Report for Meta

Full-fibre networks in Europe: state of play and future evolution

Final version for publication

3 May 2023

Ref: 706675597-183

Contents

Analysys Mason is grateful for the financial support provided by Meta in the preparation of this paper. It was produced independently by Analysys Mason, and does not reflect or prejudge Meta's own views.

Analysys Mason Limited
North West Wing, Bush House
Aldwych
London WC2B 4PJ
UK
Tel: +44 (0)20 7395 9000
london@analysysmason.com
www.analysysmason.com
Registered in England and Wales No. 5177472

Executive summary

Internet access has come a long way since the 1990s, when it was effectively a 'dial up' phone call. Over the past two decades, optical fibre has been extended towards end users, and all the way to homes and offices in the last five to ten years. Full fibre allows operators to meet not only the current demand for high-speed internet, but to provide a medium for tomorrow's even more demanding applications.

Europe is no exception: fibre networks have been expanding, driven by a combination of private investment and competition, and by ambitious policy targets to connect every European to a gigabit network by 2030. **Full-fibre networks are now available to a majority of Europeans. Nearly everyone in Spain, Portugal and France has the option to buy full-fibre-based connections; in Germany, where DSL and cable perform relatively well and deployment costs are reportedly high, fibre investment and roll-out has been slower to materialise.**[1]

This rapid increase in full-fibre network coverage can be ascribed to investment by established telecoms operators, financial investors, and the public sector. **Roll-out has been remarkably fast in countries where regulatory policies, new private investment and competition came together to reduce deployment costs and put competitive pressure on legacy networks.** In other countries, where competitors face greater costs or non-cost barriers, deployment has been slower.

Public funding and subsidies have played a crucial role, particularly where the business case for private investment has been weak, resulting in a mix of publicly-owned and subsidised infrastructure in many European countries. Throughout Europe, new investors including pension funds, infrastructure funds, private equity firms and utility companies have also been attracted to fibre by a combination of factors: stable returns, long-term upside from ongoing growth in demand, and the potential to monetise existing network assets outside of telecoms.

These investments span 'passive' infrastructure, primarily the fibre-optic cables (dark fibre)[2] and the poles and ducts that carry them, and 'active' network equipment that allows electronic communications to be transmitted to and from end users.

- **Passive infrastructure represents 75% of deployment costs on average**.[3] **These assets have very long lifespans: they will support networks for decades without the need to be replaced.**
- Active equipment includes equipment in the network to transmit data on the fibre-optic cables, and equipment in homes and other premises that act as a gateway for customers. These assets

1 France, Germany, Italy and Spain, which together represent close to 60% of EU households, have all announced they would reach 100% fibre coverage within the next five to seven years.

2 'Dark fibre' refers to fibre-optic cables excluding any equipment connected to them.

3 The percentage of costs that passive infrastructure represents can vary due to factors such as country characteristics, infrastructure sharing, and rurality; it can go up to account for 90% of deployment costs in some countries.

are shorter-lived than passive infrastructure, and will be replaced more regularly, typically with more efficient, higher-capacity equipment.

In addition to supporting fast broadband speeds and increased capacity, full-fibre networks also offer additional benefits: simpler network topology,[4] as well as lower energy consumption compared to legacy networks that help bring down the costs and environmental footprint of operating fibre networks.

Since broadband access networks have become widespread in the early 2000s, the demand for data traffic over fixed networks has grown as a result of increased adoption of richer and more varied online services. This growth in demand has been stable and sustained over time throughout Europe, but more recent growth has slowed, despite the adoption of gigabit-capable broadband. Demand is not just (or even primarily) traffic-related, however: the benefits of full-fibre networks for end users stem from the higher peak speeds they enable, and the plentiful capacity they offer.

In fact, we estimate that even current full-fibre networks, including 10Gbit/s-capable networks[5] that are fast becoming the norm in ongoing deployments, will remain capable of delivering very high speeds with no material congestion until well after 2030. As traffic grows, ongoing upgrades will be needed outside the access network, in the core and backhaul networks; these account for a small proportion of total network costs.

Future demand is uncertain of course, but one thing is clear: the promise of societal and economic benefits from gigabit connectivity, and therefore the policy rationale for seeking to get full-fibre networks throughout Europe will be realised only through the emergence and diffusion of high-bandwidth applications.

These new applications are very unlikely to overwhelm network capacity for decades: full-fibre networks are designed to be highly upgradeable, with standards and network architecture choices that will allow significant improvement in network capacity, at costs much lower than initial deployment costs for full-fibre networks in the first place. Capital investment in full-fibre networks will continue for several years, but private investment may have already reached its peak in several European countries, due in part to the speed at which fibre has been deployed in recent years, and the challenging business case associated with less dense areas still to be covered. Once deployment is complete, maintenance and upgrade costs will be sustainably reduced.

4 Fibre networks have simpler topology compared to legacy networks as fibre networks can serve the same number of end users through fewer nodes, requiring less resources and lower operating costs.

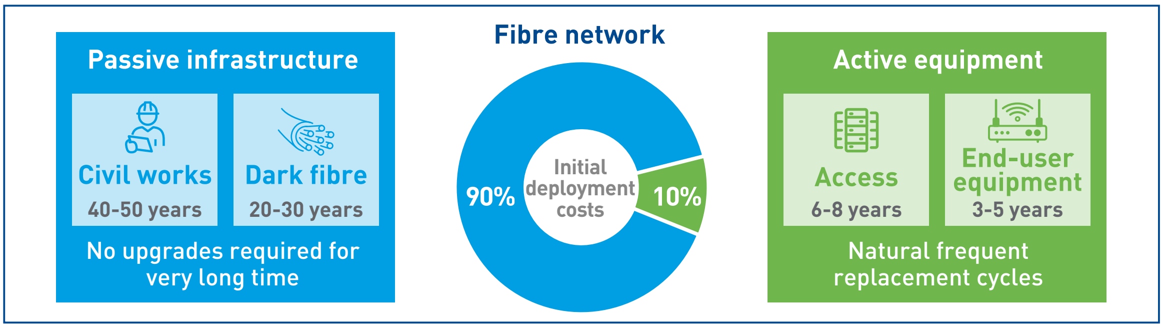
5 Primarily using the XGS-PON standard that enables 10Gbit/s symmetrical bandwidth per user subject to compatible end-user equipment.

Full fibre networks are now available to majority of European households, spurred by competition, regulation, and multiple funding sources

Very high capacity networks (VHCN) including cable covered 70% of EU households in 2021

Fibre networks deliver many benefits over legacy networks, and combine passive assets with long lifespans (the vast majority of deployment costs) and active equipment

Results in better performance across metrics compared to legacy networks

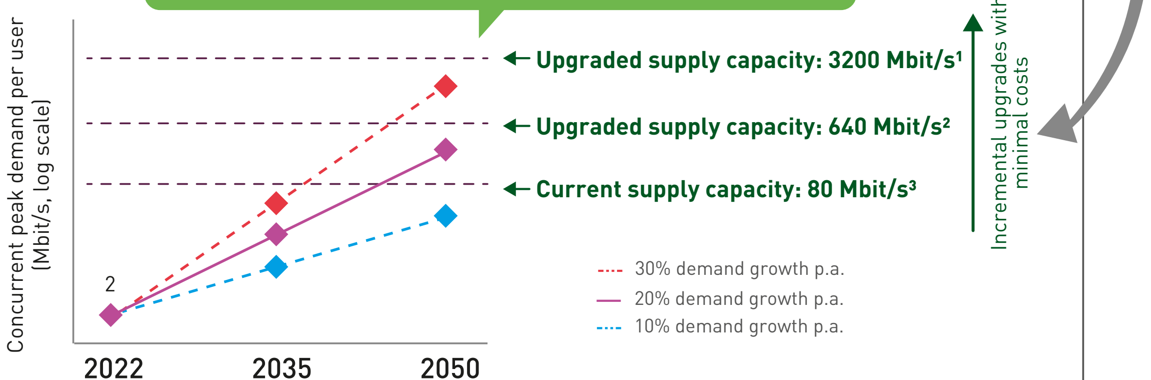


GPON-based fibre networks are highly upgradable and will be able to handle decades of demand growth at limited cost

