SUSTAINABILITY IN THE Wi-Fi INDUSTRY

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INTRODUCTION

In 2023, a total of 105.05 Terawatt Hours (TWh) of electricity was consumed by the world's 1.55 billion installed base of residential Wi-Fi Customer Premises Equipment (CPE). This figure, the equivalent of the entire average annual energy usage of 6.82 million homes within the European Union (EU), represents a major source of energy demand that must be addressed if Internet Service Providers (ISPs) and Wi-Fi CPE vendors globally are to fulfill their sustainability obligations. Yet, on its current trajectory, the annual energy consumption of Wi-Fi CPE is projected to more than double between 2023 and 2030, climbing to 215.14 TWh annually. This highlights the urgency for industry collaboration on improving the energy efficiency of Wi-Fi CPE.

This report provides a comprehensive analysis of the question of sustainability within the Wi-Fi industry. Section 2 begins with an executive summary of the report's key findings. Section 3 then provides a thorough examination of existing sustainability regulations and industry responses in three core regions: Europe, the Asia-Pacific, and North America. This enables us to identify the challenges encountered and gaps to address in the current approaches. Section 4 continues by conducting an in-depth energy profile of Wi-Fi CPE, delving into aspects such as the Wi-Fi radio, System-on-Chip (SoC), Wi-Fi protocols, and network access technology. This analysis helps us to understand the barriers that the industry faces to achieving energy efficiency, and which areas should be prioritized for improvement. Section 5 details potential methods of reducing the energy consumption of Wi-Fi CPE without sacrificing performance, which is essential to attaining sustainability initiatives. Section 6 provides data for the current and projected global Wi-Fi CPE energy demand, with which the industry can both accurately gauge the challenge at hand and identify the potential reductions to energy consumption that can be achieved if they are to implement the energy efficiency methods outlined in Section 5. Finally, Section 7 concludes with recommendations for how the industry can successfully overcome its sustainability challenge.

EXECUTIVE SUMMARY

Analysis of the current Wi-Fi ecosystem has revealed that the industry faces a multitude of energy efficiency-related challenges. These include:

- Improvements in Wi-Fi performance brought by new standards, advanced capabilities, and additional radios are all accompanied by increases in the energy consumption of equipment.
- There is currently only a marginal difference between idle- and active-state energy consumption of Wi-Fi CPE, resulting in high electricity demand even when the CPE is not in use.
- New Wi-Fi protocols are highly inefficient when first released, and energy-efficiency is not being prioritized in mainstream standardization efforts.
- The CPE is the most energy-intensive element of the entire fixed access network, meaning industry sustainability objectives will remain elusive unless CPE energy-efficiency is addressed.
- Wi-Fi radio energy efficiency is central to industry sustainability as they are responsible for a significant proportion of the Wi-Fi CPE's overall energy usage, at an average of ~80% in routers and ~37.5% in gateways.
- Digital Subscriber Line (DSL) and Data Over Cable Service Interface Specifications (DOCSIS) are energy inefficient compared to fiber optic, suggesting that the endurance of these legacy technologies inhibits sustainability.
- Energy-efficiency varies considerably between vendors, with the energy demand for similar capability Wi-Fi CPE from different vendors sometimes diverging by up to 30%.

Assessment of current governmental and industry initiatives aimed at improving energy efficiency in Wi-Fi infrastructure were found to be lacking due to the following reasons:

- Existing industry agreements are regional and/or voluntary only.
- Limited validation and enforcement of mechanisms for energy efficiency.
- Current approaches focus solely on energy consumption, but have no measures to protect performance.

Despite the lack of standardization, there are a range of currently achievable and future potential methods of improving the energy efficiency of Wi-Fi CPE. Some of the most promising include:

- Wi-Fi Radio Performance: Reducing Radio Frequency (RF) interference, improving antenna power conversion efficiency and spatial efficiency, implementing dynamic adjustment of antenna power levels, and enabling Access Point (AP) to Station (STA) communication.
- Energy-Efficient Designs: Tighter integration of components, higher density chipsets, migration to advanced access technologies, and a closer alignment of CPE capabilities with needs.
- Network Topology: Ensuring optimal placement of equipment, adopting mesh networking, and deploying Fiber-to-the-Room (FTTR).
- Intelligent Software: Developing more intelligent and dynamic sleep modes, harnessing Wi-Fi Sensing, and applying Artificial Intelligence (AI).

Considering the scale of the challenge and the fact that current approaches to tackling energy efficiency within the Wi-Fi industry have been revealed to be insufficient, it is recommended that:

- A clear industry-wide energy-efficiency standard for Wi-Fi equipment is necessary to enable the realization of sustainable networking within the industry.
- Equipment must be validated by a neutral entity with sufficient capabilities and resources.
- User Quality of Experience (QoE) must not be sacrificed for energy efficiency, or else adoption will face resistance.

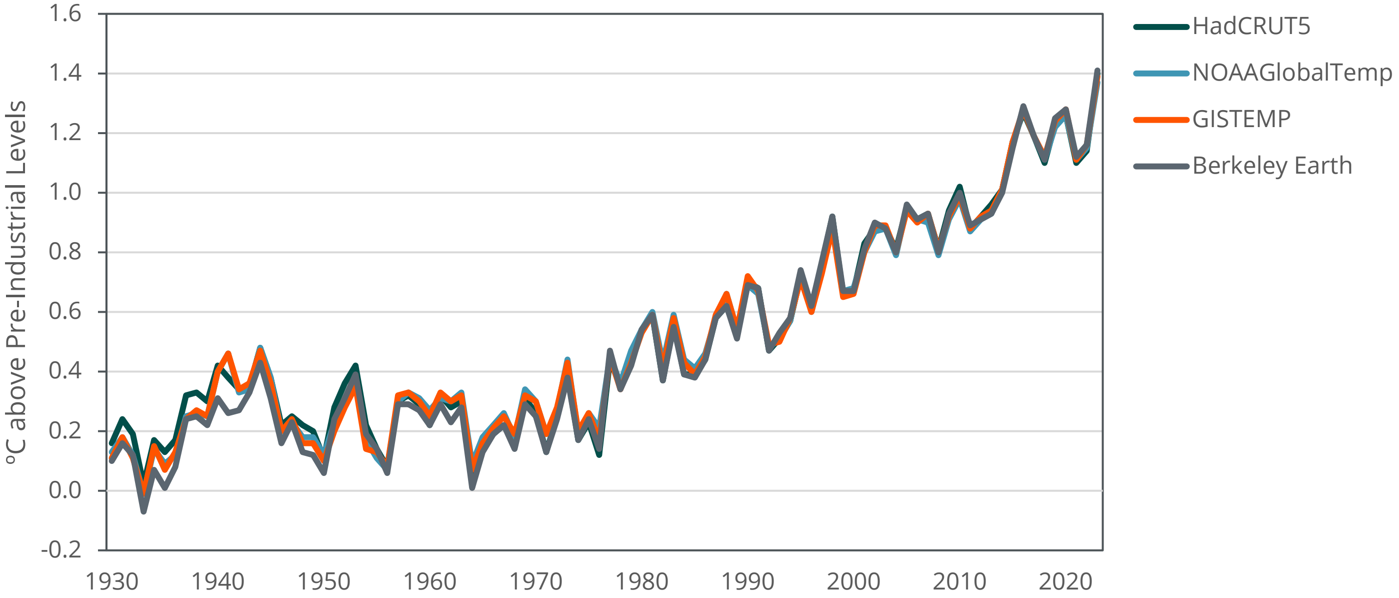
GOVERNMENT REGULATION AND INDUSTRY INITIATIVES ON WI-FI SUSTAINABILITY

BACKGROUND

The first question we must answer is this: why is the topic of sustainability a matter of urgency for the Wi-Fi industry? The answer is revealed in Chart 1, which displays the yearly increase in global mean surface temperature relative to the pre-industrial level across the period from 1930 to 2023. The results from this aggregated data are undisputed—average world temperatures have been increasing precipitously over the past century, and we are creeping close to 1.5° Celsius (C) above pre-industrial levels. Scientists have warned that such temperatures would result in a slew of disastrous environmental consequences, ranging from scorching heatwaves, devastating droughts, and torrential rain, which would, in turn, not only damage homes, livelihoods, and food security, but by some estimates could cause the global Gross Domestic Product (GDP) to contract 18% by 2050 if no action is taken. Scientific consensus holds that reducing the release of Greenhouse Gas (GHG) emissions is pivotal to halting and reversing this temperature increase, so concerned citizens globally are increasingly demanding that governments and industry act now before it is too late. Electricity generation is one of the main culprits of increasing GHG emissions, and given the large installed base of Wi-Fi CPE (1.55 billion in 2023), even small improvements in equipment energy efficiency would deliver substantial benefits in terms of reduced GHG emissions.

Chart 1: Global Mean Temperature Difference (°C)
World Markets: 1930 to 2023

(Sources: HadCRUT5, NOAAGlobalTemp, GISTEMP, Berkeley Earth)



The most conspicuous manifestation of government efforts to reduce GHG emissions is the growing number of regulations on corporate sustainability. These typically encompass increased scrutiny into a company's Scope 3 emissions, which includes emissions resulting from a customer's use of Wi-Fi CPE. In response to these government mandates, alongside shareholder pressure and the environmental concerns of their customers, ISPs are exploring new and innovative methods of reducing their broadband network's energy consumption. This drive for network energy efficiency is nothing new for ISPs, particularly those that also act as cellular operators. Many of these have already integrated sustainability into their core strategy years ago in an effort to tackle the energy efficiency challenge in their cellular networks. These operators are now turning their attention to their broadband infrastructure.

The goal of driving down broadband network energy consumption is one of the major factors causing ISPs to increasingly prioritize energy efficiency during equipment procurement. In turn, equipment suppliers must satisfy their new energy-efficiency requirements if they wish to continue selling to ISP customers. It is for this reason that many in the industry anticipate that sustainable Wi-Fi will be a phenomenon that will emerge in the residential Wi-Fi equipment space first before progressing to the enterprise market.

Yet, environmental concerns are not the only factor behind the drive for more energy-efficient residential Wi-Fi equipment. Another major consideration is reducing the operating costs of the equipment, which can save consumers money and raise the value proposition of ISP services. Electricity costs rose rapidly as a priority for consumers following the jump in energy prices in 1Q 2022, and although environmental regulation may establish the framework for sustainability in the industry, it will be the market that decides the implementation strategy.

In the remainder of this section, we will examine government and industry sustainability initiatives in three core regions: Europe, Asia-Pacific, and North America. This will help us to understand current sustainability regulations and industry responses in each region, and to identify challenges and gaps in current approaches that need to be addressed.

EUROPE

European governments have been some of the strictest in mandating sustainability targets for broadband infrastructure and guiding ISPs toward realizing these efficiency objectives. The EU has been the driving force behind this, and one of its most impactful initiatives has been the Code of Conduct on Energy Consumption of Broadband Equipment report. The code of conduct sets maximum on-state and idle-state energy consumption limits for all types of end-user equipment (e.g., residential gateways) and the network infrastructure (e.g., the Digital Subscriber Line Access Multiplexer (DSLAM) in DSL networks), for which signatories must ensure that at least 90% of new equipment meets. To stimulate continual improvements in energy efficiency, the targets are updated annually, with the latest, Version 8.1, being released in 2023. Signatories must also provide the end user with information about the power consumption of their CPE in both its on-state and idle-state.

