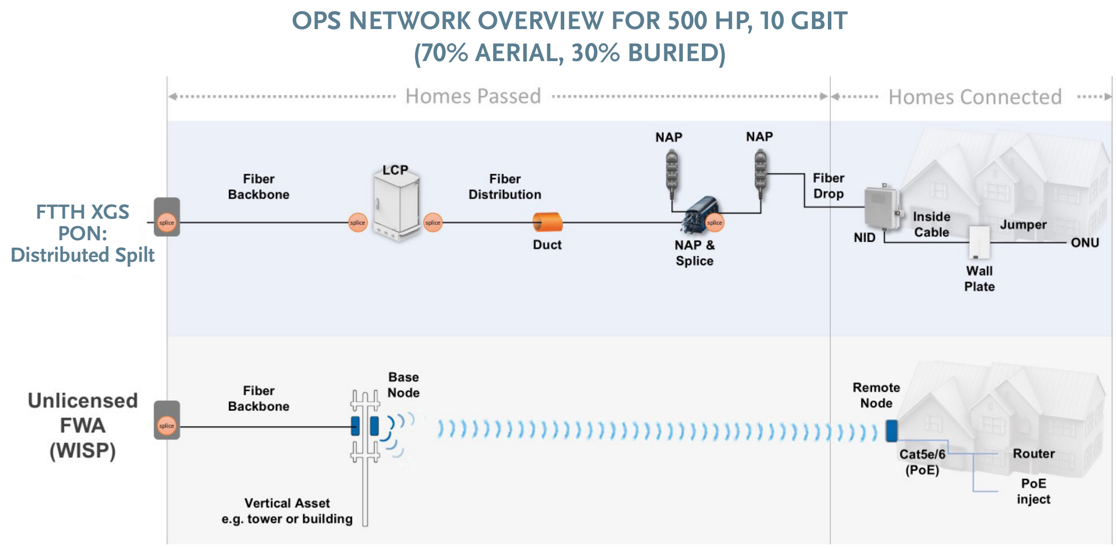

Figure 3: Outside Plant Network Overview of FTTH vs. Unlicensed FWA

For consistency in comparative analysis, we normalize each architecture to the service-group sizes defined in the underlying analyses—for example: FTTH assumes 64 homes passed per XGS PON port and a maximum achievable penetration of 100% (64 subscribers), HFC Remote PHY is modeled on a 400 homes passed serving area and a maximum achievable penetration of 100% (400 subscribers), and FWA homes-passed serving area may vary and the service take rates or penetration rate maximums are determine by FWA's data network capacity to meet the subscriber traffic loading. The actual number of subscribers supported in FWA network is largely based on network data capacity rather than coverage area. Traffic engineering methods are used to calculate the subscriber usage or traffic during busy hours to determine the number of subscribers that FWA can support in a serving area as described in section below titled "key findings comparing FTTH vs. FWA data capacity".

The manufacturing of network infrastructure components estimates the carbon footprint of each OSP network based on the quantities and types of materials required to support a greenfield deployment serving 500 suburban homes. A DOCSIS 3.1 architecture was used for the HFC model, as material specifications for DOCSIS 4.0 equipment were not available at the time of this analysis. Unlicensed FWA technology was not evaluated from an embodied carbon perspective due to available data limitations.

The network deployment and buildout analysis estimates the carbon footprint associated with installation activities for both networks, including the number of installation truck rolls and the use of on-site generator power. The network operational use analysis examines the electricity used to power networking equipment and estimates carbon footprint on an annual basis. The analysis includes electrical consumption used to power the broadband access network elements and the terminating CPE for all network types. The previous paper also discusses removing and recycling network infrastructure components, but additional analysis is needed to assess their quantitative effects on carbon footprint.

MANUFACTURING NETWORK INFRASTRUCTURE COMPONENTS & SYSTEMS

To estimate the carbon footprint associated with the manufacturing of the different components of the network, three lifecycle stages need to be considered: raw materials extraction, processing, and manufacturing. While there are published Life Cycle Assessments (LCAs that quantify the carbon footprint for certain network components such as optical fiber/cable, printed circuit boards (PCBs), and copper/copper cable, LCAs do not exist for the exact components used within these networks. Where LCAs are not available, the average-data method is used. The average-data method calculates carbon emissions based on the mass of a purchased good and an industry average emission factor [5].

Average-data method as defined by the GHG Protocol

$$CO_2e \text{ emissions for purchased goods} = \Sigma \text{ (mass of purchased good (kg)} \times \text{emission factor of purchased good per unit of mass (kg CO2ekg/))}$$

Optical fiber's carbon footprint has been calculated through an earlier LCA study from Corning. For other elements, most of the mass of network components is composed of common metals, such as aluminum, steel, copper, and/or different types of polymer raw materials. Emission factors used in the analysis are shown in Table 1 [6].

MATERIAL	EMISSION FACTOR	UNIT	SOURCE
Aluminum	8.79	kg CO_2e / kg	IPCC AR5 report
Steel	2.63	kg CO_2e / kg	IPCC 2013 GWP 100a V1.03
Mixed Metals	5.71	kg CO_2e / kg	Average of Steel and Aluminum
Copper	4	kg CO_2e / kg	https://sphera.com/2022/xml-data/processes/35a4b3f7-6e52-4e31-9894-e09d72bc0367.xml
Polymer Concrete	0.1480	kg CO2e / kg	https://www.materialstoday.com/download/88823/
Plastic	2.3	kg CO2e / kg	https://v391.ecoquery.ecoinvent.org/Details/LCIA/5485ef2b-55d1-4394-a2b8-5a4fd9e002a4/290c1f85-4cc4-4fa1-b0c8-2cb7f4276dce
Optical Fiber	2.3	kg CO2e / km	https://www.corning.com/media/worldwide/coc/documents/Fiber/white-paper/WP1000.pdf
PCB	18.6	kg CO_2e / M2	Life cycle assessment of a printed circuit board manufacturing plant in Turkey (springer.com)

Table 1: Emission Factors Used in Carbon Footprint Calculations

To enable a side-by-side comparison, the same emissions factors are used for FTTH and HFC networks, with the primary differences being the total mass of the different components contained in the respective networks.

The example calculation below compares one component of the OSP network, the distribution cabling.