Upgrade costs will be very limited compared to deployment

- Only active equipment (10% of initial costs) will require upgrades
- Unit cost of active equipment declines over time
- Flexible upgrade options with limited costs include reducing splitting ratios and natural upgrade cycles of GPON

Current PON-based fibre networks will be upgradeable to handle growth in demand until 2050 and beyond



[1] Upgrade to 50G-PON (16 users / PON)
[2] Upgrade to XGS-PON and reduce to 16 users / PON
[3] Current GPON (32 users / PON) or current XGS-PON (128 users / PON)

Notes: Capacity expressed as total downlink bandwidth in the PON divided by the number of users per PON, expressed in Mbit/s; Chart shown is not exactly to scale

1 Introduction

Internet access has come a long way since the 1990s, when it was mostly provided through 'dial up', effectively a phone call between a modem at home and one in the office of an internet service provider (ISP). Eventually, telecoms and cable networks upgraded their networks to offer DSL- and DOCSIS-based broadband connections. Speeds moved on from a few kbit/s to Mbit/s, and even tens of Mbit/s as operators upgraded their networks by pushing fibre optics deeper towards end users.

This progressive deployment of fibre deeper in networks over the past two decades has culminated, within the last five to ten years, in full fibre connections bringing very high bandwidth all the way to homes and offices that were previously connected via cable or copper lines. This progressive investment in upgrading and expanding networks is core to operators' business model.

In Europe, fibre networks have been expanding due to private investment and competition. The European Commission's Digital Decade programme[6] aims to achieve 100Mbit/s for all households by 2025 and 'Gigabit for everyone' by 2030. These very ambitious targets are playing a role in encouraging ongoing investment from different sources, including public funds, and ensuring that clear objectives are set.

In the context of the European Commission's recent publication of detailed measures to further accelerate the deployment of 'gigabit infrastructure', including fibre,[7] this paper brings together data and analysis to explain the current status of fibre deployment in Europe, the technical properties of fibre networks that are being funded by ongoing investments, and how these networks will handle future demand for data. This paper was commissioned by Meta and prepared independently by Analysys Mason, on the basis of our work with operators, investors, governments and regulators in Europe and beyond.

The structure of the remainder of this paper is as follows:

- Section 2 provides an overview of current fibre deployment in Europe, as well as the sources of funding that are enabling these deployments.
- Section 3 explains how funding is used in upgrading existing networks to full fibre and in rolling out new 'greenfield' fibre networks[8] in Europe, and the technical properties of fibre networks.
- Section 4 demonstrates the resilience of these ongoing 'full-fibre'[9] investments to growth in demand for data over the coming decades, including through efficient upgrade paths that have already been standardised.

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6 European Commission (2023), *Europe's Digital Decade*.

7 European Commission (2023), *Gigabit Infrastructure Act Proposal and Impact Assessment*.

8 Greenfield fibre networks refer to fibre-optic networks that are operated by new entrants.

9 Full-fibre networks refer to those that connect homes to the internet via a direct fibre optic link. These networks are typically designed as either point-to-point (PtP) fibre networks, where each premises connected has a dedicated fibre pair to an active switch, or as passive optical networks (PONs), where multiple connections share a fibre 'tree' controlled by the same active equipment. The vast majority of full-fibre deployments are now based on the PON technology, which also forms the focus of this paper.

2 Fibre coverage is being funded by a strong pipeline of investments from operators, governments and investors

In line with the European Commission's targets, the coverage of full-fibre networks has been steadily increasing and is now available to a majority of Europeans. Countries such as Spain and Portugal have already achieved near-universal coverage. While some nations such as Germany currently lag behind the EU average, for reasons including high deployment costs and effective legacy networks,[10] they are expected to catch up rapidly based on ongoing investments. These investments are explored in Section 2.1.

The investments required to deploy full-fibre networks are being funded in large part by established telecoms operators, including cable operators. Incumbents' incentives to deploy fibre networks vary: **where competitors are actively deploying their own fibre networks, incumbents have typically been proactive in doing so as well. In other countries, where competitors face greater costs or non-cost barriers, deployment has been slower.** We provide an overview of this state of play in Section 2.2.

In addition to direct investment from operators, significant new funding is flowing into full-fibre deployment from additional sources, which we examine further in Section 2.3:

- Public funding and subsidies have led to a combination of publicly owned or subsidised infrastructure in areas with high costs, and will continue playing a crucial role, spurred by the relaxation of State-aid rules[11] and the release of post-Covid-19 recovery funds.[12]
- Private investors including pension funds, infrastructure funds, private equity firms and utility companies are looking to gain stable returns and long-term growth potential.

These investments cover both 'passive' infrastructure, primarily the fibre-optic cables and the poles and ducts that carry them, and 'active' network equipment that allows electronic communications to be transmitted to and from end users. The nature of these investments is examined in further detail in Section 3.

2.1 Many countries in Europe have already deployed widespread fibre networks, and full-fibre networks are now available to a majority of European households

Full-fibre (fibre to the home or FTTH) network coverage of European households has doubled over the last five years, reaching 50% by mid-2021. We conservatively estimate the coverage of full-fibre networks as having reached 58% by the end of 2022, meaning that a majority of households in

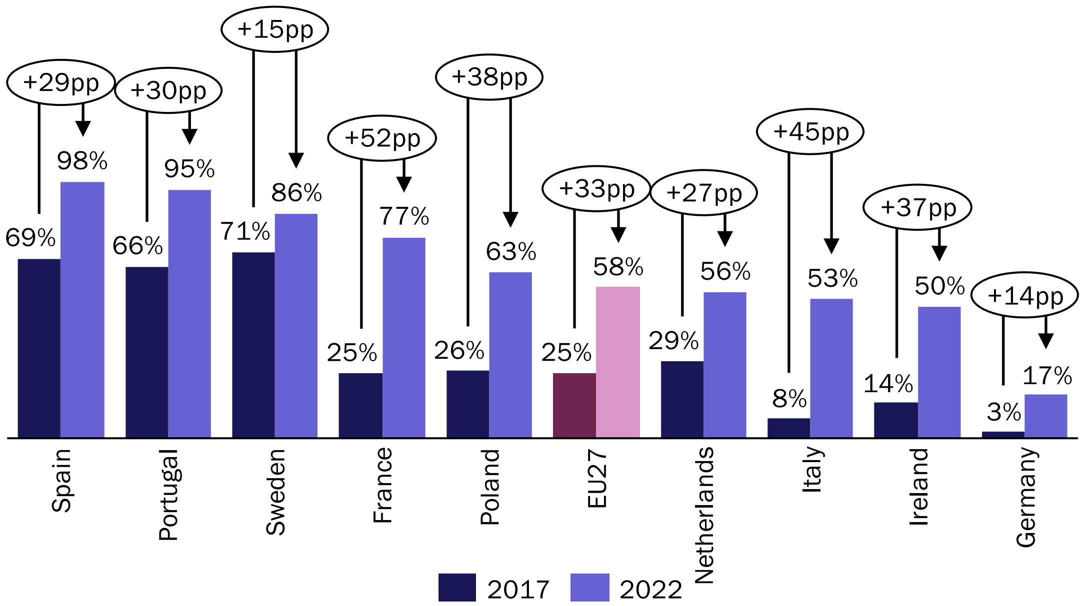
10 VDSL- and DOCSIS-based.

11 European Commission (2022), *State Aid*.

12 European Commission (accessed on 10 March 2023), *The Recovery and Resilience Facility*.

Europe now have access to full-fibre coverage.[13] So far, this has been driven by nearly full coverage in large European economies such as Spain, Portugal and France. This is shown in Figure 2.1.