Outside of the voluntary Code of Conduct, the EU has also enacted successive acts of legally-binding legislation, tightening the sustainability requirements on the industry. In October 2023, the European Commission (EC) implemented climate targets covering all key sectors of the economy, and as part of the directive, European ISPs are required to implement circular economy models and boost the energy efficiency and eco-design of products. October 2023 also saw the publication of the BEREC Report on Sustainability Indicators for Electronic Communications Networks and Services from the Body of European Regulators for Electronic Communications (BEREC). This outlines clear indicators for tracking the telecoms sector's impact on the environment, in alignment with the EU's goal of expanding environmental transparency in the telecoms sector.

At the member state level, one of the most proactive in converting these top-level EC targets into actionable policy has been France. Notably, the French national telecoms regulator, ARCEP, publishes annual energy efficiency and sustainability data for the country's fixed broadband networks. The 2023 annual survey found that the total electricity consumed by the fixed networks of the country's four main ISPs decreased by 9.7% Year-over-Year (YoY), perhaps a result of regulators scrutinizing the industry. The country is also tightening its regulation, and in 2024 is launching a new policy framework for reducing the environmental footprint of digital services, placing more stringent requirements on ISPs in the country.

Belgium also stands out as a member state with governmental institutions that have been some of the earliest and most enthusiastic in guiding the ISP industry toward fulfillment of sustainability obligations. Recently, in December 2023, Belgium telecoms regulator BIPT published its report on the sustainability of telecommunication networks and operators in Belgium, which included tracking energy consumption and overall efficiency of the modems deployed by the country's major network operators, Telenet, Proximus, Orange, and VOO. The report also assessed operator fulfillment of their sustainability initiatives.

The French and Belgium national regulators were the first to begin actively assessing the environmental impact of their local telco operators, but their example has begun to be emulated by other EU Members. For example, Finnish telecoms regulator Traficom recently began collecting data on the energy consumption and efficiency for the fixed networks of the country's major telco operators for the first time. Growing governmental regulation on energy efficiency is also evident across the bloc. Notably, in the EU's largest economy Germany, October 2023 saw the passing by the German Federal Council (Bundesrat) of the Energy Efficiency Act (Energieeffizienzgesetz - EnEfG), which imposes mandated energy-efficiency obligations on German companies. This will result in heightened focus on the energy consumption of broadband infrastructure by ISPs in the country.

Ambitious government sustainability targets, in conjunction with a population that is arguably the world's most attuned to environmental matters, have led to European ISPs setting the most aggressive energy-efficiency and net-zero targets of any region globally. Many operators have specific targets, even for Scope 3 emissions, that cover the energy consumed by the operation of a customer's Wi-Fi CPE. For example, Germany's Deutsche Telekom AG, the largest European operator by market cap, plans to achieve net-zero in Scope 3 emissions by 2040, as does Dutch operator KPN. European ISPs are also taking serious action on climate reporting. In 2023, Spanish ISP Telefónica conducted in-depth analysis of its fixed broadband network, with the main goal of understanding the full lifecycle impact of its network and to highlight the potential efficiency savings of newer access technologies. The study revealed that the Kilowatt Hour per Petabyte (kWh/PB) for the operation of a Fiber-to-the-Home (FTTH) access network was more than 20X lower than that for a copper DSL network (23.8 kWh/PB compared to 481.8 kWh/PB), quantifying the energy-efficiency savings resulting from the company's commitment to decommission all legacy copper fixed networks in Spain by 2025.

Procuring sustainable CPE has also become a priority for European ISPs. For example, French ISP Orange made efficiency one of the key selling points of its Livebox 6, which can be configured to light sleep mode (in which only telephony is kept running) to reduce power consumption by 25%, or to deep sleep mode to bring down consumption by 85%. Similarly, the flagship Internet Box from Belgium ISP Proximus promises a 24% reduction in energy consumption and a 30% lower carbon footprint compared to the operator's previous flagship modem, the b-box 3V+. The environmentally-friendly credentials of the Internet Box were so central to its value proposition that Proximus had them verified by third parties. The French testing company Bureau Veritas ran the Internet Box through lifecycle analysis to certify the CPE's carbon footprint reduction claims, and the professional services firm KPMG, alongside sustainability Software-as-a-Service (SaaS) platform Circular IQ helped determine the total eco-cost of the product. Spanish ISP Telefónica has also reported that that improved design of the CPE that the company deploys has helped reduce CPE energy consumption by 30% in recent years.

THE UNITED STATES

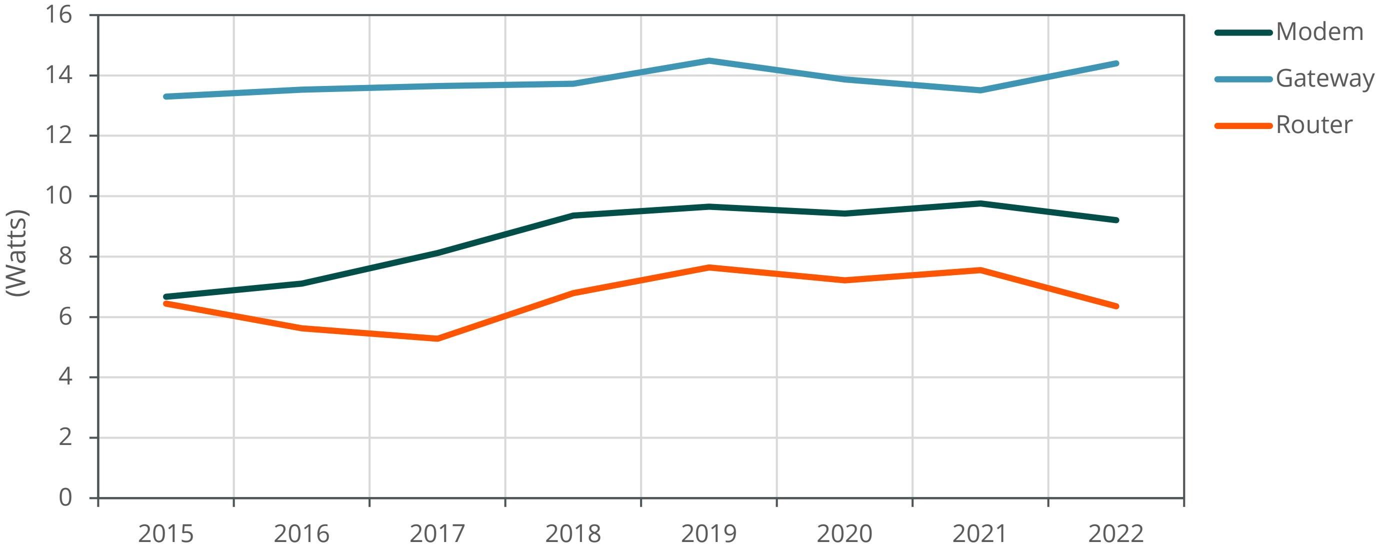
To date, the U.S. federal government has not enacted any legislation regulating the energy efficiency of broadband infrastructure, and there have been no significant initiatives undertaken by any state. Instead, progress toward sustainable broadband infrastructure has been stimulated by the "Voluntary Agreement For Ongoing Improvement To The Energy Efficiency of Small Network Equipment." Some of the largest U.S. ISPs are members, including AT&T, Verizon, Charter, and Cox. Many of the Wi-Fi CPE vendors that supply these ISPs are also signatories, including the world's largest Wi-Fi CPE vendor by shipment volume, TP-Link, which joined in 2022.

The agreement is non-binding, but sets out a range of guidelines for improving the energy efficiency of broadband CPE that member ISPs will deploy. This includes ensuring that at least 90%

of all procured CPE meet the energy-efficiency levels set by the voluntary agreement. Environmental consulting firm D+R oversees the administration, auditing, and review of the initiative, and the capability for the guidelines to be accurately tracked was strengthened in 2022, as U.S. energy firm Pacific Gas and Electric Company (PG&E) joined for the purpose of validation. If a signatory fails to meet the requirements of the voluntary agreement (as one did in 2022), then the offending company will enact a remedial plan to offset the excess energy resulting from the missed commitment, with a committee including PG&E, alongside D+R overseeing the plans for implementation.

Chart 2: Average Idle-Mode Power Consumption by hour for Residential Wi-Fi CPE Deployed in the United States

(Source: D+R International)



D+R has tracked the energy efficiency of residential broadband infrastructure equipment deployed in the United States every year since the commencement of the voluntary agreement in 2015. In 2022, approximately 41.7 million CPE units were tracked, and Chart 2 displays the average idle-mode power consumption for all the devices. It is clear from the chart that despite the voluntary agreement, energy consumption of broadband infrastructure in North America has seen no major improvement since 2015. The performance of the equipment has seen vast improvements over this time frame though, suggesting that consumers prioritize performance over energy efficiency.

ASIA-PACIFIC

The Asia-Pacific region is vast and diverse, with significant variation between the demands and concerns of its constituent countries. While it is therefore tough to make broad generalizations about the market, it is widely accepted that Asia-Pacific consumers are, on the whole, less concerned with sustainability than those in Europe. That does not mean that governments are not responding to the climate challenge though, as across the region, ambitious climate commitments have been established. Given the centrality of the region to global Wi-Fi CPE manufacturing, these policies will exert a strong influence on the Wi-Fi CPE industry.

The government of Mainland China has outlined a comprehensive framework for meeting its climate commitments, including setting a 2030 date for Peak Carbon Emissions (碳达峰) and a

2060 date for Carbon Neutrality (碳中和). Together, these two goals are referred to as the "Dual Carbon" (双碳) initiative. The country's major operators are all contributing to this agenda, and in 2023, an alliance of multiple Wi-Fi industry players, spearheaded by China Telecom, established the Green Project Group. This group aims to improve the energy efficiency of broadband networking equipment, while at the same time improving network efficiency and reducing costs for consumers.

Other governments strongly promoting energy-efficient broadband infrastructure in the region include South Korea, Japan, and Singapore. In South Korea, the Korean Energy Agency mandates that major home electronics, including residential gateways, must be equipped with power saving features. Those that fail to meet the requirements are forced to display a warning label. In Japan, the Ministry of Economy, Trade, and Industry (METI) has itself invested in promoting international standards on the energy efficiency of Information Technology (IT) equipment. Finally, Singapore's Digital Connectivity Blueprint, launched in June 2023, codifies the importance of sustainability within home connectivity networks.

For Asia-Pacific nations where governments and consumers have placed less emphasis on the environmental aspects of sustainability, the cost of operating the Wi-Fi CPE may pose a greater concern. As outlined in Section 4.4, the relative financial burden of operating equivalent equipment will be higher in lower income nations than in high income ones, as the electricity cost will constitute a larger portion of their household's total electricity bill. Consider the case of an AX3000 xDSL gateway with an hourly energy consumption of 12.1 Watts (W), which, accounting for differences in local electricity rates (as of January 2024), would cost slightly more to operate in the Philippines (US$19.1) than in the United States (US$17.5). If we view this cost as a ratio of the user's total annual income, then the financial burden for the Philippines household will be far higher than for the U.S. household. Therefore, reducing the energy consumption of Wi-Fi CPE will be extremely valuable for low income countries.