	FTTH OSP NETWORK	HFC OSP NETWORK
	ALTOS® Lite Loose Tube, Gel-Free, Single-Jacket, Single-Armored Cable 144 F, Single-mode (OS2)	Coaxial Hardline Cable P3® 750 JCASS SM MT
Length	1 km	1 km
Weight / Length	**247 kg/km**	**399 kg/km**
Optical Fiber	144 km	•
Copper	•	20 kg/km
Plastic	161 kg/km	160 kg/km
Aluminum	•	233 kg/km
Steel	69 kg/km	•
Carbon Footprint	**883 kg CO_2e**	**2,408 kg CO_2e**
Optical Fiber	144 km x 2.3 kg CO_2e/km = 331	•
Copper	•	1 km x 20 kg/km x 4 kg CO_2e/kg = **80**
Plastic	1 km x 161 kg/km x 2.3 kg CO_2e/kg = 370	1 km x 160 kg/km x 2.3 kg CO_2e/kg = **368**
Aluminum	•	1 km x 223 kg/km x 8.79 kg CO_2e/kg = **1,960**
Steel	1 km x 69 kg/km x 2.63 kg CO_2e/kg = 182	•

Table 2: Comparison of Carbon Footprint for 1 km of Distribution Cable (Buried Application) for an FTTH and HFC OSP Network

A similar calculation was done for each of the network components and the estimated total carbon footprint for each network is the sum of the carbon footprint of each of the components. Given the similarities between the Central Office (FTTH) and Head End (HFC) network components, the carbon footprint analysis is centered on the OSP portion of the network.

KEY FINDINGS

According to the analysis, the **carbon footprint associated with manufacturing the components of an all-fiber network is approximately 60% less than that of an equivalent HFC network.**

One primary difference is driven by use of cables in the all-fiber network that are smaller and lighter than those used in an HFC network. The optical fiber cables used for distribution, home connection, and in-resident cabling have on average 60% less carbon footprint than the coax cable used for the same purposes.
In the example of the distribution cable above, there are approximately **38% fewer materials needed for every km of optical fiber distribution cable compared to a coaxial hardline distribution cable.**

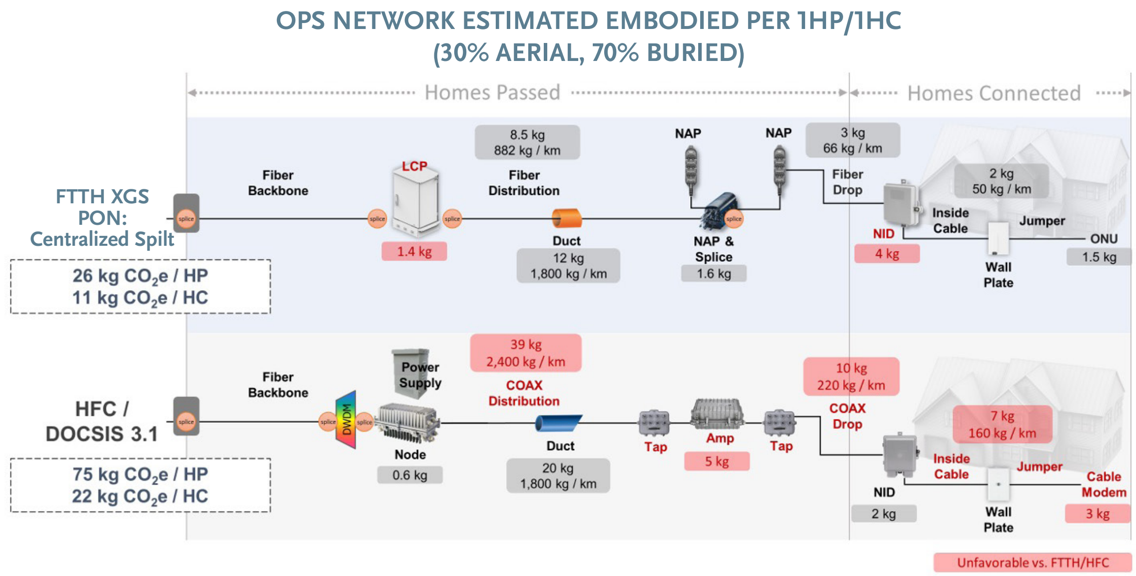

Figure 4: Carbon Footprint Associated with the Manufacturing of Network Components (Embodied Carbon), Comparison of All-Fiber and HFC OSP Network

Fiber networks benefit from fewer hardware requirements for home connections, unlike HFC networks that need additional active (powered) hardware components in the outside plant to amplify signals for similar distance and speed.

As illustrated in Figure 4, all-fiber OSP networks reduce embodied carbon by 65% for each home passed and by 50% for each home connected (vs. HFC networks).

These estimates are likely understated as they do not consider the energy and electricity used in manufacturing components, or the effects of delivering the final product to the communications service provider. Earlier LCA studies have shown that an increase in material mass correlates with greater energy and electricity consumption during manufacturing. Additionally, as material mass increases, efficiency in transportation decreases, leading to a higher carbon footprint.

A similar approach is applied in this new study, however, due to a lack of data availability, the embodied carbon associated with the manufacturing of network components for unlicensed FWA is not included. However, for FTTH rural deployment, the embodied carbon for network component manufacturing is calculated to be 25 kg CO_2e per home passed (HP) and 13 kg CO_2e per home connected (HC).

Although rural deployments require approximately twice as much distribution cable and more network access points due to lower household density, the use of lower fiber count cables (24F in rural vs. 144F in suburban) offsets this increase, leaving the carbon footprint contribution per HP of the distribution cable relatively unchanged. FTTH network's embodied carbon per subscriber at 50% take rate is 76 kg CO_2e per subscriber.

The differences between a suburban and a rural architecture for FTTH are described below:

ARCHITECTURE ELEMENT	SUBURBAN VS RURAL
Design Basis (DA size)	Both designs use a 500-homes-passed design area
Density (HH/sq mi)	Suburban: 1,000 HH/sq mi; Rural: 100 HH/sq mi (drives longer route miles "and broader serving geometry in rural).
Lot Frontage / Spacing	Suburban: 60 ft lot frontage; Rural: 145 ft lot frontage (fewer homes per route mile in rural, approximately 72 homes/route-mile assuming both
Split Topology	Suburban: Centralized Split (1x32); Rural: Distributed Split (1x8; 1x4). Centralized vs Distributed Split drives cabinet/closure placement and how distribution laterals are fed (affects field complexity and where splicing occurs).
Aerial vs. Buried Mix	Suburban: 30% aerial / 70% buried; Rural: 70% aerial / 30% buried (rural aerial-heavy assumption).
Feeder (within one DA)	Suburban feeder length shown ~1,922 ft; rural materials show feeder of similar order (~1,922 ft) with different fiber count (suburban 24F vs rural 12F).
Distribution Scale Indicator	Rural materials show total distribution cable length 38,961 ft (≈39k ft); suburban distribution in the suburban BOM shows distribution segments of 15,976–15,732 ft (aerial/buried).
Terminal Utilization Planning	Both designs assume 75% terminal utilization and homes on both sides of the distribution cable (planning basis for homes passed).

Table 3: **Key Architectural Differences Between FTTH Suburban (Central Split) and Rural (Distributed Split) Reference Designs (both Modeled for 500 homes).**

Distribution route length is internally consistent with lot frontage when assuming homes on both sides of the road; minor overlength reflects branching/splicing allowances.