Figure 2.1: FTTH household coverage across EU27 and selected countries [Source: Analysys Mason Research, 2023]



The success of FTTH household coverage in Spain and Portugal relates in part to costs, and in particular the ability to roll out fibre cheaply, reusing existing passive infrastructure. It also stems from pro-competitive policies and regulatory initiatives including national broadband plans and infrastructure-sharing regulations.[14]

France has also achieved a relatively high level of full-fibre coverage. This has been driven by significant regulatory and public funding intervention. Very early on, the regulator Arcep designed a set of rules to facilitate shared access to in-building infrastructure, which reduced barriers to investment in dense areas.[15] Furthermore, regional authorities in less-dense areas took part in a major public investment effort to fund, under a concession model (i.e. public ownership and private operation), a set of public initiative networks (PINs), which now covers 12.2 million premises[16] and provides full fibre to households, businesses and public buildings.

13 See Analysys Mason's *Fixed network data traffic: worldwide trends and forecasts 2022–2028*. The 2022 coverage value for EU27 here is similar to the 57% coverage estimate quoted by the FTTH Council Europe (2023), *FTTH Adoption Drivers and Hurdles in Europe*.

14 In public statements, Telefónica has mentioned regulatory and competitive conditions, including mandated operator access to existing infrastructure such as manholes, ducts, poles and buildings, as crucial factors to achieving high coverage rates in Spain. See Telefónica (2022), *Why Spain is a Case Study for Super-fast Broadband* and Vodafone (2013), *Vodafone and Orange to Co-Invest In Fibre to the Home In Spain*.

15 Arcep (2009), *Décision n° 2009-1106 de l'Autorité de régulation des communications électroniques et des postes en date du 22 décembre 2009* (in French).

16 There are just over 30 million households in France, and an estimated 42 million premises.

Conversely, Germany has relatively low fibre coverage so far, in part because of well-performing cable and DSL networks, and with high deployment costs often cited as a major constraint.[17] Despite some investors limiting their investment in recent months,[18] announced private and public investments are expected to contribute to a rapid increase in FTTH coverage, with a target to cover 50% of households by 2025.[19] Overall, the Federal Ministry of Transport and Digital Infrastructure (BMDV) estimated in 2022 that the private sector alone would invest EUR50 billion in fibre deployment in the coming years.[20] The public sector was also expected to contribute a further EUR12 billion in investment for fibre networks, as stated in 2019.[21]

These examples demonstrate the importance of the coexistence between public and private investment, including financial investors, in the path to full-fibre coverage that Europe has embarked on. We explore these dynamics further in the following sections, first by focusing on established operators and explaining how market competition has propelled deployment, before turning to a discussion on the contributions of public funding initiatives and financial investors.

2.2 Established telecoms operators and their shareholders have been upgrading existing fixed networks to full-fibre, spurred in part by competition

A subset of European telecom operators, including incumbents and cable operators, own and operate end-to-end networks. These operators typically reinvest a portion of their earnings into their networks to upgrade or expand their networks. This is core to establishing and maintaining profitable operations as part of the telecoms network operator business model.

These established operators have been pushing fibre deeper towards end users for nearly two decades, a process that has accelerated in part due to external factors such as regulatory initiatives and increased competition (see Annex B.1.1 for further details). During this ongoing process, operators have tended to reuse passive infrastructure including ducts, poles and in-building access wherever possible to mitigate capex costs and complexity.[22]

Importantly, these access network owners and operators have had little incentive to upgrade their access networks quickly in the absence of regulation or competition, particularly when end-user willingness to pay more for better quality and speed was limited. In fibre, this

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17 ING Think (2021), *Fibre rollout: the hardest part is yet to come*.

18 Since the start of 2023, Liberty Global-backed helloFiber and Glasfaser Direkt both announced that they would stop deployment, due to a combination of macro-economic and supply chain conditions.

19 Targets are for 100% coverage by 2030, mirroring similar (and faster) targets in France; in practice, this may not be achieved as fixed wireless access (FWA) and satellite technologies may offer sufficient performance in the last few percent of premises. See also BMDV (2022), *Gigabitstrategie der Bundesregierung verabschiedet.*

20 In March 2023, the approved joint venture (JV) between Vodafone and Altice announced plans to invest EUR7 billion in the roll-out of FTTH to 7 million households in Germany over the next six years. See Vodafone (2023), *Completion of Vodafone and Altice Joint Venture in Germany* and BMDV (2022), *Gigabitstrategie der Bundesregierung verabschiedet*.

21 BMDV (2021), *Broadband funding by the Federal Government.*

22 In some cases, however, this infrastructure is decades-old and requires capex investment.

competitive dynamic remains a major driver of investment and deployment. The competition introduced by established or new (greenfield) operators has led to increased pressure for established operators to invest.[23] As mentioned previously, this has been particularly visible in Spain, Portugal and France, where passive infrastructure has been readily available to non-incumbents.

Figure 2.2 shows announced roll-out targets of incumbents in several European markets that have likely been influenced by regulatory initiatives and competitive pressure from greenfield challengers. This table provides a non-exhaustive summary of how increasingly competitive market conditions appear to have led to incumbents announcing more ambitious deployment targets than they otherwise might have.

Figure 2.2: Announced targets from incumbents in Europe, incl. addressable premises through third-party networks [Source: Analysys Mason, Analysys Mason Research data, operators' websites, 2023]

Country	Incumbents	Incumbent FTTH coverage (2022)	Roll-out target	Implied target coverage
Spain	Telefónica (Movistar)	98%	100% coverage by 2024	100%
Portugal	Altice (MEO)	86%	N/A	N/A
France	Orange	49%	36 million by 2023	84%
Netherlands	KPN	41%	~80% coverage by 2026	80%
Poland	Orange Polska	32%	8 million by 2024	48%
Italy	TIM	27%	~60% coverage by 2026	60%
Germany	Deutsche Telekom	11%	10 million by 2024	21%

N/A: not available

2.3 Public funding and financial investors are contributing significantly to new fibre build, and also enable the entry of new competitors that apply pressure to incumbents

It is not only established operators and their shareholders, but also public funding and financial investors that are supporting ongoing FTTH deployment. While public funding encourages investment in less-dense areas, financial investors support new greenfield networks where long-term returns can be achieved. Both of these sources inject funds into the fibre market directly, but also indirectly, by supporting new operators that apply competitive pressure to incumbents, as illustrated in Section 2.2.

Public funding accounts for about 10% of network deployment costs already spent in Europe by 2022 (see Annex B.1.2 for further details). Public funding will continue to play a significant role as

23 Study for Ofcom by WIK-Consult (2015), *Competition & investment: An analysis of the drivers of superfast broadband;* CityFibre (2018), *DCMS – Future Telecoms Infrastructure Review* and GOV.UK (2022), *Future Telecoms Infrastructure Review (Additional Evidence)*.

households in less-dense areas are progressively covered with the help of public funding. This will continue to happen through different models (subsidies or direct intervention)[24] and different sources: the European Commission published revised State-aid guidelines specifically designed to be directed at broadband, and the EU Recovery and Resilience Facility provides for EUR338 billion in grants, of which EUR100 billion is expected to be directed to digital infrastructure and other initiatives. This is developed further in Annex B.1.3. Furthermore, the EU's proposed Gigabit Infrastructure Act seeks to significantly decrease the remaining fibre deployment expenses by EUR14.5 billion, as mentioned in Section 3.2.

Another important trend in recent years has been the degree of interest in both mature and greenfield digital infrastructure from institutional investors (pension funds, specialised infrastructure funds, private equity investors) and companies outside the telecom sector (e.g. utilities). **The long-term viability and stable returns of these assets make them highly attractive for investors with long time horizons and low-to-moderate risk appetites.** As a result, the number of players backed by external investors in the fibre market has increased significantly. This investment typically takes three possible forms:

- **Carve-outs of established networks** which allows incumbents and cable operators to raise capital and to jointly roll out fibre networks (in the case of partnerships), implying that when established operators announce large fibre network roll-outs, a significant chunk of the network might actually be funded by external investors, and not by the operators or their shareholders.
- **New capital investment in greenfield fibre networks** which involve establishing new challenger fibre operators, where large investors have been heavily investing across different projects in Europe, while others have focussed on one or two fibre deals.
- **Investment to expand non-telecoms networks** such as utilities companies that can leverage already existing passive networks and construction know-how, as seen in the Nordic countries.