SHORTCOMINGS OF CURRENT APPROACHES

SUSTAINABILITY INITIATIVES BY EUROPEAN GOVERNMENTS AND ISPS

Analysis of governmental and industry initiatives aimed at improving energy efficiency in Wi-Fi infrastructure has revealed several key important takeaways:

- **Lack of a Commonly Accepted Standard:** The absence of a widely respected standard leaves governments and ecosystem participants unclear as to the definition of an energy-efficient Wi-Fi CPE, rendering compliance and enforcement challenging, and resulting in broad variation between markets. International standards are especially important considering the tightening global regulation toward broadband infrastructure.
- **Limited Validation and Enforcement Mechanisms:** The EU's Code of Conduct is based on self-reporting, whereas enforcement of the U.S. Voluntary Agreement is overseen by private companies (D+R, PG&E). In neither case is there an unbiased industry body with the expertise, capacity, and authority to set efficiency targets and verify compliance.
- **Current Industry Agreements Are Regional:** The voluntary agreements examined above are tied to specific territories, with only limited impact outside of their respective regions. While there may be some technology spillover to other regions, a global standard would enable simplicity, economies of scale, and facilitate the achievement of industry-wide sustainability goals.

- **Current Approaches Focus Solely on Energy Consumption:** The existing voluntary initiatives on Wi-Fi CPE sustainability in the EU and the United States have no mechanisms to protect performance, meaning that user experience would be sacrificed to achieve environmental goals.
- **Consumers Unable to Assess CPE Energy Efficiency:** Although many ISPs have actively promoted the sustainability of their CPE (as French ISP Orange did for its Livebox 6, or Belgium ISP Proximus did for its Internet Box), consumers have no metrics by which they can measure and compare CPE energy efficiency, and ISPs have no tools to convey this value to their customers. Industry-wide standards would enable consumers to make informed judgements on the true sustainability credentials of the hardware they are using.

MEASURING THE CURRENT IMPACT OF BROADBAND INFRASTRUCTURE ON THE ENVIRONMENT

It is widely accepted that Wi-Fi is a more energy-efficient technology than cellular (4G/5G). Indeed, in the run-up to the recent 2023 World Radiocommunication Conference, it was argued by the Wi-Fi Alliance (WFA) that licensing the upper 6 Gigahertz (GHz) band for 5G would result in a 16% higher energy consumption rate in Europe by 2023 than if the band were made unlicensed for Wi-Fi. Yet, this relative efficiency does not negate the sizable energy output that Wi-Fi is still responsible for, and with the power demand increasing alongside the expanded capabilities and capacity of the latest Wi-Fi technologies, the issue is becoming increasingly pertinent.

Residential Wi-Fi CPE is composed of multiple components, the most important being a processor, memory, multiple Local Area Network (LAN) interfaces (Wi-Fi radios, Ethernet), and if it is a gateway, a Wide Area Network (WAN) interface (DSL, DOCSIS, Passive Optical Network (PON)). This section assesses the impact of each individual component, followed by an examination of the energy profile of standard residential Wi-Fi CPE, and concludes with an interpretation of how the findings impact Wi-Fi sustainability.

ENERGY CONSUMPTION OF WI-FI RADIOS

The power consumption of the Wi-Fi radios is contingent on myriad factors, ranging from the Wi-Fi protocol of the radio to its maximum channel width support. Consequently, there is a high degree of divergence in the energy consumption of each Wi-Fi radio based on its performance. For example, a standard 2x2 Multiple Input, Multiple Output (MIMO) 802.11n 2.4 GHz radio with support for ≤40 Megahertz (MHz) channels will, on average, require 0.6 W to 0.8 W in an idle-state and 1.2 W to 1.6 W in an active state, whereas a 4x4 802.11ax 5 GHz radio with support for ≤160 MHz channels may demand 3.1 W to 3.5 W when idle and 3.6 W to 4 W when active. The above levels are broadly representative of the industry, because although there are no strict global requirements on the power consumption of different types of Wi-Fi radios in residential Wi-Fi equipment, there is typically no more than a ±20% variation between equivalent performance Wi-Fi radios from different vendors.

In practice, most deployed CPE today are dual band, with one 2x2 MIMO radio each for 2.4 GHz and 5 GHz, respectively. Given this, and assuming maximum channel support of 40 MHz for 802.11n, 80 MHz for 802.11ac, and 160 MHz for 802.11ax, it can be expected that the Wi-Fi radios of standard home routers would require the energy consumption levels shown in Table 1.

Table 1: Average Power Values for 802.11 Radios in Standard Dual-Band Residential CPE

(Source: ABI Research)

Standard	Idle-State	On-State
802.11n	**1.4 W to 1.6 W**	**2.8 W to 3.2 W**
802.11ac	**3.0 W to 3.4 W**	**3.8 W to 4.2 W**
802.11ax	**5.0 W to 5.4 W**	**5.8 W to 6.2 W**

The introduction of 802.11be further complicates the situation, with certain features, including support for the 6 GHz band and 320 MHz channels, significantly increasing power consumption requirements. Moreover, because the standard has only just been finalized, current 802.11be equipment is immature, with aspects ranging from filter designs to 5 GHz/6 GHz band coexistence technologies still in the process of being optimized for the new technology. For this reason, the wattage required for 802.11be radios of standard tri-band (2.4 GHz, 5 GHz, 6 GHz) 802.11be CPE, at present, can approach 15 W. That said, the power efficiency of 802.11be should see rapid improvements over the coming years, much in the same way that the power efficiency of previous standards, most recently 802.11ax, improved as the standard matured.

This all reveals several key realities of Wi-Fi radios within CPE that have significant impacts on the energy consumption of equipment:

- **Improved Capabilities and Capacity Drive Up Energy Consumption:** The more advanced the Wi-Fi features (channel width, MIMO, etc.), the higher the energy consumption. This suggests that aside from improving energy efficiency through engineering improvements, it is also important for capabilities to be aligned with user needs to ensure that resources are not wasted.
- **Marginal Difference between Idle- and Active-State Energy Consumption:** It can be observed that there is only a slight difference between the idle- and active-state energy consumption of Wi-Fi CPE. For example, a 2x2 MIMO 802.11ax radio operating on the 5 GHz band with ≤160 MHz channel width support will consume 2.8 W to 3.0 W in idle-mode and 3.0 W to 3.4 W in active-mode. This reveals that idle-mode is not producing large energy savings for the standard Wi-Fi CPE.
- **New Standards Are Highly Inefficient When First Introduced:** A lack of hardware optimization means that new Wi-Fi standards are typically highly inefficient on introduction, only for efficiency to improve with optimization over time. This was the case for 802.11ac and 802.11ax, and is expected to hold true for 802.11be also. This reality is also something to keep in mind for introducing 802.11bn in 2027/2028.

ENERGY CONSUMPTION OF MODEMS

One of the most energy-intensive components of residential Wi-Fi infrastructure is the modem, via which data from the LAN connects to the Internet. These modems, which may be external or internal to the Wi-Fi CPE, typically support one of the three main fixed broadband access technologies. While we are just concerned with the energy consumption of the modem within residential gateways in this study, we will also explore the efficiency of the broader access network to help put the broader sustainability profile of the technology into context.

DIGITAL SUBSCRIBER LINE (DSL)

DSL is a legacy technology that uses existing telephone lines to transport data. The technology has seen gradual improvements to its performance with subsequent technological updates, progressing from ADSL to ADSL2+, VDSL, and finally VDSL2-Vectoring. DSL is still common in Europe and the Middle East & Africa; in 2023, DSL was the access technology for 42.3% of fixed broadband subscribers in Europe and 62.31% in the Middle East & Africa. One of the major drawbacks of DSL is that it suffers from severe length restrictions, with the usable data rate declining precipitously the further the subscriber is located along the cable. In practice, the data rate drops to below 50 Megabits per Second (Mbps), even when only several hundred meters along the cable. To compensate for this challenge, fiber optic connected DSLAMs are placed close to the subscriber's premises, and shorter copper cable lines run the distance between the consumer premises and the DSLAM (typically in a street cabinet). Unfortunately, operating these DSLAMs requires additional electricity, which adds considerably to the power consumption of DSL networks.

HYBRID FIBER-COAXIAL (HFC)

HFC cables, which were typically originally installed for cable television, can also transfer data for broadband access via the DOCSIS standard. DOCSIS is the most prevalent in North America, where 67.6% of all fixed broadband subscribers relied on the technology in 2023. DOCSIS has also undergone periodic advancements with new standards, with the most common currently being DOCSIS 3.0 and DOCSIS 3.1. In 2023, 31.9% of shipped residential modems and gateways supported DOCSIS 3.0, while 68.9% supported DOCSIS 3.1.

While DOCSIS over HFC does not face length restrictions like DSL, it still requires an additional network element similar to a DSLAM called a Cable Modem Termination System (CMTS), which again requires electricity for operation. The CMTS is the hub that links the fiber node connecting to the core network on the one side, and the cable connections of all the subscribers in the service group on the other. A major downside of HFC is that it is a shared medium, meaning that the total data rate delivered to the CMTS via the fiber node is shared among the service group of subscribers. This means that the larger the number of subscribers in a service group, the smaller the portion of the total data rate that each user can receive. This makes the technology less energy efficient the larger the desired data rate.

PASSIVE OPTICAL NETWORK (PON)

In contrast to DSL or HFC with DOCSIS, where the subscriber is connected to the core network via a copper cable leading to a DSLAM or CMTS, PON connects the subscriber through a fiber-optic cable that terminates directly at their house (FTTH) or even their room (Fiber-to-the-Room (FTTR)). FTTH/FTTR network access is the most advanced technology considered in this paper, and it is the most prevalent in the Asia-Pacific region, where 82.2% of all fixed broadband subscriptions were connected with fiber in 2023.

Fiber-optic cables used for broadband networks consist of numerous thin strands of glass bundled together within a tube casing. Data are then transferred via light passing through the glass strands. The networking standards for transferring data over fiber (PON, GPON, XGS-PON) are all point-to-multipoint architectures, in which a passive optical splitter divides the connection from a single optical fiber to serve multiple premises. Fiber-optic cables are capable of handling significantly higher data rates than possible with copper cable, and these cables can extend for tens of kilometers without any degradation of this data rate. This means that the technology does not require additional active network elements that themselves consume power, delivering vastly improved energy efficiency compared to competing technologies.

IMPACT OF FIXED ACCESS TECHNOLOGY ON ENERGY CONSUMPTION

As outlined above, the energy efficiency of both DSL and HFC with DOCSIS is negatively affected by the multiple network elements (central office, street cabinet, etc.) required for their operation, which all consume additional energy. In contrast, FTTH requires minimal additional network elements to run, helping it be the most energy-efficient fixed network access technology. This has been supported by recent quantitative research. For example, a recent study of German fixed access networks found that households served by FTTH-GPON would consume approximately 56 kWh per person each year, which equated to approximately 5.3% of the typical annual energy consumption of a four-person family (~4,200 kWh/year). In contrast, VDSL2-Vectoring would require 61 kWh per person each year, the equivalent of 5.8% of the average four-person family's annual energy consumption. The worst performer was HFC with DOCSIS 3.0 (measured with a typical service group size of 256 subscribers), which demanded approximately 88 kWh per person per year, amounting to 8.4% of the average four-person household's energy consumption.