NETWORK INFRASTRUCTURE DEPLOYMENT AND BUILDOUT

The carbon footprint associated with the installation of networks is calculated based on the amount of fuel burned, either diesel or gasoline, and total distance traveled. The amount of fuel burned is estimated based on the number of trips from the garage to the worksite and back, the time engines run on site either in idle or moving during construction, and the use of generators for electricity at work sites.

Standard emission factors from a typical passenger vehicle, as defined by EPA, are used and shown below [7].

How much tailpipe carbon dioxide (CO_2) is created from burning one gallon of fuel?

- CO_2 emissions from a gallon of gasoline: 8,881 grams CO_2/gallon
- CO_2 emissions from a gallon of diesel: 10,180 grams CO_2/gallon

KEY FINDINGS

When determining the carbon footprint on a per-home basis, installation of an all-fiber network is estimated to generate approximately 15.8 kg of CO_2e for each home, which is 7% less than the estimated 17kg of CO_2e when installing an HFC network. Most of the carbon footprint in both networks arises from boring and pulling cable, with any additional CO_2e from the HFC network attributed to the requirement of additional taps and amplifiers. When looking at homes connected, both all-fiber and HFC have equivalent carbon footprints of about 9 kgCO_2e per home connected. For context, the installation carbon footprint for passing a home in either network equates to the emissions from burning approximately 2 gallons of gasoline, with connecting those homes accounting for another gallon's worth of emissions on average.

OPS NETWORK INSTALLATION CARBON PER 1HP/1HC (30% AERIAL, 70% BURIED)

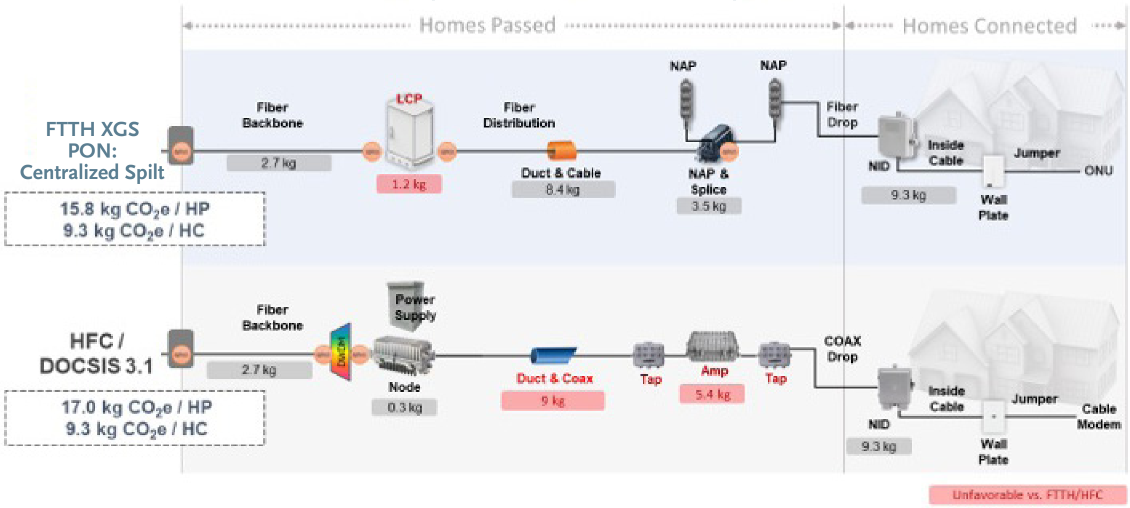

Figure 5: Carbon Footprint Associated with Network Installation, Comparison of All-Fiber and HFC OSP Network

Similarly, using Corning's FTTH deployment data and a FWA study published by Tarana ([Source: Tarana white paper]), the comparison finds FTTH installation results in 320 kg CO2e per subscriber (assuming a 50% penetration), versus 466 kg CO_2e for FWA (based on 14 subscribers).

FTTH: CORNING STUDY	
Trench a Mile of Cable	
Time (Days)	5.28
Fiber Conduit per Day Trenched (Feet)	1,000
Trencher Diesel Fuel Uses per Hour (gph)	3
Diesel (Gallons)	127
CO_2e per Gallon of Diesel Fuel (lbs)	22
CO_2e (lbs/mile)	2,844
Workforce Responsible for Laying a Mile of Cable	
Works (Total)	12
Daily Roundtrip Drive to Worksite (Miles)	50
Total Commute per Mile of Fiber	288
Average US Fuel Economy (mpg)	11
Gasoline Consumed per Mile (Gallons)	26
CO_2 per Gallon of Gasoline (lbs)	20
CO_2 (lbs/miles)	511
Total Miles/Subscriber	.11
Take Rate	**50%**
Total lbs CO_2 per Subscriber	**705**
Total kgs CO_2 per Subscriber	**320**

FWA: TARANA G1 STUDY	
Erect a Tower	
Time (Days)	10
Trencher Diesel Fuel Use per Hour (gph)	32
Diesel (Gallons)	2,544
CO_2e per Gallon of Diesel Fuel (lbs)	23
CO_2e (lbs/tower)	57,240
Workforce Responsible to Erect a Tower	
Works (Total)	5
Daily Roundtrip Drive to Worksite (Miles)	20
Total Commute per Mile of Fiber	1000
Average US Fuel Economy (mpg)	25
Gasoline Consumed per Mile (Gallons)	39
CO_2 per Gallon of Gasoline (lbs)	19
CO_2 (lbs/tower)	764
Tower Availability	75%
Subscribers per Tower	**14.1**
Total lbs CO_2 per Subscriber	**1,028**
Total kgs CO_2 per Subscriber	**466**

Figure 6: Key Assumptions [Source: Corning Internal Data vs. Tarana G1 Study].

NETWORK OPERATIONAL USE (ELECTRICITY)

The electricity used to power networking equipment will continue to generate carbon emissions if non-renewable electricity sources are used. This analysis is based on several models built to examine the electricity consumption and thus operational carbon footprint of networks using FTTH with XGS-PON (10 Gigabit Symmetrical PON) technology and HFC with DOCSIS 4.0 ESD technology. These models examine different deployment architectures that affect power consumption, accounting for both the service provider's access network and the customer-powered CPE.
Despite technological differences, their core network functions are similar, allowing a direct comparison of electricity usage and the resulting operational carbon footprint.

The telecom sector recognizes that all-fiber networks consume less power due to fewer powered network devices needed to carry data signals between the provider's facility and the consumer's home. Most broadband service providers using fixed wireline networks have transitioned to fiber to the home for new constructions. Both Telco and Cable providers with existing service areas using copper twisted pair or coaxial cables to the home respectively, known as brownfield, have transitioned some of those legacy networks to fiber to the home, albeit at different rates. Upfront costs make transitioning legacy networks to FTTH a careful consideration decision. This paper does not suggest that a shift e.g. to FTTH should be based solely on energy savings and carbon footprint reduction. Other factors including fiber's superior performance, reliability and durability are also vital. As both Telco and Cable providers use FTTH in both new builds and brownfield overbuilds, this paper highlights the carbon footprint benefits of adopting FTTH and PON technologies. This section examines the electricity consumption of FTTH using XGS-PON technology in several system architecture types. These include configurations where the Optical Line Terminal (OLT) is installed in central offices or headend facilities, placed within street cabinets, and integrated into aluminum node housings that are mounted on cables strung between telephone poles or situated on the ground.