This private investment has resulted in significant new capital (equity and debt) being injected into European fibre investments. We estimate the capital already committed by these 'external' investors reaches at least 20% of total fibre network investment required by 2027.[25]

Investment in full-fibre networks goes into developing future-proof networks. In Section 3 below, we show that funding mainly goes toward passive infrastructure, which has a very long lifespan. We also explain how the natural replacement cycle of active equipment increases capacity, and finally detail the future-proof characteristics of fibre networks in comparison to other access technologies. This technical information explains why the fibre networks are expected to remain robust into the far future, regardless of the uncertainty around demand growth, as discussed in Section 4.

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24 PIN refer to Public Initiative Networks which are set up and owned by local authorities and run as concessions with private partners.

25 This is a very conservative estimate, which only includes major deals that are already completed.

3 Full-fibre network investment spans long- and short-lived assets, and will lead to more efficient networks

Fibre networks can be broadly split between passive infrastructure and active equipment elements, as described in Section 3.1. Different operators such as incumbents and new challengers will have different strategies and starting points, but the technical characteristics of these two categories are more or less the same across different fibre networks, regardless of their starting points.

In Europe, investments in full-fibre networks are driven by the need to upgrade dense, long-lived passive infrastructure. As described in Section 3.2, this includes deploying fibre-optic cables (referred to as 'dark' fibre) and upgrading or deploying the ducts, poles and other civil works that are required to carry this fibre. **These upgraded passive infrastructure items (or new deployments in the case of greenfield networks) have very long lifespans and nearly limitless capacity,[26] and will support networks for decades without requiring replacement.** Active equipment, across the part of the networks that connects to end users (referred to as the access network) and the backhaul and core transmission part of the networks, represents a smaller portion of the upfront network investment. Active equipment has a shorter lifespan than passive infrastructure, and will be replaced more regularly, along similar cycles as existing equipment in legacy copper and cable networks.

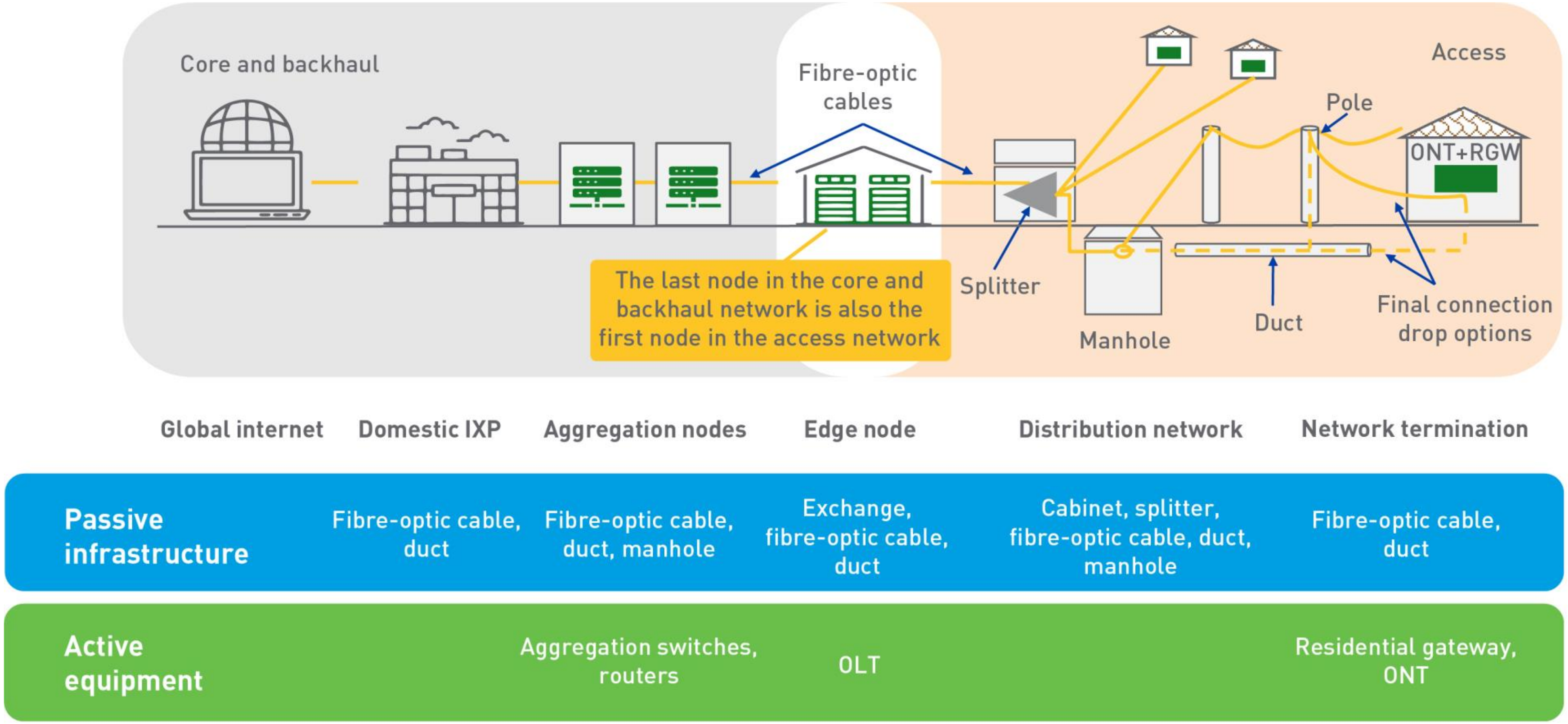
In addition to supporting fast broadband speeds and increased capacity, full-fibre networks also offer numerous benefits due to their simpler topology through fewer nodes (hence less resources and lower costs) and lower energy consumption compared to legacy networks. These characteristics help bring down the costs of operating fibre networks, and are explained further in Section 2.3

3.1 Deploying full-fibre networks involves investments in various network segments, in passive infrastructure and active equipment, by incumbents and challengers

Full-fibre networks require investment in passive infrastructure and active equipment across various network segments (core and backhaul, as well as access), as depicted in Figure 3.1 below. It is worth noting that incumbent operators (including cable companies) and challenger operators would typically have different approaches to investing in certain parts of the networks, given their different starting points.

26 Passive elements such as poles and ducts can support a finite number of fibre cables, and each dark fibre strand, with a diameter of less than 1mm, could potentially carry Tbit/s of bandwidth, therefore the physical capacity limits of these passive elements is thousands or millions of times the limits imposed by active equipment standards

Figure 3.1: Illustration of the active and passive components of a full-fibre network; in PtP-based networks, there is no splitter and individual fibre pairs go all the way to the edge node [Source: Analysys Mason, 2023]



Note: IXP = internet exchange point, OLT = optical line termination, ONT = optical network termination

Core and backhaul networks are relatively mature in most European countries,[27] and are also smaller in scale compared to access networks, meaning that the bulk of investment in fibre goes towards access networks. **Incumbent operators (including cable operators) are upgrading existing access networks from legacy technologies to fibre, and are able to reuse existing passive infrastructure that they already own, which helps to save on deployment cost and time.** New entrants, on the other hand, need to either build their own infrastructure or lease infrastructure from more established network providers (operators and dark fibre providers such as utilities).[28]

Infrastructure sharing generally allows new entrants to reduce their capex requirements significantly and accelerate their time to market, and as such, regulators in most European countries have mandated infrastructure sharing.[29] Proposals from the European Commission under the Gigabit Infrastructure Act[30] are intended to enable more infrastructure sharing, including by mandating 'pre-fiberisation' of new or substantially renovated buildings (which reduces the connection cost significantly) and by ensuring non-telecoms network owners play an expanded role in accommodating fibre deployment in their passive infrastructure.