Table 2: Energy Consumption of Main Broadband Access Technologies

(Source: Breide et al., Energy Consumption of Telecommunication Access Networks, 2021)

Broadband Access	DSL (VDSL2-Vectoring)	HFC (DOCSIS 3.0)	FTTH (GPON)
kWh/year per person	**61**	**88**	**56**
Ratio of average four-person household annual energy consumption (4,200 kWh/year)	**5.8%**	**8.4%**	**5.3%**
Equivalent in CO2 emissions (tons/year)	**1,850**	**2,663**	**1,685**

The efficiency of FTTH is amplified when we consider the power required per data unit. A 2023 study conducted by ISP Telefónica and verified by the Spanish standardization institute AENOR reported that the kWh per gigabyte for the operation of a FTTH access network was more than 20X lower than that for a copper DSL network (0.0000238 kWh/Gigabyte (GB) compared to 0.0004818 kWh/PB). Chart 3, derived from the same German fixed access network study discussed above, displays a similarly high discrepancy. Contrasting Table 2 with Chart 3 also reveals that although HFC with DOCSIS demands more power to function than VDSL2, the higher data rates possible with the technology (theoretically 1 Gigabyte per Second (Gbps) compared to 52 Mbps) means that DOCSIS is considerably more efficient when viewed from an kWh/GB standpoint. The kWh/GB efficiency is even greater with fiber optic, and so the greater the data demand, the higher the efficiency gains of fiber-optic access compared to DSL and HFC.

Chart 3: kWh per Gigabyte for Major Broadband Access Technologies

(Source: Breide et al., Energy Consumption of Telecommunication Access Networks, 2021)

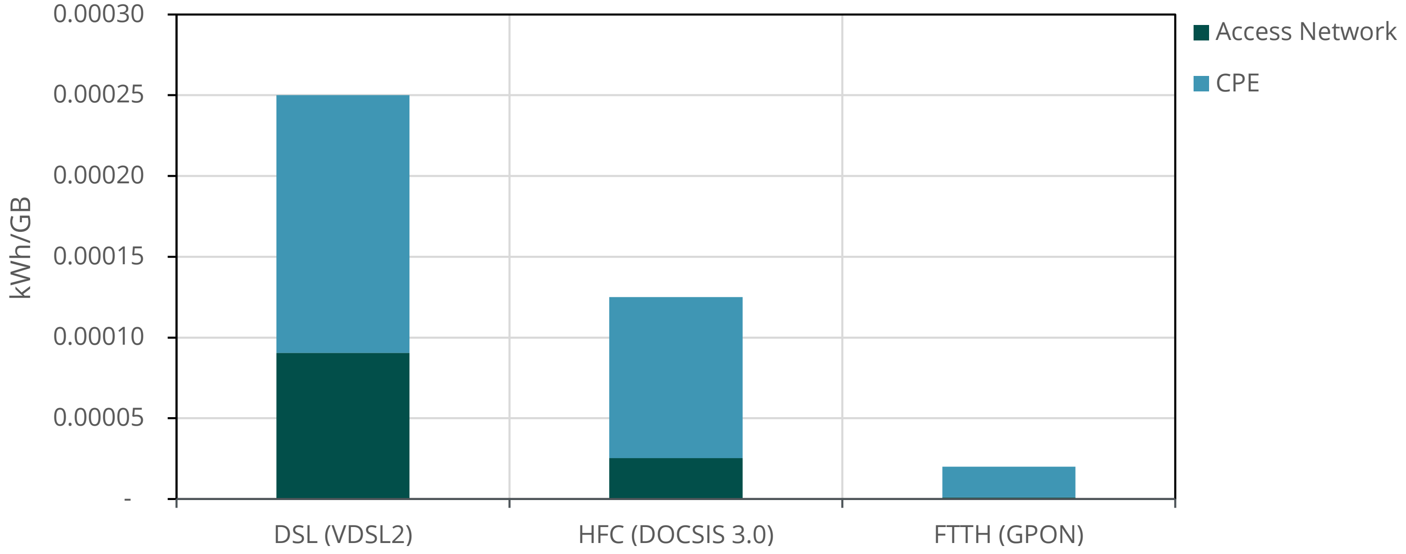


Chart 3 also illustrates another vital piece of information—that for all fixed access types, it is the CPE that consumes the largest portion of the total required energy. For FTTH (GPON) access, the CPE accounts for almost 95% of all the required electricity. For reference as to the approximate energy requirements for fixed access modems within standard Wi-Fi CPE, consult Table 3.

Table 3: Power Values for Home Gateway WAN Interfaces

(Source: ABI Research)

Standard	Idle-State	On-State
VDSL2	**3.0 W to 4.0 W**	**3.5 W to 4.5 W**
GPON	**2.5 W to 3.0 W**	**2.8 W to 3.5 W**
XGS-PON	**3.0 W to 3.5 W**	**4.5 W to 6.0 W**
DOCSIS 3.0	**4.5 W to 5.5 W**	**5.0 W to 6.0 W**
DOCSIS 3.1	**8.0 W to 10.0 W**	**12.0 W to 15.0 W**

The above analysis has highlighted some key insights from fixed access, which we should pay attention to:

- **The CPE Is the Most Energy-Intensive Aspect of the Network:** The research reveals that the CPE is responsible for a majority of the network energy consumption for all fixed access technologies. Therefore, it is clear that more energy-efficient CPE designs are essential to bringing large reductions in the energy consumption necessary for broadband networking.

- **Fiber Is the Most Efficient Access Technology:** The results above decidedly confirm that fiber is the most energy-efficient fixed access technology when viewed from any metric. This highlights the importance of migrating away from legacy DSL and DOCSIS and toward fiber.

ENERGY CONSUMPTION OF ADDITIONAL COMPONENTS

Aside from the Wi-Fi radios and modems, residential Wi-Fi infrastructure also contains numerous other components that also all require energy to operate. These include Ethernet ports for LAN, memory or processor chipsets, or chipsets for other short-range wireless connectivity protocols such as Bluetooth® or Matter. While the energy requirements of these aspects individually may be relatively minor, in aggregate they still are responsible for adding significantly to the energy consumption of equipment. Table 4 outlines the typical levels of some major additional components in Wi-Fi CPE.

Table 4: Power Values for Additional Home Gateway Components

(Source: ABI Research)

Standard	Idle-State	On-State
1 Fast Ethernet Port	**0.2 W**	**0.2 W**
1 Gigabit Ethernet Port	**0.2 W**	**0.3 W**
2.5 Gigabit Ethernet Port	**0.8 W**	**2.4 W**
5 Gigabit Ethernet Port	**0.8 W**	**2.5 W**
10 Gigabit Ethernet Port	**1.5 W**	**3.5 W**
Network Processor	**0.3 W**	**0.4 W**
AI Processor	**0.5 W**	**0.5 W**
Bluetooth®	**0.1 W**	**1.0 W**
Zigbee	**0.1 W**	**0.1 W**
NFC	**0.2 W**	**0.2 W**
USB 3.0	**0.1 W**	**0.1 W**
USB 3.1	**0.1 W**	**0.1 W**
FXS (first interface)	**0.2 W**	**0.8 W**
FXS (additional interface)	**0.2 W**	**0.2 W**

Of the above, the Ethernet port consumes the highest amount of power, with an average 3.5 W for an active 10 Gigabit Ethernet (10GE) port. The power consumed by other Ethernet port standards is also not insignificant, as is the network processor, which demands 0.4 W in an active state. Bluetooth®, which is increasingly commonplace in residential Wi-Fi CPE, requires 0.2 W when active. Thus, based on the above, the network processor, Bluetooth® capabilities, and 10

GE port on a standard Wi-Fi CPE would contribute 1.9 W when idle or 4.1 when active to the total energy consumption of residential Wi-Fi infrastructure.

This list highlights something very important—that non-essential components still consume energy. Consider an AI processor, for example. This specialized computing unit designed for performing accelerated calculations can offer valuable benefits to the consumer, but if it is not being leveraged, then its idle energy expenditure is wasted. Excess Ethernet ports are likewise an accessory that may not be necessary.

REFERENCE EQUIPMENT

The preceding three sections have examined the individual components of a typical Wi-Fi gateway. This section examines the energy profiles of some standard gateways that have been deployed, and from these examples, we can infer some key realities of the Wi-Fi CPE industry that impact sustainability. Table 5 and Table 6 list the specifications for a range of typical residential gateways that have been deployed by major ISPs in recent years. The details are based on real models, but the Stock Keeping Unit (SKU), Original Device Manufacturer (ODM), and partnering ISP have been anonymized.

First, Table 5 outlines the energy consumption of the constituent components in a standard AX6000 dual-band XGS-PON gateway, which is broadly representative of gateways which have been deployed by ISPs worldwide.

Table 5: Power Consumption for Standard AX6000 Dual-Band XGS-PON Gateway

(Source: ABI Research)

Component	Number	Idle-State Energy Consumption	On-State Energy Consumption
XGS-PON WAN	**1**	**3.0 W**	**4.8 W**
802.11 radio (ax, 4x4, 5 GHz, 160 MHz)	**1**	**2.6 W**	**3.2 W**
802.11 radio (ax, 4x4, 2.4 GHz)	**1**	**2.3 W**	**2.8 W**
10GE RJ-45 port	**1**	**1.5 W**	**3.5 W**
GE RJ-45 port	**4**	**0.8 W**	**1.2 W**
SoC	**1**	**0.3 W**	**0.4 W**
USB 3.0	**1**	**0.1 W**	**0.1 W**
Total		**10.6 W**	**16.0 W**

Second, Table 6 illustrates the typical energy consumption and costs of standard residential gateways. For each, key metrics have been provided, alongside an estimation for the cost of operation, with the annual energy costs calculated based on the national average price per kWh in the market for the listed operator in January 2024.

Table 6: Energy Consumption and Local Operational Costs of Residential Gateways Deployed by Major ISPs

(Source: ABI Research)

Access Technology	802.11 Standard	Throughput	Deployed Country	Average Watts/Hour (standard mode)	Est. Annual Energy Consumption	Est. Annual Cost (US$)
xDSL	**802.11ax**	**3000 Mbps**	**Germany**	**9.5 W**	**83.2 kWh**	**$36.4**
xDSL	**802.11ax**	**3000 Mbps**	**United States**	**12.14 W**	**106.3 kWh**	**$17.5**
DOCSIS 3.1	**802.11ac**	**2200 Mbps**	**Czechia**	**24.0 W**	**210.2 kWh**	**$73.9**
DOCSIS 3.1	**802.11ax**	**3000 Mbps**	**United States**	**23.0 W**	**201.5 kWh**	**$33.2**
DOCSIS 3.0	**802.11n**	**300 Mbps**	**Moldova**	**9.5 W**	**83.2 kWh**	**$18.1**
GPON	**802.11ax**	**3000 Mbps**	**Italy**	**9.5 W**	**83.2 kWh**	**$34.5**
xDSL/PON	**802.11ax**	**5400 Mbps**	**Belgium**	**10.0W**	**87.6 kWh**	**$41.7**
GPON	**802.11ac**	**1200 Mbps**	**Brazil**	**3.5 W**	**30.7 kWh**	**$5.1**
GPON	**802.11ax**	**3000 Mbps**	**Thailand**	**8.46 W**	**74.1 kWh**	**$10.4**

The key takeaways from the above analysis are the following:

- **Minor Difference between Idle and Active Modes:** As seen in Table 5, variations between the energy consumption of the idle and active modes of the gateway, and for most of the individual components that make up the gateway, are only around 33%. This figure, which is broadly representative of gateways across the industry, highlights the fact that idle modes do not produce significant reductions in energy consumption.
- **Wi-Fi Radios Responsible for Large Portion of Overall Energy Usage:** The CPE profile in Table 5 also reveals that the Wi-Fi radios are responsible for ~37.5% of the total active-mode energy consumption of the gateway, reflecting the importance of energy efficiency technologies in this area.
- **Relative Inefficiency of DOCSIS:** The analysis reaffirmed the conclusion of Section 4.2 that DOCSIS CPE is the least energy-efficient fixed access technology. When comparing similar performance AX3000 CPE in Table 6, a reference AX3000 xDSL gateway requires 131.4 kWh for operation annually, and an AX3000 GPON gateway just 83.2 kWh, whereas the AX3000 DOCSIS 3.1 gateway demands 201.5 kWh. The latest standard DOCSIS 4.0, which will begin reaching the market in 2024, will again increase the potential data rates, but will not address the core power inefficiencies of the technology.
- **Large Variation between Vendors:** Analysis of the CPE in Table 6 also reveals that the similarly performing CPE from different vendors may have highly divergent energy demands. Comparing the two AX3000 xDSL gateways at the top of the table (which are from different vendors), the 83.2 kWh of electricity consumed annually by the first solution is 21.7% lower than the 106.3 kWh of electricity consumed by the second.