Additionally, this section also examines the use of HFC networks using DOCSIS 4.0 ESD technology across different architecture types such as remote PHY device (RPD) attached to a virtual Cable Modem Termination System (vCMTS), as well as the remote MACPHY device (RMD) architecture that functions independently of a vCMTS and its related network equipment.

FTTH Using XGS-PON Technology Electricity Consumption and Carbon Footprint

All use cases assume a 64-way split and the applicable distances are based on current optical technologies, meaning each XGS-PON port could serve up to 64 homes or customers connected. Some providers might opt for a 128-way split, which would reduce the serving area distances, but improve energy efficiency and carbon footprint per homes passed. However, we present data assuming the more typical 64-way split to reflect common practice.

As shown in Figure 7, the facility-based OLT assumes a unified system architecture that consolidates Broadband Network Gateway (BNG) as well as OLT functions, and this system architecture does not require any powered network equipment in the outside plant. This assumed an OLT in a temperature-controlled facility using C-temp class E1 double density optics to support a 64-way split over up to 20 kilometers (km)of distance between the OLT and Optical Network Unit (ONU) serving area. This system architecture represents the lowest power solution for the access network segment.

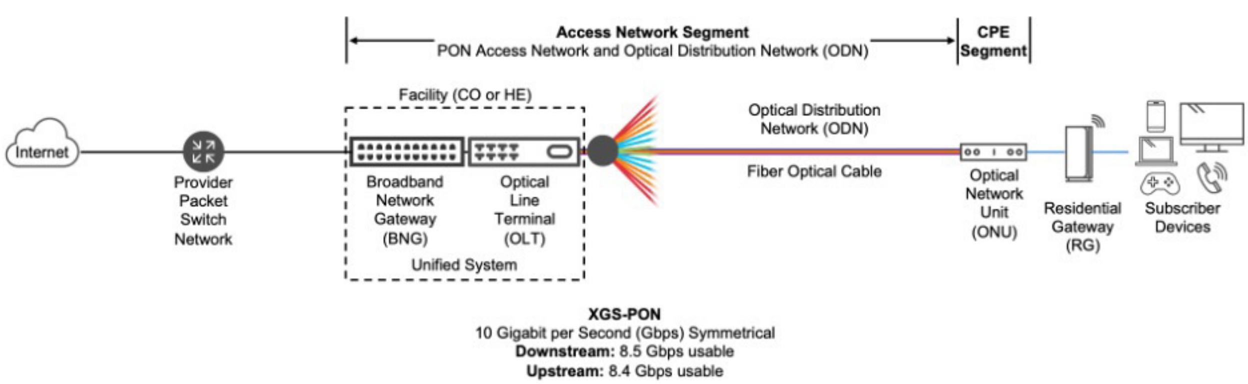

Figure 7: Facility-Based OLT and BNG Unified System

Figure 8 illustrates an OLT in an uncontrolled temperature street cabinet using I-temp class N2 double density optics to support a 64-way split over up to 18.7 km of distance between the OLT and ONU serving area. This assumes a layer 2 OLT that is performing traffic management functions, and an aggregation router that is placed at the facility to connect to the OLT.

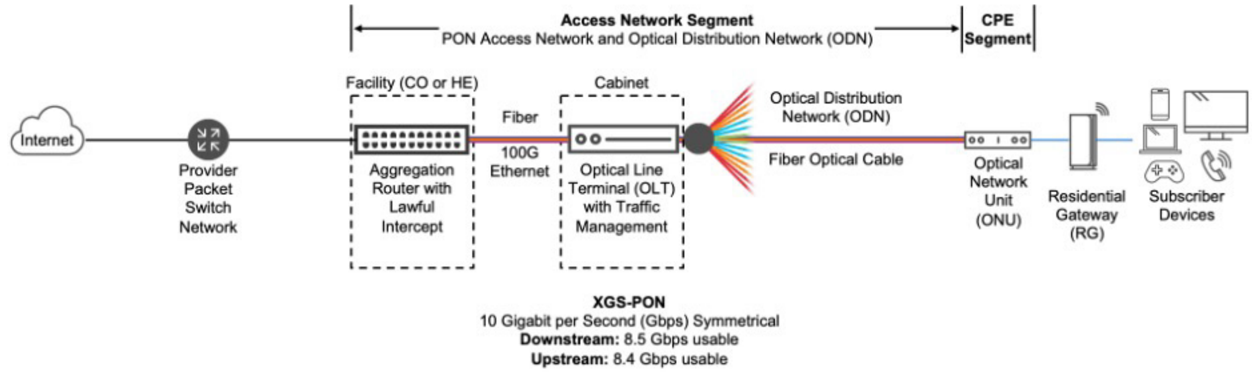

Figure 8: Cabinet-Based OLT System

Figure 9 illustrates an OLT in a temperature hardened node housing using I-temp class E1 optics to support a 64-way split over up to 23.2 km of distance between the OLT and ONU serving area. This assumes a layer 2 OLT that is performing traffic management functions, and an aggregation router that is placed at the facility to connect to the OLT.

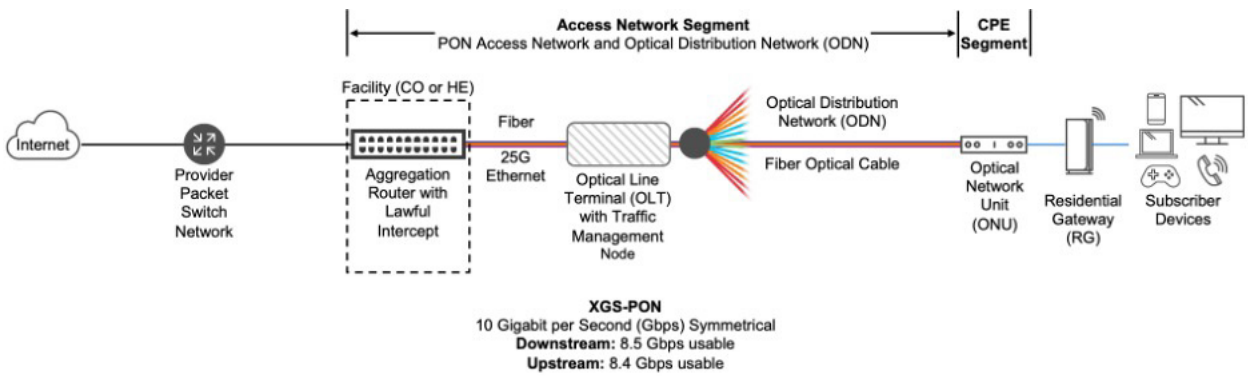

Figure 9: Node-Based OLT System

The FTTH using XGS-PON customer premises equipment segment is the same for all models and had a maximum annual electricity consumption of 105.1 kilowatt hours (kWhs) and an associated annual carbon footprint of 43.84 kilograms of CO_2e.