Overall, many premises are already being covered (or 'passed') by more than one physical network; these networks may share passive infrastructure including in-building cabling, or in some cases may be entirely physically separate. In the rest of this section, we consider an individual nationwide network with its own passive infrastructure and discuss, where relevant, the nuances for operators that are upgrading existing networks, operators that are deploying new networks using existing passive assets such as ducts and poles, and operators that are deploying entirely new networks from the ground up.[31]

Different network assets can be grouped into passive infrastructure and active equipment, and the two categories of assets tend to have different technical characteristics. While passive infrastructure assets tend to have very long lifespans, active equipment tends to include electronic components that result in shorter lifespans and a need for these types of assets to be periodically replaced. The next

27 Fibre-based core and backhaul transmission networks have been in operation in Europe since the 1980s, operated by incumbents such as Deutsche Telekom and Orange, as well as long-distance and metro operators such as euNetworks, Lyntia and GTT that provide core and backhaul transmission products to smaller operators that choose not to build their own core and backhaul infrastructure. Core networking equipment is generally also entirely fibre based, and is generally not limited in terms of capacity.

28 Some new entrants may already own some network infrastructure – this is the case for utility and transport network operators typically.

29 The implementation of such practices has led to a significant reduction in the time and cost required to deploy access networks, as evidenced by successful examples in Spain and Portugal (see Section 2.1). Recently, the European Commission has also published a proposal for the Gigabit Infrastructure Act as part of its connectivity initiatives, along with a consultation. The Act aims to increase co-ordination between the operators for the deployment of infrastructure, and ensure that relevant players have access to the infrastructure.

30 European Commission (2023), *Gigabit Infrastructure Act Proposal and Impact Assessment*.

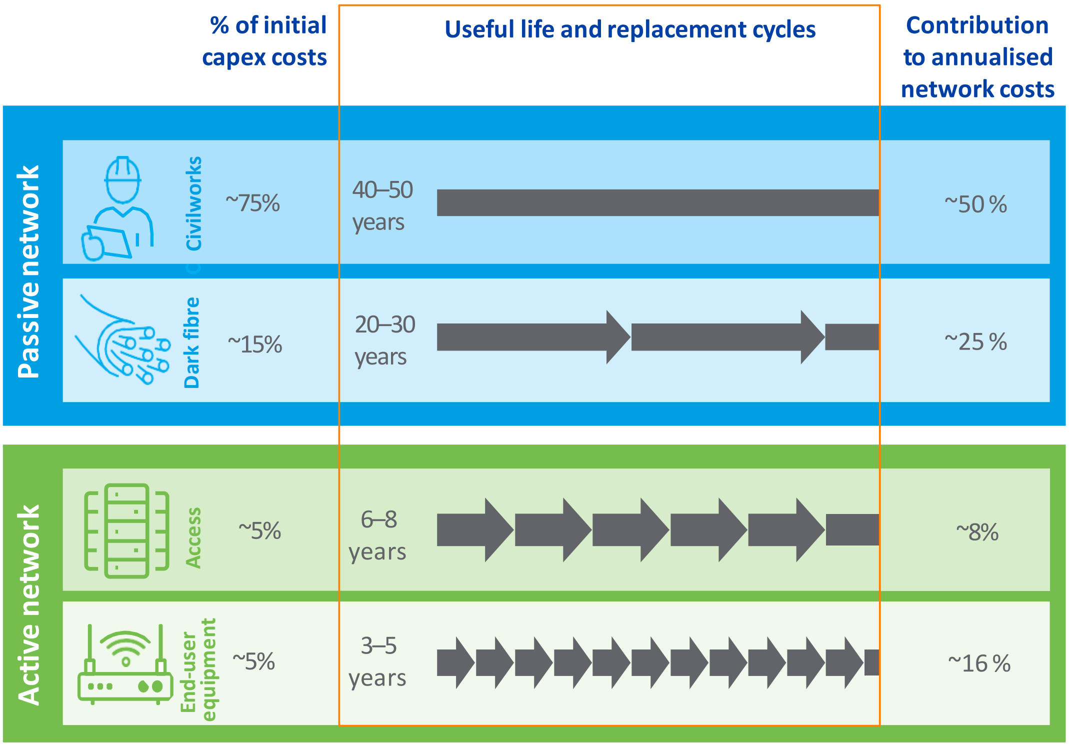
31 The most common case in Europe involves the reuse of some, but not all, of the existing passive infrastructure used for copper or cable networks, which are then shared with other operators. With an average networks per premises of two and the ability to reuse civil works for 50% of the roll-out, this would mean that typical deployment costs for an individual network may need to cover 25% of the civil works cost of a greenfield network.

sections detail these characteristics for the passive and active elements of the network, and illustrate how they contribute to the total cost of a fibre network.

3.2 Passive infrastructure attracts the vast majority of upfront investment, while active equipment accounts for a smaller portion but requires periodic replacement

Figure 3.2 below provides an overview of the split of investment required to deploy a nationwide fibre network in a 'typical' European country. Despite sometimes wide variations in cost structure between networks and countries,[32] this provides a good indication of the broad distribution of costs between major categories of costs.

Figure 3.2: Diagram of network elements contribution to capex costs, replacement cycles and contribution to annualised network costs [Source: Analysys Mason, 2023]



Passive assets include infrastructure, materials and capitalised labour required to deploy the fibre and splitters that make up the 'bones' of the network. **These assets have long lifespans and do not have a set capacity limitation, as detailed further in Annex B.2.1. Operators typically depreciate these assets over 40-50 years, but in reality, they often make periodic investments to maintain the assets and prolong their operational life instead of replacing them.** Hence, these assets can be reused as long as they are physically sound, and can support successive generations of

32 Based on the work we have done for operators and investors, in the context of established and greenfield deployment, with multiple combinations of funding sources, we are mindful of the degree of variability that exists depending on the country, operator and strategy followed.

optical technology, including XGS-PON, and new and upcoming standards such as 50G-PON and beyond (as we discuss in Section 4 below).

The cost to construct and upgrade passive infrastructure spans a range of activities, including ensuring that existing ducts and poles are fit to support fibre and can be accessed and used to do so. Passive equipment and labour represent the majority of the costs of a gigabit passive optical network (GPON) fibre optics roll-out. We estimate that on average, 70–80% of total network deployment cost is allocated to civil works including labour, depending on the extent of reusability of the infrastructure and whether it can be shared between multiple fibre networks,[33] and a further 15–20% is allocated to the roll-out of fibre-optic cables.

We note that the European Commission's recent proposals for a Gigabit Infrastructure Act are intended to reduce frictions, costs and time to market in the deployment of passive infrastructure. The European Commission's impact assessment suggests that future roll-out costs could reduce by EUR14.5 billion as a result of these proposals.[34]

Active network equipment includes optical and electronic equipment to transmit data over the fibre network. This equipment can sit at the end user's location, in the form of an optical network termination (ONT) in a GPON network, or in the network. GPON networks include optical line termination (OLT) equipment in the first active node closest to the end user, which is then connected through backhaul links to the core network of the operator. This core network includes a variety of platforms that already exist in DSL or cable networks, and transmission links that are upgraded on a regular basis to handle growing demand.

Active equipment accounts for a small proportion (about 10%) of the initial cost of deploying full-fibre networks in most networks.[35] These assets have shorter lifespans than passive infrastructure, as demonstrated in Annex B.2.2. Their performance deteriorates over time as there are more components that can wear out, and the performance of new equipment increases at a given price level.

While active assets have a short lifespan, their capacity increases over time through natural replacement cycles that incur stable costs. This is illustrated in Figure 3.3 and Figure 3.4 below for active network equipment (OLT) and end-user active equipment (ONT), based on our discussions with equipment vendors. The amount of time that it takes the unit cost of active equipment for a subsequent generation to decline to the cost level of a previous generation typically aligns with the

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33 With greater infrastructure sharing, the proportion of passive equipment costs would be lower. In Spain, deployment costs are extremely low: Vodafone's and Orange's initial roll-out plans involved 6 million homes passed for investment of EUR1 billion, a cost of ~EUR167 per home passed. In practice, since that time we understand that the cost per home passed in Spain has been materially lower for most operators. Regardless, even in these low-cost deployments in Spain, about 65% of the cost lies in the passive infrastructure, including labour, with the remainder in electronics and connectors.

In higher-cost roll-outs, the electronics and connector cost will not scale significantly, and most of the additional cost will be in civil works and passive equipment. In a roll-out with a cost per home passed of EUR700, therefore, the share of costs that is related to passive equipment would be ~90%.