- **Higher Performance Does Not Necessarily Mean Higher Consumption:** Table 6 highlights cases of high-performance gateways that consumed less power than those with lower capabilities. Notably, the AC2200 DOCSIS 3.1 gateway in Table 6 demands more power (210.2 kWh) than the AX3000 DOCSIS 3.1 gateway (201.5 kWh).
- **CPE Energy Costs Constitute Larger Portion of Spending in Lower Income Markets:** Because CPE will consume the same amount of power irrespective of the market it is deployed in, operating the CPE will exert a higher financial burden on markets with lower incomes than higher income ones, assuming energy costs are equal. In many cases though, energy costs are not equal. Consider the case of the DOCSIS 3.1 gateway deployed in Czechia shown in Table 6. The CPE is not only less energy efficient than the DOCSIS 3.1 gateway deployed in the United States (despite having inferior specifications), but due to the higher energy costs in Czechia, the annual cost adds up to over double that of the U.S.-deployed DOCSIS 3.1 gateway.

METHODS OF IMPROVING ENERGY EFFICIENCY

Section 4 established the importance of increasing energy efficiency within broadband infrastructure, and Section 3 examined government and industry responses. This section explores methods of attaining the energy efficiency that the industry demands. Each section below deals with an individual aspect of Wi-Fi CPE, although, in practice, many will act in unison.

WI-FI PERFORMANCE

Wi-Fi radios are some of the largest energy consumers within the Wi-Fi CPE, meaning that improving RF performance is central to achieving greater energy efficiency. Yet, despite the centrality, achieving improvements in this area will be slow, not only due to the technical expertise required to develop the advances, but also because the replacement of existing equipment is necessary. The methods below are the main modifications to Wi-Fi performance that could deliver energy-efficiency gains.

- **Reduce RF Interference:** Interference is inefficiency in the RF environment. Not only does it impact performance, but it also increases energy consumption due to the additional transmissions required to compensate for the obstructed ones. Methods to reduce RF interference include spectrum planning and beamforming.
- **Improve Antenna Power Conversion Efficiency:** In typical CPE, only a portion of the input power into the antenna is successfully converted into RF waves because energy is lost in the antenna's internal circuitry. Methods for reducing this loss without impeding performance include integrating the antenna and Power Amplifier (PA).
- **Improve Antenna Spatial Efficiency:** Antenna transmissions are imprecise, and often only a portion of the projected energy reaches the target area. Alongside wasting RF resources, this also impacts the network's performance by causing additional interference in other areas. Further optimizations to antenna designs and beamforming can help reduce this.
- **Shut Down Radios When Not in Use:** As detailed in Section 4.1, an idle radio still consumes considerable energy. Therefore, it is advised that as many radios as possible should be deactivated when possible to maximize energy savings. Instead of having all radios awaiting activity, just one could remain active, pinging for activity, with instructions to wake others if the need arises.

- **Dynamic Adjustment to Antenna Power Levels:** Power output of the antenna should be dynamic and continually adjusted based on user needs. This means that if the customer is close, less power should be emitted, whereas if they are further away, more power can be emitted.
- **AP-STA Communication:** Currently, the communication between Wi-Fi CPE (APs) and the devices (clients or STAs) is random and not scheduled, something that results in a high degree of inefficiency. Although the potential benefits of greater communication between the AP and STA are clear, it is a challenging feature to develop, and thus is not expected to materialize for a long period of time. At present, such a feature is under consideration for inclusion in Wi-Fi 8.

ENERGY-EFFICIENT DESIGN

This section explores actions that can help improve the energy efficiency of Wi-Fi CPE design. It is important to note that energy-efficient designs typically also bring additional performance and consumer satisfaction benefits, so the steps below can help achieve multiple goals simultaneously. For example, smaller, more compact CPE will improve the aesthetics, as well as the energy efficiency of the equipment. Likewise, improving heat dissipation will also quell the concerns that some customers have toward the heat of CPE (the reporting of overheating CPE is a common customer complaint that operators must troubleshoot).

- **Chipset Transistor Density:** Higher-density chipsets can offer a higher level of performance relative to their size, and therefore can provide greater energy efficiency. Whilst 28 Nanometer (nm) chipsets are common in CPE today, moving toward more advanced chipsets would deliver a significant boost to efficiency.
- **Advanced Access Technologies:** As detailed in Section 4.2, PON is the most efficient access technology, and CPE with this technology should be prioritized.
- **Integrated Components:** Integrating components together can improve energy efficiency. Gateways that integrate modems with Wi-Fi are more energy efficient than separate modems and Wi-Fi routers. Similarly, integrated antennas with PAs can also help enhance antenna power conversion efficiency.
- **Align CPE Capabilities with Needs:** Although the demands of each customer are unique, ISPs typically have only one or a limited range of stock CPE that they deploy. This one-size-fits-all approach often means that customers find themselves with models equipped with capabilities that exceed their needs, or support features that are irrelevant. Because these idle features still consume energy, it is recommended that ISPs work to better align the capabilities of CPE with the demands of the customer. If possible, certain abilities should be disabled if not needed by the users (e.g., Universal Serial Bus (USB) ports or AI chipsets).
- **Holistic Approaches:** Wi-Fi radios and chipsets are often the focus of energy-efficiency initiatives, primarily because improvements to these elements can bring the greatest reductions to the overall energy consumption of equipment. While this is true, it remains the case that many auxiliary components of standard Wi-Fi CPE are not optimized for energy efficiency. Vendors should, therefore, take a holistic approach to energy-efficient design, focusing on achieving efficiency gains in all areas of the network, instead of just targeting low-hanging fruit.

NETWORK TOPOLOGY

Topology is an often-overlooked aspect of the network that exerts a large influence on overall performance and energy efficiency. Additionally, many of the topology-related methods for improving energy efficiency are also those that can be implemented rapidly, meaning that they are immediately actionable. Below are some of the ways in which topology can be leveraged for reducing the energy consumption of the Wi-Fi CPE.

- **Optimal Placement:** Suboptimal network topologies or obstructions degrade performance, in turn reducing energy efficiency. Unfortunately, poor network topologies are common because the typical consumer does not have the expertise to configure their network. Therefore, tools should be developed and implemented by equipment vendors and ISPs to help optimize topologies. One method is using device configuration during setup, with the CPE scanning the environment (either through communicating with client devices or through Wi-Fi Sensing) to identify the ideal deployment location.
- **Mesh Networking:** Although increasing the number of network nodes might appear counter-productive to reducing energy consumption, it is possible to leverage mesh networking to bring down energy consumption. This is because with mesh networking, each individual node can emit a lower power level (~6 Decibel-Milliwatts (dBm)) sufficient for their limited area of coverage, and can strategically power down when their respective area is not in use. In contrast, having one central CPE requires higher power levels (>20 dBm) to cover a broader area, and the equipment cannot dynamically shut down when certain areas are not used.
- **FTTR:** Fiber is the most energy-efficient access technology, and rapid rollout of FTTH over the past decade has helped deliver strong energy-efficiency gains to consumers. With FTTR, the performance and energy efficiency gains of fiber can penetrate deeper into the network. Furthermore, as with mesh networking, FTTR offers the prospect of disabling sections of the network when not in use, further reducing idle power consumption.

SOFTWARE OPTIMIZATIONS

In contrast to hardware-level modifications, which require the installation of new equipment, software-level technologies can be deployed remotely and often on equipment already in use, assuming the existing CPE supports the capabilities. Moreover, software can be continuously tested and improved via Over-the-Air (OTA) updates, allowing for continual optimization. For this reason, software-level modifications are more likely to deliver tangible energy-efficiency gains in the near term. Below are some of the software-level enhancements that can support energy efficiency.

- **Improved Sleep Mode:** As outlined in Section 4.4, the idle modes of standard Wi-Fi CPE deployed today typically consume around 66% of active mode energy, a surprisingly high figure that points to significant energy wastage when the CPE is not in use. Sleep modes should, therefore, be improved to both save more energy when not in use and be more reactive to environmental changes. For the former, Wi-Fi CPE should be designed to have more components switch off or enter basic mode when not in use, while the latter could be achieved through Wi-Fi Sensing (discussed below) via an app or with the detection of client activity.

- **Wi-Fi Sensing:** In recent years, healthcare and security have been identified as the most likely killer applications of the nascent Wi-Fi Sensing technology, but energy efficiency should also be added to the list. Wi-Fi Sensing offers an inexpensive, precise, and non-obtrusive method for detecting environmental changes, enabling the performance of the CPE to dynamically adjust alongside the movement of people or objects. In practice, this could mean that Wi-Fi CPE would be able to identify when the user has left the room, so it could automatically enter sleep mode.
- **AI:** User needs are diverse, so it would be near impossible to produce a common AI program that would perfectly satisfy all user demands. Therefore, algorithms that are continuously refined based on user-specific feedback should be developed.

CHALLENGES TO IMPLEMENTATION

Despite the high potential, there will be significant challenges to realizing the potential of these energy-saving technologies. These include:

- **Insufficient Supply of Hardware:** Energy-efficient components may not be readily available for vendors to use, leading them to continue to rely upon standard, non-energy-efficient components.
- **Potential Performance Decreases Deterring Adoption:** Consumers will be resistant to energy-efficiency improvements if the user QoE suffers as a result.
- **Extended Replacement Timelines:** ISPs typically only replace their subscribers' Wi-Fi CPE every 3 to 5 years, meaning that it will take just as many years for new energy-efficient hardware to be deployed market wide.
- **Lack of Awareness of New Technologies:** Adoption of energy-efficient Wi-Fi CPE may be delayed simply because consumers do not know it exists.
- **Low Return on Investment (ROI):** There are few monetization opportunities for sustainable Wi-Fi CPE, and the cost savings from reduced energy consumption are minimal.
- **Higher Equipment Costs:** Incorporating sustainable components and technologies may increase the Bill of Materials (BOM), an added cost that some consumers and operators may not be willing to pay.
- **No Entity Responsible for Wi-Fi Sustainability:** An industry body is necessary to represent and promote sustainable technologies and practices within the Wi-Fi industry.