HFC Using DOCSIS 4.0 ESD Technology Electricity Consumption and Carbon Footprint

The electricity consumption of HFC using DOCSIS 4.0 ESD technology in the system architecture of remote PHY device (RPD) with a virtual CMTS (vCMTS) as well as the required networking components is shown in Figure 10. DOCSIS 4.0 ESD assumes a spectrum band plan ranging from 5 MHz to 1794 MHz, with the upstream occupying 5 to 492 MHz and the downstream ranging from 588 to 1794 MHz, which would have the data capacity to compete with XGS-PON. It is assumed the spectrum is entirely DOCSIS 3.1/4.0 technology and digital video spectrum has been removed to maximize data capacity.

Figure 10 is a high-level illustration of the HFC and DOCSIS networking systems. It shows the access network segment, highlighting the components that contribute to power calculations in the analysis. The illustration is based on an area serving 400 homes passed (HP), with details on OSP network elements like the DOCSIS 4.0 1.8 GHz Remote PHY (RPD) Node, ten 1.8 GHz Bridger Amplifiers, and fourteen 1.8 GHz Line Extender Amplifiers, drawing from power estimates in a published SCTE 2022 paper[8]. The HFC using DOCSIS 4.0 ESD customer premises equipment segment had a maximum annual electricity consumption of 127.9 kWhs and an annual carbon footprint of 53.33 kilograms of CO_2e.

The key findings of the SCTE paper, complemented by our analysis, reveal that energy consumption for HFC and DOCSIS is predominantly attributed to outside plant network elements. Our findings indicate that such elements account for more than 98% of the power consumed by the network's access segment, with the remaining approximately 2% of power allocated to the shared network devices in the access network segment, to include the aggregation router, leaf switch-router, and vCMTS. The remote MACPHY system architecture is also examined but had an insignificant improvement in power consumption and carbon footprint. This is attributed to the high-power usage of the outside plant network equipment, even when data center components are unnecessary, as shown in Table 4.

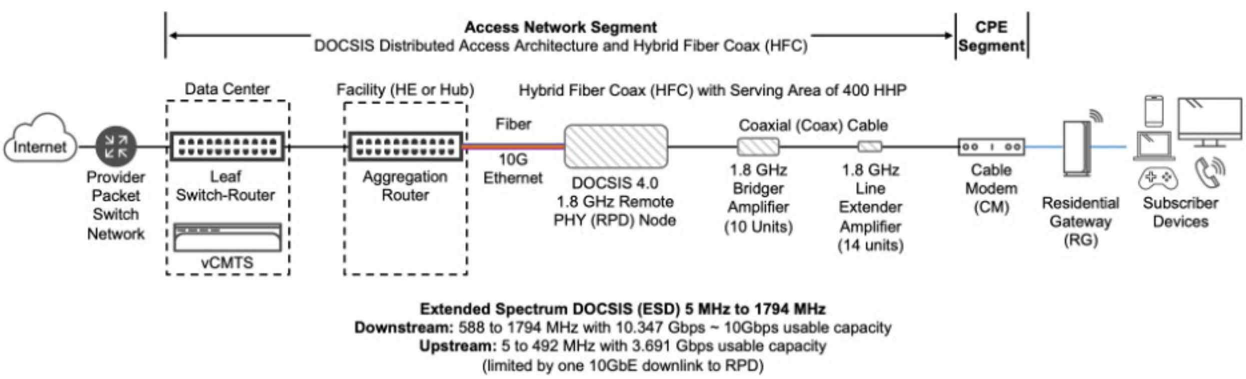

Figure 10: DOCSIS 4.0 ESD Using vCMTS and Remote PHY

The Working Group sourced electricity consumption and capacity data for BNG, OLT, and ONU sourced from Calix, DOCSIS 4.0 1.8 GHz Remote PHY Node and amplifiers sourced from CommScope[8], vCMTS server and chip data from Intel Corporation[9], aggregation router data from Arista Networks [10], leaf switch-router data from Arista Networks[11], and DOCSIS 4.0 ESD cable modem data from Hitron[12].

KEY FINDINGS COMPARING FTTH VS. HFC ANNUAL ELECTRICITY CONSUMPTION AND CO_2E

A DOCSIS 4.0 HFC access network requires considerably more electricity and therefore results in a higher carbon footprint than a comparable XGS-PON network by any metric, either per homes passed or per subscriber.

FTTH XGS-PON network technology reduces power consumption and operational carbon footprint by 93% to 96% when compared with HFC and DOCSIS 4.0 ESD.

TECHNOLOGY	ACCESS NETWORK SEGMENT	ANNUAL KILOWATT HOURS (KWH)S PER HP	ANNUAL KILOGRAMS CO2E PER HP	ANNUAL FTTH / XGS-PON DECREASE COMPARED TO HFC / DOCSIS 4.0 RPD
FTTH / XGS-PON	Facility-based OLT with 64 HHP per port	1.01	0.42	96.4%
FTTH / XGS-PON	Cabinet-based OLT with 64 HHP per port	1.19	0.50	95.7%
FTTH / XGS-PON	Node-based OLT with 64 HHP per port	2.00	0.83	92.8%
HFC / DOCSIS 4.0	Remote PHY and vCMTS (RPD)	27.66	11.53	•
HFC / DOCSIS 4.0	Remote MACPHY Device (RMD)	27.29	11.38	•

Table 4: FTTH / XGS-PON vs. HFC / DOCSIS 4.0 Access Network Segment Electricity & CO_2e

Although less pronounced, fiber technology also offers significant carbon footprint savings over HFC at the customer's premises. A typical XGS-PON ONT is responsible for 43.84 kilograms of CO_2e annually, in contrast to 53.33 kilograms from a DOCSIS 4.0 cable modem, resulting in a 17.8% decrease in carbon footprint for the XGS-PON ONT.

HFC and DOCSIS systems have high electricity consumption due to outside plant network components, including the DOCSIS RPD node and amplifiers. FTTH and XGS-PON have no outside plant powered network elements or use minimal power when cabinet or node based OLTs are placed in the outside plant, serving a wide area of customers.