34 European Commission (2023), *Gigabit Infrastructure Act Proposal and Impact Assessment.*

35 10% figure includes all active equipment except home routers.

replacement cycle of active equipment spanning 8–10 years. This decline in costs is driven by technological advances (e.g. in semiconductor and optical technology) and global economies of scale, as more and more network capacity is deployed worldwide.

Figure 3.3: Expected price evolution of OLT [Source: Analysys Mason, 2023]

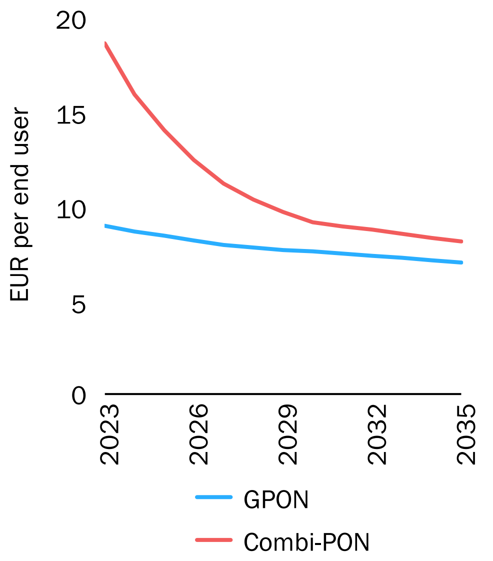
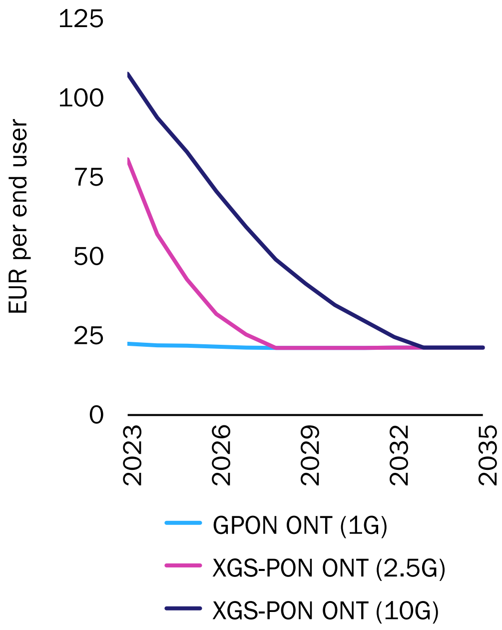


Figure 3.4: Expected price evolution of ONT [Source: Analysys Mason, 2023]



Over time, the percentage of cumulative capex that active equipment accounts for as a share of total cumulative capex grows with each replacement cycle. It is important to understand that although new generations of active equipment are able to handle higher capacities (at similar costs to equipment from previous generations), **the capex spent is fundamentally driven by a need to replace, as opposed to upgrade, active equipment from previous generations**.

As a result, the vast majority of initial investment in fibre networks flows into passive infrastructure; however, once these assets are built, they will last for decades before needing replacement. Meanwhile, active equipment accounts for a smaller percentage of upfront cost, but requires more frequent replacement.[36] This ensures that a significant share of ongoing network capacity growth is automatically built into natural 'replacement capex' cycles. While small amounts of additional 'upgrade capex' might be needed in certain circumstances, the vast majority of network capacity growth is driven by natural replacements and the marketing benefits of offering higher speeds, as opposed to capacity-driven upgrades.

Section 3.3 below further explains how the properties of fibre networks provide other cost and non-cost benefits over legacy networks.

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36 Network deployment costs are typically classified as cost per premises passed (CPPP) and cost per premises connected (CPPC), especially in business plans developed for financial deals. CPPP is incurred to be able to offer a service in a given area, and CPPC is only incurred when a customer is connected to the network (and starts paying a subscription). The split between CPPP and CPPC can vary greatly for similar reasons as the cost of deployment varies, but the cost to connect a customer, i.e. CPPC is typically around half the CPPP.

3.3 Fibre networks are able to deliver better performance and lower running costs than legacy networks and offer potential routes for significant future savings

The European Commission has identified fibre as the "next generation technology to meet future bandwidth demands".[37] The natural properties of fibre enable it to transmit data at higher speeds and with greater bandwidth compared to copper or cable. Fibre networks also outperform legacy networks in other performance- and cost-related dimensions, as they have lower operating expenses and energy consumption.[38]

Fibre also does not experience the same drop in performance over longer distances (lengths of local loop) that other legacy technologies do (see Annex B.3.1 for further details). This allows full-fibre networks to deliver strong performance characteristics even in areas that are far (up to 20km) from the network's 'active' node, where the OLT is located.[39] As fibre-based networks are less affected by water than electrical-based networks like DSL or cable, they generally experience fewer network faults and **are more reliable and less expensive to maintain than legacy networks**, as demonstrated through various examples seen in Annex B.3.1.

Moreover, fibre networks are more environmentally friendly than copper or cable-based networks as they consume less power (around 90-95% less power and 80% less carbon dioxide emissions per end user), as detailed in Annex B.3.1. In addition to the natural properties of fibre that enable better performance and operations than legacy networks, fibre can also unlock additional and significant benefits for network operators in the medium and long term, as illustrated below.

In the medium term, fibre networks can be organised in less complicated and more efficient ways than legacy networks. Fibre networks require fewer nodes, due to their resilient performance over long distances, and also exhibit higher splitting ratios,[40] meaning that more endpoints can be connected to a single connection point. Each local exchange in a full-fibre network is thus, in principle, able to serve a larger number of users than in legacy networks. This can therefore enable changes to network topologies that make more efficient use of network resources, leading to reduced costs for network deployment and maintenance, as well as improved network performance and scalability. As a result of the transition to fibre, network topologies are expected to be simplified, reducing the number of local exchanges and the associated cost of operating these exchanges, which

37 European Commission (2022), *Broadband: Technology comparison*.

38 See for example a report commissioned by Ofcom from WIK (2018), *The Benefits of Ultrafast Broadband Deployment and* WIK-Consult (2020), *Copper switch-off.*

39 GPON fibre networks can deliver signals over distances up to 20km.

40 Splitting ratios refer to the number of end users that can be connected to a single network connection point, such as a port on a switch or a splitter. In a fibre network, splitting ratios of 1:32, 1:64 or higher are common, which means that up to 32 or 64 endpoints can be connected to a single port without significant signal degradation. This is much higher than the typical splitting ratios of cable or copper networks, which are usually limited to 1:8 or 1:16.

is reflected in various copper decommissioning programmes announced in various European markets,[41] as can be seen in Annex B.3.2.

The evolution of passive optical network (PON) technology is explored further in Section 4. At present, standards provide for access networks to be able to handle up to 50Gbit/s peak speeds per connection[42], shared between the users in connections of an individual PON, and it seems likely this will continue to evolve to exceed 100Gbit/s in time.

Over the longer term, more advanced technologies such as hollow-core fibre are expected to enable very-high-capacity core network links to be upgraded further (see Annex B.3.2). This unique feature would, in principle, enable even higher bandwidths and lower latency than typical fibre-optic cables, by enabling the transmission of data at close to the speed of light.[43]

In this section and in Annex B.3, we have discussed how investments in fibre coverage mainly contribute to the deployment of passive infrastructure assets with long lifespans, while network capacity is expected to increase naturally as part of the ongoing replacement of active equipment, at cost levels that are similar to those of previous generations of active equipment due to ongoing improvements in technology. We have also explained how the natural properties of fibre enable better-performing, more cost-efficient, and more environmentally friendly networks upon initial operation, but also over longer time horizons. In the next section, we explain how fibre networks are expected to be able to deliver these ongoing improvements in performance at stable cost levels, regardless of future demand for data, using illustrative models and multiple demand scenarios to reflect uncertainty regarding future applications.

41 The EC's draft Gigabit Infrastructure Act proposes to reduce decommissioning timeframes, which would help unlock the benefits of fibre networks more quickly and support the EU's Digital Decade and green agenda.

42 50G-PON is a standardised technology that enables 50Gbit/s peak speeds, but is not yet commercially deployed.