CALCULATING THE GLOBAL ENERGY CONSUMPTION OF WI-FI CPE

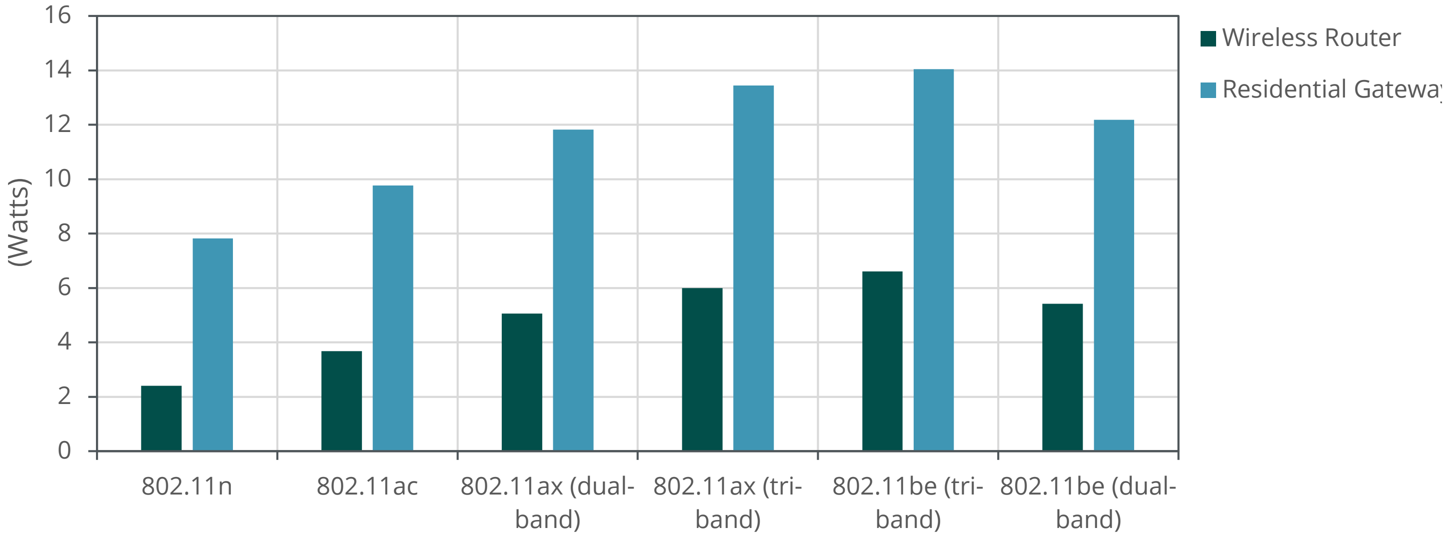
ABI Research has conducted an in-depth energy profile analysis of the current and projected global Wi-Fi CPE installed base to ascertain the total energy that it demands annually. Energy consumption data have been calculated for the years 2023 through 2030, with granularity into the Wi-Fi CPE product type (router, gateway, extender, etc.), CPE component (radio, SoC, etc.), and Wi-Fi protocol (802.11ac, 802.11ax, 802.11be, etc.). It is hoped that, armed with these figures, the industry can both accurately gauge the challenge at hand and identify the potential reductions to energy consumption that can be achieved if they are to implement the energy-efficiency methods outlined in Section 5.

WORLDWIDE ENERGY CONSUMPTION BY RESIDENTIAL WI-FI CPE IN 2023

ABI Research has calculated that the total energy consumed by residential Wi-Fi CPE globally in 2023 was 105.05 Terawatt Hours (TWh). With a 2023 global Wi-Fi CPE installed base of 1.55 billion, this equates to approximately 60.0 kWh per Wi-Fi CPE, or an average energy consumption of 6.0 W/hour. This figure gives us an idea of the energy required by typical Wi-Fi CPE, but the actual energy consumption varies considerably between Wi-Fi CPE product type and the supporting protocol. Chart 4 displays the average energy consumption for wireless gateways and routers by protocol. Note that for gateways, the energy consumed by the WAN access (DSL, DOCSIS, PON) is included, which significantly adds to the overall energy consumption.

Chart 4: Average Hourly Power Consumption for Wi-Fi Routers and Gateways by Protocol

(Source: ABI Research)



PROJECTED GROWTH IN ENERGY CONSUMPTION THROUGH 2030

Assuming the energy-efficiency technologies outlined in Section 5 are not implemented, the total annual energy consumption of Wi-Fi CPE is projected to more than double between 2023 and 2030, jumping from 105.05 TWh to 215.14 TWh. This increase in energy consumption will be led by a combination of the following factors:

GROWING INSTALLED BASE

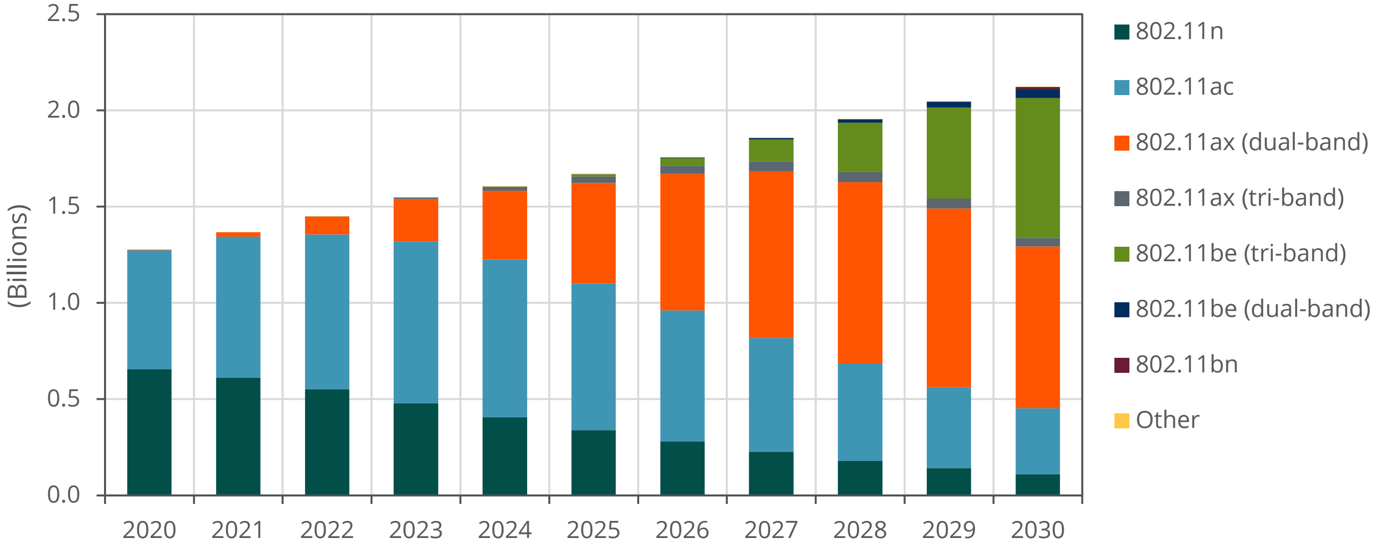
As shown in Chart 5, the global installed base of Wi-Fi CPE is projected to climb at a Compound Annual Growth Rate (CAGR) of 4.6% between 2023 and 2030, increasing from 1.54 billion to 2.12 billion. The expansion of this installed base will be led by two key dynamics:

1) An increased number of connected homes, reflected by a 14.8% increase in the number of worldwide broadband subscriptions over the period.

2) An expansion of multiple CPE households. This includes mesh infrastructure, with an installed base increasing by 144.9% over the period.

Chart 5: Global Installed Base of Wi-Fi CPE by Protocol

(Source: ABI Research)

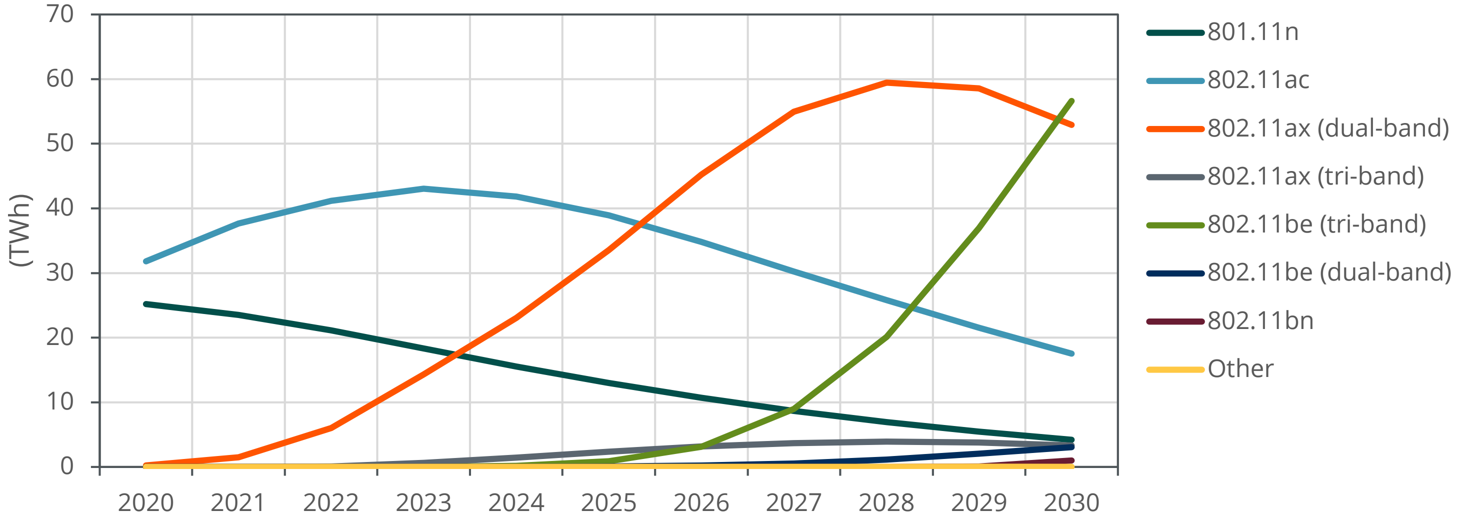


HIGHER POWER CONSUMPTION OF ADVANCED 802.11 PROTOCOLS

On account of their higher performance capabilities, the more advanced Wi-Fi standards are projected to consume more electricity to function than earlier protocols. Therefore, as the installed base of Wi-Fi CPE gradually shifts toward more advanced standards (illustrated in chart 5), the energy consumption will increase concurrently. This dynamic is revealed in Chart 6, which displays the total annual energy consumed by each Wi-Fi CPE supporting different Wi-Fi standards across the period from 2020 to 2030.