FWA Technology Electricity Consumption and Carbon Footprint

The FWA internetworking technology examined is based on purpose-built or proprietary networking hardware and software that may use 3 GHz, 5 GHz or 6 GHz spectrum. There are several companies offering purpose-built FWA solutions, and the study sources publicly available materials for the analysis of electricity consumption, data capacity and CO_2e. The FWA reference network, shown in Figure 11, uses source data from Tarana Networks' purpose-built proprietary FWA base nodes (BNs) and remote nodes (RNs) that enable wireless connectivity between the tower and homes and businesses. The additional networking components are required to deliver an FWA broadband internet experience. These include a virtual BNG (vBNG) with source data from Intel Corporation as well as leaf switch-router and aggregation router with source data from Arista Networks.

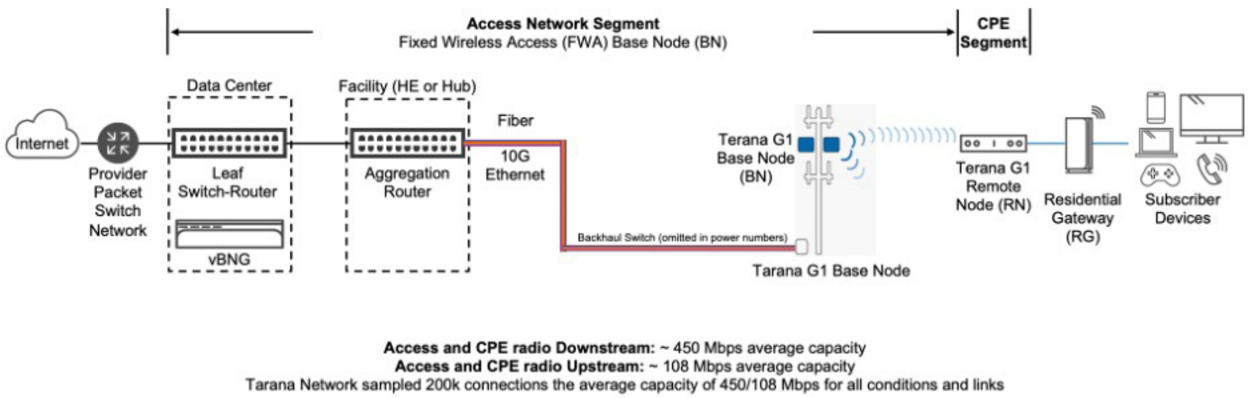

Figure 11: Fixed Wireless Access (FWA)

The FWA industry may use licensed 3 GHz and unlicensed spectrum 5GHz and 6GHz bands. The 3 GHz spectrum band between 3.550 – 3.700 GHz, known as Citizens Broadband Radio Service (CBRS) or Band 48, is 150 MHz wide in the United States. The CBRS band does not always require a license. It uses a three-tiered system of incumbent access for licensed, priority access licenses, and general authorized access, which is licensed-by-rule, allowing open access without a specific, individual license. The 5 GHz band for FWA utilizes unlicensed spectrum that can occupy 5.1 – 5.8 GHz designated by the FCC. The 6 GHz FWA does not require a license in the U.S., as the FCC has authorized it for unlicensed shared use. The FCC authorized 1,200 MHz of spectrum that can occupy 5.925 – 7.125 GHz for unlicensed use, enabling Wi-Fi 6E, Wi-Fi 7, and outdoor FWA. The outdoor use of 6 GHz FWA must use Automated Frequency Coordination (AFC) to protect existing licensed microwave incumbents. The use of 5G cellular-based broadband technologies offers additional spectrum choices.

The electrical consumption estimates in the FWA analysis use published data from Tarana Networks' next-generation fixed wireless access (ngFWA) G1 base nodes (BNs) and G1 Remote Nodes (RNs). Tarana has several G1 BN products, each designed for specific spectrum bands or frequency covering 3 GHz, 5 GHz bands, or a G1 BN supporting both 5 GHz & 6 GHz bands and all share a power consumption of 275 watts assuming a typical 55°C temperature[16]. The newer G2 BN product supports all the spectrum bands and thus has greater data capacity and higher power at 420 watts. The analysis assumes the G1 base nodes. FWA BNs are placed on a tower in the community serving area and the service provider builds fiber optic cable to connect to the FWA BNs. The FWA base node provides wireless access to a serving area, and the number of homes that could be served depends on many factors. The FWA base nodes alone do not provide internet connectivity. Figure 11 illustrates the additional networking equipment needed to enable broadband internet service delivery. The aggregation router, leaf switch-router and virtual BNG server platform provide connectivity and subscriber network processing for many FWA base node serving areas, thus are shared. The electricity consumption for those shared access segment systems has an allocated electricity consumption per FWA base node serving area of 22.92 watts. Our findings calculate 297.92 watts per FWA access network segment, assuming FWA BN at 275 watts and the additional equipment at 22.92 watts. The FWA base node element accounts for 92.3% of the total electricity in the access network segment with the remaining 7.7% for the shared network elements. Examining the FWA access network segment at 292.92 watts over 24 hours and 365 days a year operation has an annual electricity consumption of 2609.75 kilowatt hours (kWhs) with an annual carbon footprint of 1088.27 kilograms of CO_2e.

The electricity consumption of FWA access network segment versus FTTH / XGS-PON access network segment are compared side-by-side. The three OLT deployment options as shown in figures 7, 8 and 9 are applicable in urban, suburban, and rural markets. This section compares the rural deployments of FWA versus FTTH / XGS-PON using a remote node-based OLT (Figure 9) as this is used in many rural deployments. The FTTH node-based OLT and all other networking components in the access network segment allocates 14.6 watts per XGS-PON serving area. Examining the FTTH XGS-PON access network segment at 14.6 watts over 24 hours a day and 365 days a year operation has an annual electricity consumption of 128 kilowatt hours (kWhs) with an annual carbon footprint of 53.38 kilograms of CO_2e.

KEY FINDINGS COMPARING FTTH VS. FWA ANNUAL ELECTRICITY CONSUMPTION AND CO_2e

The difference in the electricity consumption between FTTH / XGS-PON vs. FWA is substantial as described above and summarized in Table 5 below. Additionally, FTTH / XGS-PON supports much higher data capacity and many more subscribers per serving area compared to FWA; both are examined in the next section. When comparing FTTH and HFC access network segment electricity and CO_2e calculations described in this paper and in the earlier 2024 analysis, the relevant figure of merit for comparison was the electricity and CO_2e per homes passed (HP). Since the data capacity for XGS/PON and DOCSIS 4.0 ESD both support a higher service subscription take rate in their respective homes passed serving areas, a HP metric for comparison was reasonable. But a comparison between FTTH / XGS-PON vs. FWA cannot reasonably use the same homes passed metric due to FWA having lower data capacity and low number of subscribers supported per serving area compared to XGS-PON. Thus, the table below compares the annual kilowatt hours (kWh) and kilograms of CO_2e per serving area, not homes passed. This data shows that when FTTH is economically viable in rural deployments that the service provider can expect an additional benefit of 95% lower electricity consumption resulting in lower costs and CO_2e when compared to FWA.