43 See Analysys Mason (2022), *Hollow-core fibre for low latency and increased bandwidth: the next game-changer in optical cables*.

4 Full-fibre networks are designed to handle future capacity requirements at relatively limited incremental costs

Since broadband access networks have become widespread in the early 2000s, the demand for data traffic over fixed networks has grown as a result of increased adoption of richer and more varied online services. This growth in demand has been stable and sustained over time throughout Europe, but more recent growth has been slower, despite the adoption of gigabit-capable broadband.[44]

Concerns from large European operators on the sustainability of their network investments have largely focused on the role of traffic levels on network costs. However, using traffic as the main indicator for growth in network usage is not sufficiently nuanced to create a comprehensive understanding of the impact on network costs.

The nature of 'demand' for full-fibre access networks combines different concepts: the resulting traffic that networks carry, which is then a product of peak speed demand by individual users, and the aggregate concurrent demand for bandwidth across multiple users (i.e. concurrent bandwidth), to which fixed networks are dimensioned. We discuss this in Section 4.1.

By definition, popular uses today are adapted to the current generation of access networks. How future demand will drive the utilisation of full-fibre networks (in terms of the ability to deliver the services that customers expect) remains uncertain, and will depend on the emergence and diffusion to consumers of high-bandwidth applications that are not yet mature.

However current full-fibre networks will remain capable of delivering very high speeds and handle even aggressive demand growth scenarios at least until 2030 as shown in Section 4.2. As traffic grows, ongoing upgrades will be needed in the core and backhaul networks – these account for a small proportion of total network costs.[45]

In the long term, upgrades to fibre networks may become necessary if and when new online services and applications emerge and become popular across a wide range of users. Preparations are already being made for these upgrades as part of the deployment of full-fibre networks. Already-existing standards and network architecture choices can be introduced that will allow significant improvement in network capacity at limited cost, much lower than those involved in deploying full-fibre networks in the first place.

The discussion of the nature, capability and costs of these upgrades in Section 4.3 concludes this paper.

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44 See the expected 14% sustained fixed traffic growth in Ericsson's *Mobility Report November 2022*.

45 See, for example, Analysys Mason's *Netflix's Open Connect program and codec optimisation helped ISPs save over USD1 billion globally in 2021.*

4.1 Demand for traffic continues to grow, but at a declining rate, and there is uncertainty on future demand levels and the resulting impact on network bandwidth requirements

Traffic on fixed broadband networks has been growing at steady rates over time, driven by growing use of the internet, in terms of applications, online services and other forms of content sharing. Growth has slowed in the last few years, as take-up and intensity of use of the main mass-market applications (video streaming, gaming) have matured across European markets. The trend was disrupted temporarily at the beginning of the Covid-19 pandemic due to lockdowns, as discussed below. Further data and analysis of the drivers of demand and capacity in full fibre networks is provided in Annex B.4.

Although traffic can be a useful metric, it is not a particularly relevant measure of demand on fixed networks.[46] What is limited in every fixed broadband network is end-user speed (i.e. peak bandwidth requirements of applications), and concurrent bandwidth used simultaneously by end users who share capacity at various levels of the network, as discussed below.

The applications that drive traffic growth today typically require peak speeds of up to 25–30Mbit/s even in the case of relatively demanding applications such as cloud gaming and 4K IPTV connection. Individual speed requirements are limited to large file downloads, including OS updates and games. However, such requirements are sporadic for most users, and can be managed across multiple users through scheduling, which is something that content providers and ISPs collaborate on routinely.

Individual peak speed requirements are aggregated across different usage times and characteristics of multiple users, forming an over demand for 'concurrent bandwidth' in shared parts of the network. Aggregate usage across networks is significantly below the peak speeds offered and has grown relatively slowly over time. Analysys Mason Research data shows that peak concurrent throughput across Europe per end user averaged 2Mbit/s in 2022, which is considerably lower than individual peak speed demand by individual users (further details are shown in Annex B.4.3). The growth has also been slower than traffic, for example, BT reported 25.5Tbit/s peak concurrent bandwidth in 2021, and 28Tbit/s in 2022, a growth of 10%. Furthermore, we often refer to these numbers as 'peak of peaks': demand only reaches these levels very rarely. Hence, networks are being engineered to provide good quality of experience even at the busiest times, and many ISPs have been extremely adept at managing these peaks.

In the future, demand and the applications that will fuel it, might change. However, they are not well understood, and appear to be several years away from being ready for take-up at scale. Applications such as extended reality (augmented reality/virtual reality or AR/VR) will take time to mature and become technically and economically viable, before then diffusing more broadly. This expansion is likely to be through fixed networks initially, which are less sensitive to growth in traffic demand as further discussed in Section 4.2 and Section 4.3.

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46 Commercially, wired fixed broadband connections (including full-fibre connections) are nearly uniformly 'unmetered'. Outside of fair use policies to prevent abuse, broadband service providers do not charge for traffic given extremely low incremental cost for traffic.

4.2 Current fibre networks are capable of supporting yet-to-emerge applications and sustained growth in traffic for decades to come, with limited incremental investment

Generally, growth in demand is driven by increased adoption of existing online services by more people, as well as the emergence of new online applications and services. In Europe, growth in new users of existing applications (e.g. older demographics replacing terrestrial or satellite TV with streaming) is expected to slow down. As a result, future demand will increasingly depend on the emergence and adoption of new applications. Current full-fibre networks are being engineered to provide significant capacity for growth, supported by fibre backhaul that already offers high capacity and backbone networks that represent a modest share of network costs.

Emerging online applications still need time to mature before potential adoption at scale

As mentioned in Section 4.1, existing applications such as video streaming do not typically require high speeds and can be handled by most DSL-based connections. The AR/VR applications that currently exist have bandwidth requirements similar to other applications. However, in the future requirements might evolve: bandwidth requirements of future AR/VR applications remain poorly understood, and estimates vary widely depending on the delivery model, the end-user equipment, and the resolution offered; we have seen estimates as low as 25Mbit/s (for current applications) and as high as 2Gbit/s (for hypothetical future applications). Achieving low latency is also often quoted as a significant factor for future applications such as AR/VR. While latency and bandwidth are not the same thing and latency is impacted by physical and logical routing of packets on the internet, they are nevertheless closely related. In general higher bandwidth reduces the effective latency perceived by end users.

Although AR/VR applications are expected to become more widespread in the future, **at present they continue to face challenges with mass adoption due to limited use cases, and a lack of affordable end-user equipment.**[47] Gartner predicts that some applications, such as virtual events and real-time collaboration with complex overlays with the real world, are not to be expected to mature until around 2030 at the earliest.[48] The study notes that the maturation of the 'metaverse' will require further advancement on both its applications and adjacent technologies (e.g. immersive tech, computer vision and ecosystem).

It should also be noted that the companies which are investing heavily in developing AR/VR applications (such as Meta), seem to focus on ensuring adequate in-home connectivity (i.e. from the end-user premises connection point to the device), as opposed to network capacity (from the external network to the end-user premises connection point). Ongoing developments in Wi-Fi 7 and other initiatives such as 'fibre to

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47 AR/VR headsets are not expected to be mass market for another few years, as headset global shipments are forecast to represent only 2% of mobile phone shipments. In addition, 10GE capable end-user devices are currently restricted to high-end motherboards for gaming, with prices that are prohibitive except to the highly price-inelastic users.

In addition, AR devices are expected to take years of progress to offer transformative experiences as further detailed in: Meta (2023), *Network Fee Proposals Are Based on a False Premise.*

48 Gartner (2022), *Metaverse Evolution Will Be Phased; Here's What It Means for Tech Product Strategy*.

the room',[49] are expected to improve the internet ecosystem through better in-house connectivity which will also play a vital role for adoption of future applications that demand higher speeds.