Chart 6: Total Annual Power Consumption of 802.11 radios within Wi-Fi CPE by Protocol

(Source: ABI Research)

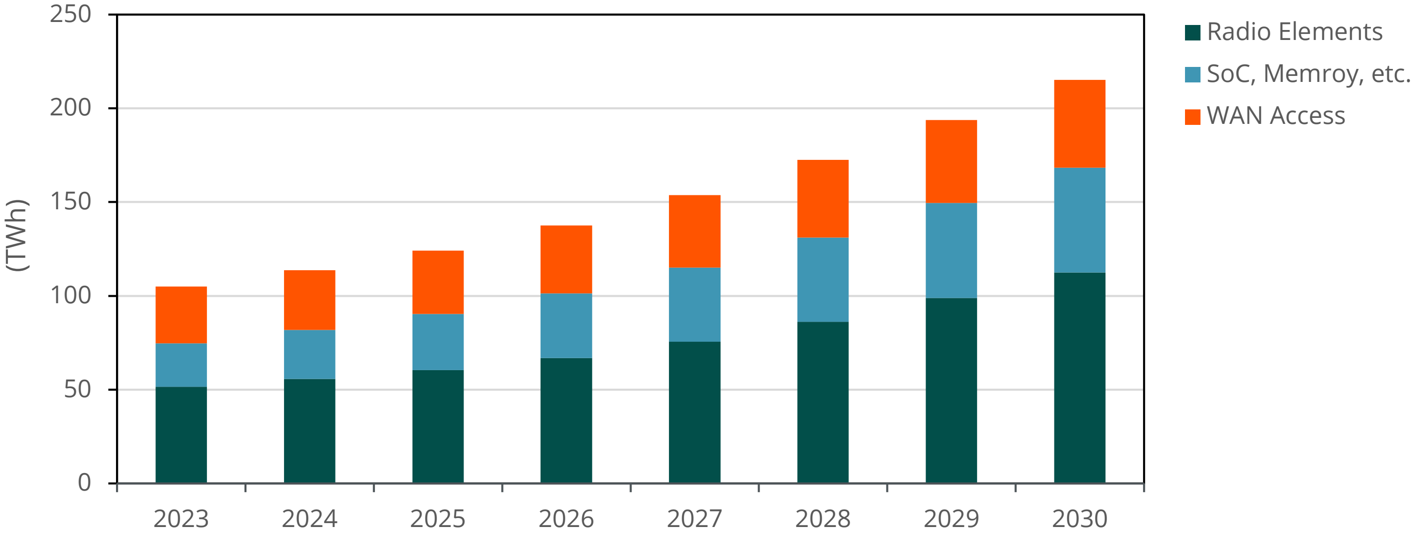


INCREASE IN THE NUMBER OF 802.11 RADIOS

Compatibility with the 6 GHz spectrum band introduced by tri-band 802.11ax and 802.11be is enabling Wi-Fi to gradually transition from a dual-band technology (with support for 2.4 GHz and 5 GHz only) to a tri-band one (with additional support for 6 GHz). This will be the main trigger behind a projected increase in the percentage of total residential Wi-Fi CPE shipments equipped with three radios from 29.0% in 2023 to 66.6% in 2030. Dual-radio Wi-Fi CPE will fall from 66.7% of the total to 25.9% over the same time period. The expansion in the number of radios will naturally raise the total electricity demand of Wi-Fi CPE, with an individual 802.11be radio having an active energy consumption of over 3 W. Alongside this, advancements in the performance of these radios, such as enlargements in the maximum channel width support or higher MIMO configurations, will also drive up the radio's energy consumption. This increase in the projected electricity demand for the operation of Wi-Fi radios relative to the rest of the components is illustrated in Chart 7.

Chart 7: Annual Global Energy Consumption of Wi-Fi CPE by Components

(Source: ABI Research)



POTENTIAL IMPACTS OF ADVANCED SLEEP MODES

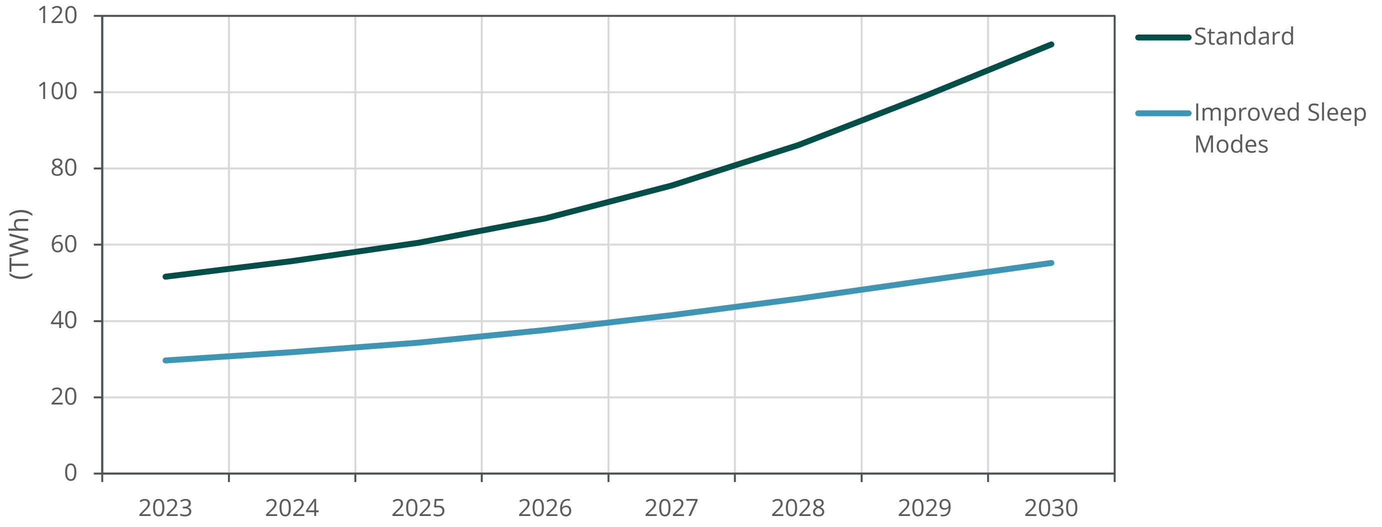
As outlined in Section 5, there are a range of currently achievable and potential future technologies that can be applied to reduce the energy consumption of residential Wi-Fi CPE. This section assesses one of the most impactful and most attainable methods—improved sleep modes for CPE. If implemented correctly, this energy-efficiency technology alone could reduce the 2030 energy consumption of residential Wi-Fi infrastructure from 215.1 TWh to 138.7 TWh.

Advanced sleep mode involves intelligently deactivating radio abilities and minimizing CPE processing when the equipment is in demand, due to the user not being home or asleep. Section 5 showed that this can be achieved through user detection methods such as Wi-Fi Sensing or client application monitoring, and/or advanced AI algorithms. When in sleep mode, it will be possible for all but one radio to deactivate to conserve power. The remaining active radio can then be set to a low-power mode, and tasked with periodically pinging the environment for the purpose of detecting any arising client demand.

The application of advanced sleep modes has the potential to significantly reduce the annual energy demand of Wi-Fi radios within Wi-Fi CPE. As illustrated in Chart 8, it would be possible to reduce Wi-Fi radio energy consumption by 42.8% in 2024, increasing to 50.9% in 2030. The reason for the growth in the energy reductions via improved sleep modes as the decade advances is that as Wi-Fi CPE gradually incorporates an increased number of radios, there is additional opportunity to deactivate radios to save energy.

Chart 8: Global Annual Energy Consumption of Wi-Fi CPE 802.11 Radios with and without the Application of Advanced Sleep Modes

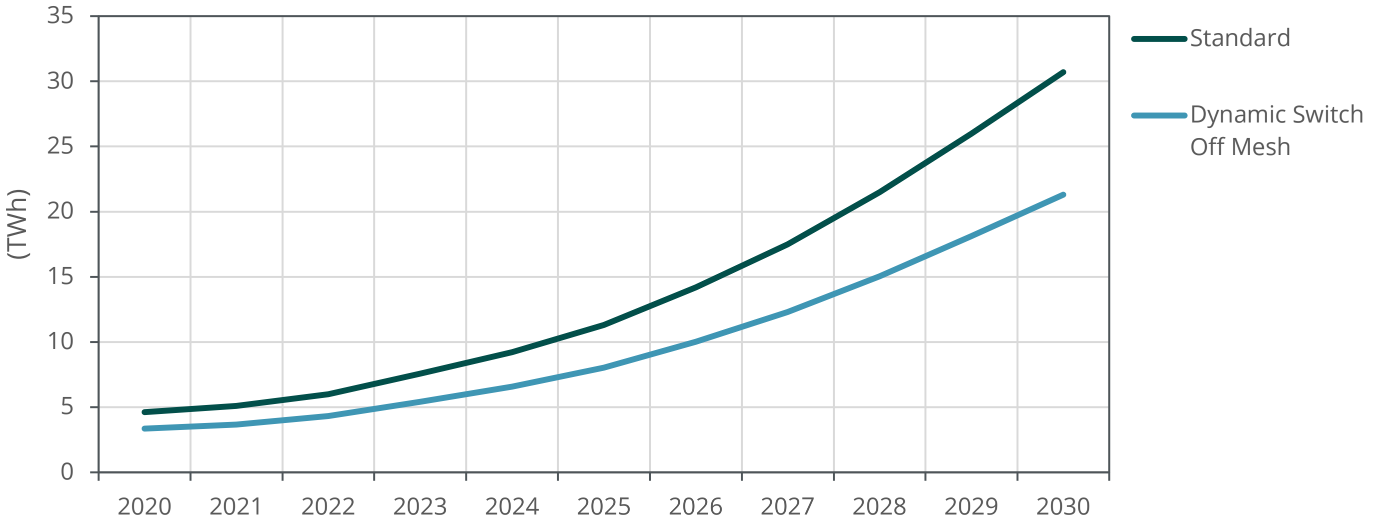
(Source: ABI Research)



The potential for energy savings is even greater when applying advanced sleep modes to mesh CPE. While an expanding number of mesh nodes does significantly enlarge the energy required for the entire network, if it is possible for mesh nodes to dynamically power down when there is no human presence in the room in which they are located, this can greatly reduce their energy consumption. It has been calculated that, if implemented, this could reduce the energy consumption of a mesh CPE product type by a further 30.6% by 2030.

Chart 9: Global Annual Energy Consumption of Mesh Wi-Fi CPE

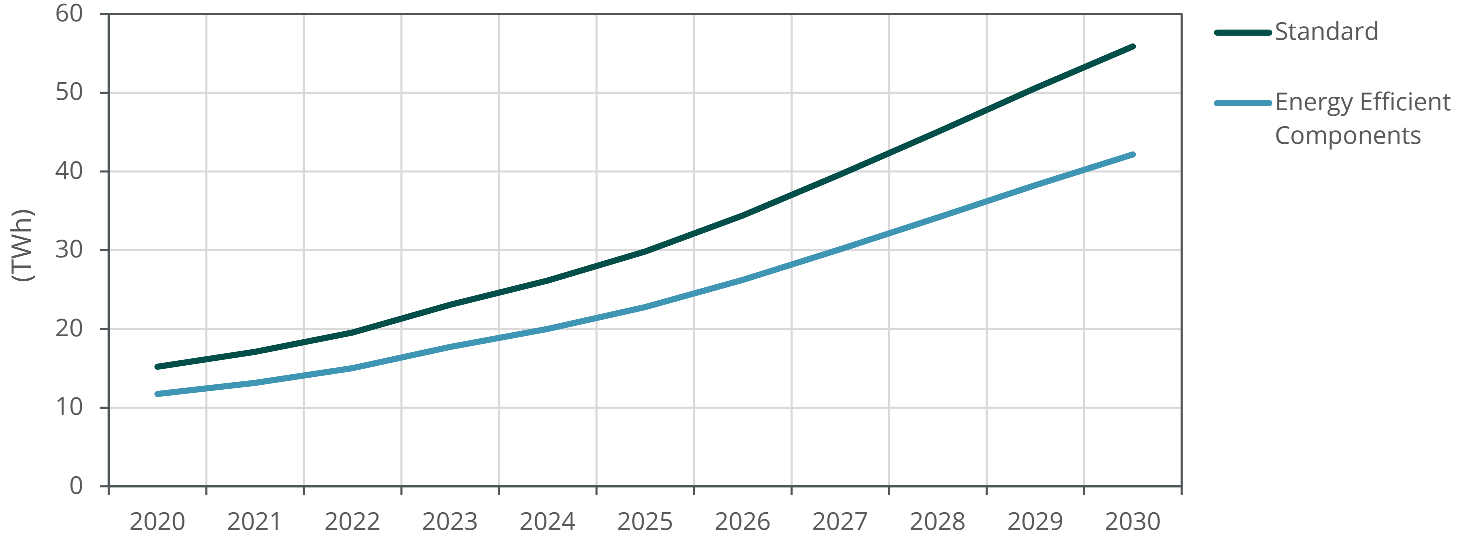
(Source: ABI Research)



Finally, alongside reducing the energy usage of the radio, lowering the processing requirements on the CPE when it is in sleep mode could deliver a further 24.6% reduction in the electricity demand for other semiconductor components within the CPE by 2030. Chart 10 illustrates the potential savings in this field.