TECHNOLOGY	ACCESS NETWORK SEGMENT	ANNUAL KILOWATT HOURS (KWH)S PER SERVING AREA	ANNUAL KILOGRAMS CO_2e PER SERVING AREA	ANNUAL FTTH / XGS-PON DECREASE COMPARED TO FWA
FTTH	Node-Based OLT	128	53.38	95.0%
FWA	FWA Base Node	2610	1088	•

Table 5: FTTH vs. FWA Access Network Segment Electricity & CO_2e

The CPE segment assumes a Tarana G1 Remote Node (RN) is placed in each home. There are several G1 RN product models based on spectrum and data capacity that range in power consumption from 45, 40 or 32 watts[16]. The FWA Tarana G1 remote node at 40 watts has a customer premises equipment (CPE) segment annual electricity consumption of 350.4 kilowatt hours (kWhs) and an associated annual carbon footprint of 146.12 kilograms of CO_2e. In comparison FTTH using XGS-PON customer premises equipment segment has a maximum annual electricity consumption of 105.1 kilowatt hours (kWhs) and an associated annual carbon footprint of 43.84 kilograms of CO_2e.

TECHNOLOGY	CUSTOMER PREMISES EQUIPMENT SEGMENT	ANNUAL KILOWATT HOURS (KWH)S PER SUBSCRIBER	ANNUAL KILOGRAMS CO2E PER SUBSCRIBER	ANNUAL FTTH / XGS-PON DECREASE COMPARED TO FWA
FTTH	Optical Network Unit	105.1	43.84	70%
FWA	FWA Remote Node	350.4	146.12	•

Table 6: FTTH vs. FWA Customer Premises Equipment Segment Electricity & CO_2

This data shows that when FTTH is economically viable in rural deployments that the subscriber has the additional benefit of 70% lower electricity consumption resulting in lower cost and CO_2e when compared to FWA.

Network Data Capacity Analysis

Today, consumers have the choice of selecting high-speed internet from many service providers and the technologies used may not be understood. Internet providers can use different access network technologies each having dissimilar data capacities. One of the differences is the telecommunication media used to deliver the service such as telephone twisted-pair cable, coaxial cable, fiber optic cable or wireless. These physical media types carry data signals to enable internet services using various network technologies. For example, twisted-pair cable may use digital subscriber line (DSL) technology, coaxial cable may use DOCSIS, MoCA or G.hn, fiber optic cable could use PON or Ethernet, and wireless could use Wi-Fi, 4G / 5G, or FWA purpose-built proprietary technologies as described in this paper.

DOCSIS and FWA access network technologies both use radio frequency (RF) communications to deliver data. In RF communications the theoretical maximum data rate is sometimes calculated using all available spectrum and optimal network conditions. Technologies that use RF typically see an impact in data rate capacity when accounting for signal degradation, overhead, and interference that reduce the usable real-world data link capacity, especially in wireless communications.

The HFC / DOCSIS 4.0 capacity analysis, both in this paper and in our 2024 study, assumed the cable industry would free up existing spectrum, currently used for digital TV, as well as invest in the outside plant infrastructure and in facility-based data network equipment. This investment would nearly double the amount of available RF spectrum transmitted through their wireline coaxial network to support a spectrum range of 5 MHz to 1794 MHz. These analyses were a forward-looking study that assumed cable's continuous investment in creating and filling the spectrum with DOCSIS 4.0 to approach the capacity levels of XGS-PON. Figure 10 assumes that the entire ESD spectrum was filled with DOCSIS 4.0 with a usable downstream capacity of 10347 Mbps and upstream of 3691 Mbps. Reaching this capacity would require a significant investment in HFC outside plant upgrades, replacement and upgrades of digital TV set-tops to IPTV set-tops or TV apps, and DOCSIS hardware and software licenses.

Fiber optical cable has the capability of delivering the highest data capacity over the longest distances when compared to the other media types. Service providers that use fiber optical cable all the way to the home often use passive optical networking (PON) technology. The use of PON technology to businesses and homes has been used for nearly two decades by nearly all types of communications service providers. Some service providers use several PON technologies layered on the same fiber, each having different wavelength assignments and data capacity rates. The XGS-PON technology used in this study has a nominal data rate of 10 Gbps in both the downstream and upstream direction, called symmetrical. The usable data capacity of XGS-PON, which accounts for protocol overhead, is approximately 8.5 Gbps or 8500 Mbps symmetrical per serving area. Additional PON wavelengths and technologies can provide even more data capacity to each serving area, for example some providers having previously deployed GPON with approximately 2.3 Gbps downstream and 1.2 Gbps upstream can add XGS-PON to provide 8.5 Gbps additional symmetrical capacity per serving area. In the future, FTTH CSPs may add 50 Gigabit PON (50G-PON) with a usable capacity of approximately 42 Gbps or 42,000 Mbps symmetrical per serving area. FTTH with XGS-PON provides significantly more capacity than DOCSIS networks in service today. Fiber service providers can in this way easily stay ahead of demand by adding more capacity where and when needed using the same fiber infrastructure. This means that FTTH networks could have 50 Gbps of usable symmetrical data capacity in a serving area or neighborhood, when supporting both XGS-PON and 50G-PON technologies on the same fiber network. Clearly, fiber has the data capacity advantage in the delivery of data services to neighborhood and business serving areas. The data capacity analysis of FTTH versus HFC and FWA is compared below.

KEY FINDINGS COMPARING FTTH VS. HFC DATA CAPACITY

The study of FTTH / XGS vs. HFC / DOCSIS 4.0 examined the access network segment electricity and carbon dioxide equivalent (CO_2e) usage and stated this as a per homes passed (HP) metric. This was reasonable because the data capacity of each could support high service subscription take rates. The HFC / DOCSIS 4.0 network assumed more downstream capacity, and it also assumed 400 HP and this is considerably more HP than FTTH / PON. In comparison to XGS-PON which assumed a 64 HP serving area and 8.5 Gbps of usable capacity. FTTH / XGS-PON networks could easily support a 100% take rate without congestion or slowdowns, even during peak traffic periods. There would be enough unused capacity for continued traffic growth rates into the future.

KEY FINDINGS COMPARING FTTH VS. FWA DATA CAPACITY

The theoretical capacity and real-world capacity of wireless network can vary substantially. The data capacity of FWA stated in Figure 11 uses an average downstream capacity of 450 Mbps and an upstream of 108 Mbps based on real-world ISP deployment data from Tarana Networks[16]. This data measured 200,000 connections and considered all conditions and links[16]. Comparing this capacity versus FTTH / XGS-PON with downstream capacity of 8500 Mbps and upstream of 8400 Mbps illustrates why the substantially lower data capacity of FWA compared to FTTH / XGS and HFC / DOCSIS 4.0 needs to be considered in the analysis.

The number of customers supported in a FWA serving area will not be governed by the distance but rather FWA's capacity to meet the subscriber traffic loading and pass a speed test during peak period. The number of homes passed in the coverage area of FWA is not considered because average data capacity of FWA is significantly lower compared to FTTH / PON and represents the limiting factor in the comparison.

Consider an average FWA downstream capacity of 450 Mbps and an average upstream capacity of 108 Mbps. The FCC has defined 100 Mbps downstream and 20 Mbps upstream speed as a broadband service minimum. The next step is to determine the subscriber traffic load during peak periods. In 2022, a study found that the per subscriber traffic load on average during busy hour busy day (BHBD) "was 3.5 Mbps per subscriber [16]. Assuming a conservative compound annual growth rate (CAGR) of 15% per year, though 2036 this would increase the BHBD average traffic per subscriber from 3.5 Mbps in 2022 to 24.76 Mbps by 2036. Considering the FWA average downstream capacity of 450 Mbps and reserving 100 Mbps of capacity to pass an FCC speed test during BHBH the capacity allocated for BHBD subscriber traffic is 350 Mbps. Based on these assumptions (350 Mbps / 24.76 Mbps per Sub BHBD Traffic in the year 2036 = 14.1), this suggests that FWA can effectively support 14.1 subscribers per serving area.

Considering FTTH / XGS-PON with downstream capacity of 8500 Mbps and reserving 100 Mbps of capacity to pass an FCC speed test during BHBH the capacity allocated for BHBD subscriber traffic is 8400 Mbps. Assuming a 64 HP serving area and assuming all are subscribers, this means that PON could support 131 Mbps per subscriber (8400/64). Considering the forecasted 24.76 Mbps per Sub BHBD Traffic in the year 2036 and assuming all 64 HP are subscribers, this means the BHBD traffic load is 1584.64 Mbps (64 subs* 24.76 Mbps). This means that PON would have nearly 7 Gbps of spare capacity given those assumptions. As a result, FTTH providers can offer much higher service tier speeds than the FCC minimum of 100 Mbps for broadband and support more subscribers than FWA.

Fiber Broadband ASSOCIATION

KEY FINDINGS COMPARING FTTH VS. FWA PER SUBSCRIBER ELECTRICITY & CO_2e IMPACT

Any comparison of FTTH vs. FWA should be on a per subscriber basis for electricity and carbon dioxide equivalent (CO_2e). Accounting for a smaller data capacity per subscriber and a reduced number of subscribers supported by FWA versus the high data capacity and high number of subscribers supported by FTTH the results of our analysis are summarized in Table 7.

Network segment annual kilowatt hours (kWh) and CO_2e per serving area were summarized earlier in Table 5. Assuming 64 subscribers supported by FTTH and 14 subscribers supported by FWA, Table 5 per serving area values are divided accordingly to yield the per subscriber values for annual kilowatt hours (kWh) and CO_2e, shown in Table 7.

TECHNOLOGY	ACCESS NETWORK SEGMENT EFFECTIVE NUMBER OF SUBSCRIBERS SUPPORTED	ANNUAL KILOWATT HOURS (KWH)S PER SUBSCRIBER	ANNUAL KILOGRAMS CO_2e PER SUBSCRIBER	ANNUAL FTTH / XGS-PON DECREASE COMPARED TO FWA
FTTH	64	2	0.83	98.93%
FWA	14	186.41	77.73	•

Table 7: FTTH vs. FWA Access Network Segment per Subscriber Electricity & CO_2e

The data capacity, serving area and subscribers supported by FWA were examined as an electricity and carbon dioxide equivalent (CO_2e) both per serving area, shown in Table 4, and as a per subscriber metric shown in Table 6.

Considering both the FTTH vs. FWA Customer Premises Equipment Segment in Table 6 and the Access Network Segment calculated per subscriber in Table 7, the total electricity consumption & CO_2e per subscriber is compared in Table 8.

TECHNOLOGY	ANNUAL KILOWATT HOURS (KWH)S PER SUBSCRIBER	ANNUAL KILOGRAMS CO_2e PER SUBSCRIBER	ANNUAL FTTH / XGS-PON DECREASE COMPARED TO FWA
FTTH	107.1	44.67	80%
FWA	536.81	223.85	•

Table 8: FTTH vs. FWA Access Network and CPE Segment per Subscriber Electricity & CO_2e

From this comparison our study clearly shows that fiber to the home provides both energy consumption, cost and carbon footprint advantages when compared to HFC / DOCSIS and FWA.

SUMMARY: FIBER IS MORE SUSTAINABLE

Fiber networks offer significant carbon footprint advantages over HFC networks, from manufacturing of the components, through installation and operation of the network. In the manufacturing of its components, a **FTTH PON network reduces embodied carbon by 60%** compared to an HFC network, due to lighter cables and fewer active network components. The carbon footprint associated with **installation of a fiber network is 7% less than in an HFC network and 31% less than a FWA network.**

Operationally, an **FTTH XGS-PON ONT reduces carbon footprint by 96%** versus a DOCSIS 4.0 cable modem and by 18% at the customer premises. An **FTTH XGS PON network reduces carbon footprint by 98%** versus a comparable FWA using purpose-built or proprietary networking hardware and software devices. At the customer premises, an **FTTH XGS-PON ONT reduces carbon footprint by 80%** versus an FWA purpose-built or proprietary remote node modem. Overall, this analysis demonstrates that a fiber network is the more sustainable choice for broadband infrastructure deployment than either DOCSIS or FWA network approaches. This paper narrowly focuses on the carbon impact of these technologies and should be a component in the overall analysis and selection process. Many service providers have chosen a fiber first approach to new-build deployment areas. However, as stated in the introduction there may be some areas where FWA is the only viable broadband technology due to the costs to build, deploy, and maintain a network in remote rural and underserved areas, making carbon and electricity consumption secondary considerations.

	PER HOME PASSED			PER HOME CONNECTED		
CARBON FOOTPRINT	HFC Kg CO_2e	FTTHkg CO_2e	Δ	HFC Kg CO_2e	FTTHkg CO2e	Δ
Manufacturing	75	26	â 65%	22	11	â 50%
Installation	17	16	â 7%	9	9	•
Operational (Annual)	12	0.4	â 96%	53	44	â 18%

Figure 12: Carbon Emissions of HFC vs. FTTH Network for a Suburban Deployment

This new study indicates that unlicensed FWA operational emissions are higher than FTTH in the modeled case, but missing embodied carbon for FWA prevents a complete lifecycle total.

CARBON FOOTPRINT per subscriber for FTTH and FWA considering the Customer Premises Equipment Segment (Table 6) and allocation per subscriber for the network access segment (Table 7)	FWA Kg CO_2e	FTTH kg CO_2e	Δ
Manufacturing	•	76	•
Installation	466	320	â 31%
Operational (Annual)	223	44	â 80%

Figure 13: Total Carbon Footprint Allocation per Subscriber for FTTH and FWA

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