Chart 10: Global Annual Energy Consumption of SoC and Memory within Wi-Fi CPE

(Source: ABI Research)



ADDRESSING WI-FI'S SUSTAINABILITY CHALLENGE

THE IMPORTANCE OF STANDARDIZATION

The analysis conducted by this report has demonstrated that the energy efficiency of Wi-Fi CPE remains a pressing challenge for the industry, with the projected annual energy demand of Wi-F CPE increasing from 105.05 TWh to 215.14 TWh between 2023 and 2030 (representing a 105% increase) if no action is taken. Yet, despite the clear urgency of the issue, this report also revealed that current approaches to addressing the question are insufficient, with only non-binding regional agreements on energy consumption and a low level of prioritization for sustainability within official standardization initiatives. This is regrettable, as the industry is unanimous in its belief that greater energy efficiency within Wi-Fi CPE is possible, and numerous potential technologies and techniques have been proposed to help reduce Wi-Fi CPE energy consumption without sacrificing performance. The challenge, therefore, is not a lack of ability, but rather a lack of stimulation and guidance for the ecosystem.

Overcoming the sustainability challenge within Wi-Fi will require a clear and universally recognized standardization framework to help stimulate the energy-efficient design, manufacturing, and operation of Wi-Fi CPE. The foundation of this framework should be strict energy consumption requirements for each component within Wi-Fi CPE. The framework should also mandate the adoption of technologies that can deliver improvements to energy efficiency without sacrificing performance.

Establishing this framework demands industry-wide participation, not only because the tight interconnectedness of the global electronics supply chain means that without collaboration the initiative is doomed to fail, but also because widespread engagement can enable the sharing of best practices among participants. Supervision of the framework should be the responsibility of a neutral body equipped with the knowledge, capabilities, and resources for standardization certification and validation.

THE WORLD WLAN APPLICATION ALLIANCE

The World WLAN Application Alliance (WAA) is a non-profit association for the Wireless Local Area Network (WLAN) industry dedicated to the mission of providing the best WLAN experience for society. The WAA aims to differentiate itself from existing industry bodies such as the WFA and the Wireless Broadband Alliance (WBA) through its focus on improving WLAN application and the end-user experience. This involves the goal of establishing a scenario-based WLAN certification system and a complete performance standard system. The WAA is committed to creating an open and international WLAN industry development platform, and reflecting this, the association's broad membership base spans chipset developers, CPE manufacturers, and operators.

In 1Q 2024, the WAA launched its first work group, which is centered on sustainability. The work group aims to provide Wi-Fi standardization for sustainability that will address the energy-efficiency challenge that the industry is facing. The belief is that such standardization will prove vital toward achieving the sustainability goals that governments and the industry sector are currently pursuing.

WAA MEMBER PROFILES

CHINA TELECOM

China Telecom is one of world's largest telecommunications companies that serves more than 410 million subscribers and provides connectivity for more than 190 million households. China Telecom is an industry leader in gigabit broadband, gigabit Wi-Fi, and 5G, and is a major innovator in numerous critical emerging technologies, including AI, cloud services, and network security. China Telecom has a goal of accelerating digital connectivity, supporting reliable fast speeds and delivering guaranteed high Quality of Service (QoS) to all its customers. China Telecom is also committed to building a sustainable network across its business in line with the Dual Carbon initiative. Through the application of innovative sustainable and low carbon technologies, China Telecom aims to improve sustainability across the telecoms sector and to encourage sustainable lifestyles.

CHINA MOBILE LIMITED

China Mobile iis a global leader in communication and information services, with an expansive network, market leading subscriber base, strong brand value, and a prominent position in market capitalization. The company aims to become a 'network powerhouse,' contributing to China's digital transformation and playing a pivotal role in constructing a smart society. China Mobile is committed to top-notch business performance, to expanding the development space for information services, and independently developing a technological innovation engine.

China Mobile is strategically building a cutting-edge information infrastructure, with a focus on 5G, computational power networks, and capability platforms. The goal is to establish an innovative information service system characterized by ‘connection + computational power + capability.’ China Mobile provides high-quality information services that meet and stimulate digitized demands across all scenarios, including production, life, and governance. China Mobile consistently considers green energy conservation as the central focus of business development.

China Mobile is venturing into the realm of smart homes, striving to ensure that your home is highly connected, intelligent, and enjoyable. They are utilizing advanced technologies such as FTTR and WLAN routers as the foundation, with a focus on establishing a robust home network. They have introduced a variety of smart devices that cater to different scenarios, all of which employ cloud technology to provide you with a top-notch home connection. Currently, over 120 million households are utilizing China Mobile’s smart devices, with 90% of new devices equipped with Wi-Fi 6. China Mobile aims to establish Wi-Fi 6/Wi-Fi 7 as the standard in the country, providing a seamless internet experience and enabling a smarter lifestyle.

HUAWEI TECHNOLOGIES CO., LTD.

Founded in 1987, Huawei is a leading global provider of information and communications technology (ICT) infrastructure and smart devices. It has 207,000 employees and operates in over 170 countries and regions, serving more than 3 billion people around the world. Huawei is committed to bringing digital to every person, home and organization for a fully connected, intelligent world.

Huawei actively responds to the national “Carbon Peak Action Plan before 2030” and sets a positive energy saving goal. It is estimated that, by 2030, the unit energy consumption of home network products (such as ONT/FTTR) will be reduced by 55% compared with that in 2019. With this goal, it aims to build green and agile all-optical home networks.

Huawei actively participates in the formulation of international and domestic energy-saving standards, such as ITU-T SG5, ETSI TC EE, CCSA, FTTR industry standards, and enterprise standards, and continuously promotes the implementation of low-power green energy-saving indicators.

In terms of product design, Huawei continuously develops green and energy-saving WLAN products by selecting high-efficiency power adapters, high-efficiency Direct Current (DC)/DC, advanced chip technologies and new energy-saving architectures, and energy-saving measures for Wi-Fi, Ethernet, and optical modules.

ZTE CORPORATION

ZTE is a world leading provider of innovative and comprehensive communication and information technology solutions. The company provides solutions for telecommunications operators, governments, enterprises, and retail consumers in over 160 countries and regions worldwide, serving more than 1/4 of the global population.

As a leading player in the ICT industry, ZTE is committed to improving energy efficiency within its products and services. As early as 2005 the company established an environmental management system based on the ISO14001 international standard and passed third-party certification. ZTE has also invested heavily in energy conservation and consumption reduction technology for its fixed network WLAN terminal products, a product type for which ZTE has consistently maintained a market leading market share. Going forward ZTE aims to work together with the WAA alliance to promote the achievement of energy conservation and consumption reduction goals for fixed network WLAN terminal products.

In addition, ZTE is a major contributor to the development of industry standards such as IEEE, ITU-T SG5, WFA, CCSA, and FTTR. Within these bodies ZTE is continuously promoting the evolution and implementation of green and energy-saving standards.

NEW H3C TECHNOLOGIES CO., LTD.

H3C is an industry leader in the provision of digital solutions, and is committed to becoming the most trusted partner of its customers in their quest for business innovation and digital transformation. Through the deep layout of the entire industrial chain of “cloud-network-compute-storage-terminal,” it is constantly improving the capability of digitalization and intelligence. It offers a full portfolio of digital infrastructure products, spanning compute, storage, networking, 5G, security, terminal and related domains, and providing a comprehensive one-stop digital platform that includes cloud computing, big data, AI, industrial Internet, information security, intelligent connectivity, and edge computing, as well as end-to-end technical services. HC3 is also the exclusive provider of HPE® servers, storage, and associated technical services in China.

H3C, based on years of industry practice and technological accumulation, has continuously released a series of intelligent native Wi-Fi products and promoted the wide use of Wi-Fi 7 various industries. With continuous technological innovation, product iteration, and practical experience, H3C has maintained the top market share position in the enterprise WLAN market of China for 14 consecutive years (2009 to 2022), becoming a strong navigator in the industry.

HISILICON TECHNOLOGY CO., LTD.

HiSilicon is a leading global fabless semiconductors company. Founded in 1991 as Huawei’s ASIC Design Center, HiSilicon became an independent, wholly-owned subsidiary of Huawei in 2004. It provides trusted and cutting-edge semiconductor products and services for smart devices, which have helped build tomorrow’s smart city, smart home, smart mobility solutions.

FIBERHOME TELECOMMUNICATION TECHNOLOGIES CO., LTD.

FiberHome is an internationally renowned provider of information and communication network products and solutions, always focusing on the progress and development of the global information and communication industry. The company has a rich WLAN product line, covering WLAN products such as ONT, AP, 5G CPE, FTTR, etc., with a cumulative shipment volume of billions and a market coverage of over 50 countries, serving over 300 million users.

FiberHome adheres to the practice of green and low-carbon, advocates sustainable development, has passed the ISO 14001 environmental management system certification, and has been awarded the title of "Green Factory" by the Ministry of Industry and Information Technology of China. Its multiple products have obtained the ISO 14067 product carbon footprint verification certificate. FiberHome is willing to work with all sectors of society to safeguard the green and low-carbon economy and contribute to the achievement of the United Nations Sustainable Development Goals (SDGs).

SHENZHEN LONGSAILING SEMICONDUCTOR CO., LTD.

Shenzhen Longsailing Semiconductor Co. Ltd., established in March 2021, commits to advancing high-performance communication chip development and commercialization. The enterprise sets its sights on ascending to a top-tier position in chip design globally, prioritizing the innovation of Wi-Fi 6 and Wi-Fi 7 AP chips with self-owned Intellectual Property Rights (IPR). With Research and Development ()R&D centers across diverse Chinese metropolises such as Shenzhen, Shanghai, Nanjing, Chengdu, Dalian, and Suzhou, Longsailing's core team boasts a wealth of expertise from the industry's foremost companies, with substantial experience in communication chip R&D and market operations. The firm plays an active role in shaping industry standards and is a member of the WAA, in addition to participating in other standard-setting organizations like the WFA, China Communications Standards Association (CCSA), and Sparklink.

REALSIL

Realsil Microelectronics is a subsidiary of leading semiconductor design company Realtek. It has extensive experience in wireless connectivity chipset design, and since its founding in 2001, has released chipsets supporting all the major 802.11 standards (a/b/g/n/ac/ax). Going forward, it will continue to release chipsets supporting the latest 802.11 6E and 802.11be standards. Realsil also prides itself on its close relationship that it maintains with its customers. Realsil's main wireless connectivity chipset series include the following:

- **Wireless CPE:** RTL8196, RTL8197, RTL8198, etc. This includes chipsets supporting 150 Mbps single band 802.11n through to 3,000 Mbps supporting dual-band 802.11ax.
- **Wireless Adapter:** RTL8188, RTL8192, RTL882x, RTL883x, RTL885x, etc. Spans single band Wi-Fi 4 and dual-band Wi-Fi 6, as well as the latest Bluetooth® standards. These wireless adapter chipsets are used in numerous home electronics devices, including notebooks, televisions, refrigerators, air conditioners, robot vacuum cleaners, and much more. They are also used in driving recorders and across devices in many industrial sectors.
- **Intelligent IoT:** Realsil was an early entrant into the intelligent IoT market, and today is one of the industry's leading vendors. Its products include the fifth-generation Ameba series of semiconductors, which range from basic single band 802.11n to the newest industry-first dual-band 802.11ax intelligent audio chipset.

Published February 2024

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