At present, it is unclear what the pace of evolution and adoption of new applications may be, including for AR/VR, artificial intelligence, digital twins or smart city applications, which may benefit from faster peak speeds and higher capacities. As such, there is uncertainty with regard to how end-user demand for future applications would drive network bandwidth usage. In the following sub-sections we show that, even in the case of very-high demand growth through emergence of new high-bandwidth applications,[50] the natural evolution of current fibre networks should enable them to accommodate the growth in demand.[51]

Current fibre networks are capable of supporting sustained growth in demand for decades to come, without the need for significant ongoing upgrade costs

As mentioned in Section 4.1, full-fibre access networks that use PON technology typically split a fixed amount of capacity between several users (typically between 32 and 128 users when fully connected). Networks currently being deployed in Europe use a combination of GPON and XGS-PON, which can be run concurrently on some OLTs with the deployment of Combi-PON cards. GPON offers 2.5Gbit/s per PON, and XGS-PON offers up to 10Gbit/s per PON, as discussed in Annex B.2.2.[52]

The bandwidth 'provisioned' per end user in each PON is determined by the total bandwidth in the PON (which depends on the technology) and the number of users connected. Figure 4.1 below shows this for a range of typical deployment architectures, including 25G-PON (a Nokia-specific evolution of the standard) and the recently standardised 50G-PON. Importantly and as explained previously, this is simply an average: in practice the available bandwidth per user will be much greater.

Provisioned bandwidth per user (Mbit/s)	Connections per PON		
	32	64	128
GPON	80	50	20
XGS-PON	320	160	80
25G-PON	800	400	200
50G-PON	1600	800	400

Figure 4.1: PON bandwidth per connected user [Source: Analysys Mason, 2023]

49 See Analysys Mason (2020), *F5G: new frontiers for fibre access*.

50 ETNO estimates that VR users might require five times as much data compared to the traditional HD video. ETNO (2022), *Europe's internet ecosystem: socio-economic benefits of a fairer balance between tech giants and telecom operators.*

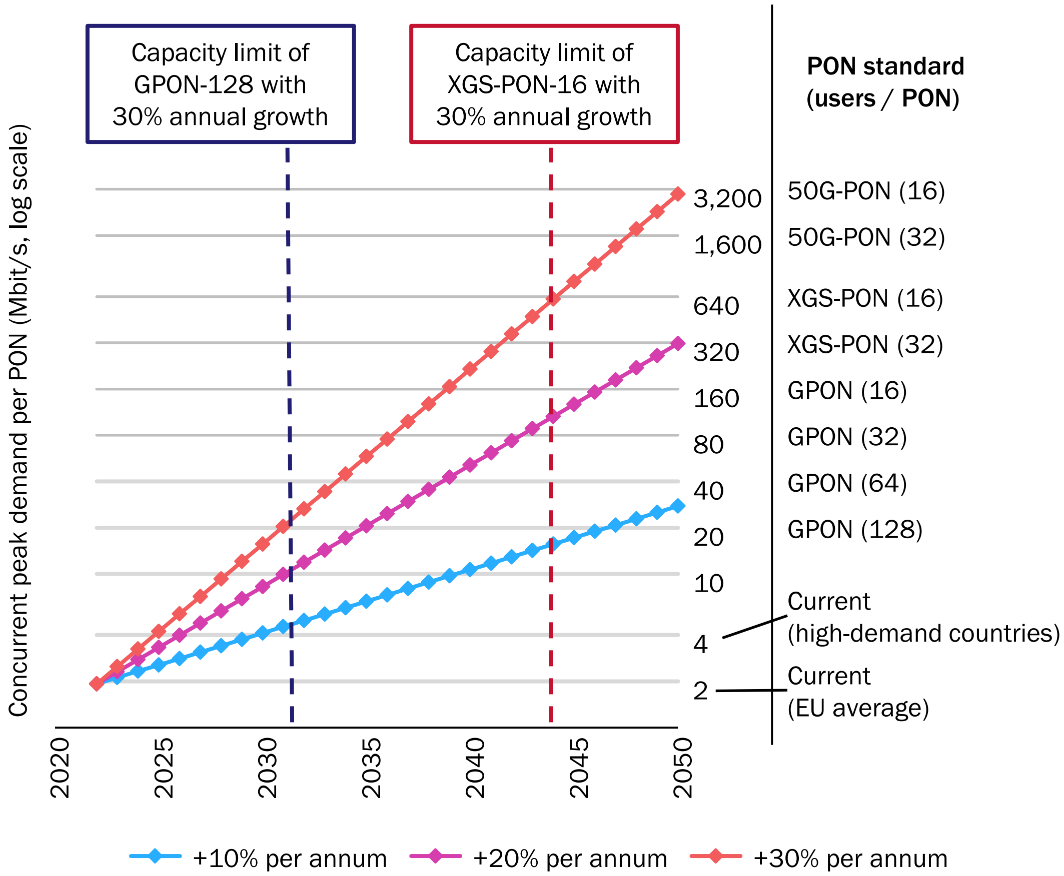
51 BEREC's preliminary assessment also shows that the internet has proven its ability to cope with increasing traffic volumes, changes in demand patterns, technology and business models. BEREC (2022), *BEREC preliminary assessment of the underlying assumptions of payments from large CAPs to ISPs*.

52 GPON offers asymmetrical 2.5Gbit/s downstream bandwidth and 1.25Gbit/s upstream bandwidth, while XGS-PON is symmetrical. ComReg (2023), *ODN Sharing Report*.

For reference, ISPs are currently provisioning around 4–5Mbit/s per user in high-demand countries, and concurrent demand across networks is on average 2Mbit/s per user. Even a GPON network with 128 users per PON offers ten times this capacity, and GPON networks are typically configured with a maximum of 64 users per PON.[53]

As mentioned previously, there is significant uncertainty regarding the rate at which new applications will emerge, and the extent to which these will have an impact on growth in bandwidth requirements. However, we can show illustratively how different growth rates for concurrent demand in individual PONs may stress the capacity available in PON-based networks over the next 20–30 years. Figure 4.2 below shows growth rates in concurrent demand of 10%, 20% and 30%, from a current base of 2Mbit/s.[54] This shows clearly that even already-standardised PON versions will be able to handle concurrent peak demand until at least 2050 and significantly later if demand continues growing at current rates; as demand for speed and bandwidth increases, new versions of PON standards offering 100Gbit/s and more per PON will be developed.

Figure 4.2: Projected growth in concurrent peak demand per PON (Mbit/s per end user) vs. different PON standards and number of connections per PON [Source: Analysys Mason, 2023]



53 For comparison, Singapore's national broadband network is configured to have a maximum of 24 residential connections per PON.

54 This represents the average across Europe and there are higher-traffic markets with 4Mbit/s dimensioning.

Existing networks can withstand significant demand growth for many years. If concurrent peak demand per PON grew at 30% per annum constantly, a GPON network with 128 connections per PON would still be able to accommodate this demand until the early 2030s.

In addition, upgrades to XGS-PON and 50G-PON over time, coupled with lower splitting ratios, would enable existing networks to accommodate future demand until 2050 even in a scenario with high, sustained growth in demand.

Whilst demand growth is by nature uncertain, recent growth in concurrent peak demand across mature networks in the last three years has been below 20%. With a 20% growth rate, XGS-PON with 32 connections per PON (effectively already a relatively mature technology being deployed by many networks today) would be sufficient to accommodate demand growth until 2050.

Core and backhaul networks are in continuous evolution, with large economies of scale and constant improvement in capacity and costs

In core and backhaul networks, traffic is aggregated from the access network, resulting in further gains from multiplexing demand from more and more users. Core and backhaul networks are sensitive to concurrent demand for bandwidth, and active equipment is upgraded and added regularly as demand increases. However, the cost of upgrading core and backhaul networks represents a very small portion of total network costs, and also tends to be relatively stable over time.

The relationship between fixed network traffic and total network costs has also been explored in other recent reports by Analysys Mason.[55] Globally, core and backhaul costs represent 5–10% of revenue depending on the operator. In European countries, where national transmission is generally competitive, costs are at the low end of this scale. **Core and backhaul costs are also relatively stable over time**, due to ongoing technological improvement and falling prices, enabling increasingly cost-efficient capacity upgrades (i.e. from 1 to 10 to 100Gbit/s and beyond). As a result, even the traffic-sensitive components of fixed networks (i.e. core and backhaul) tend to be upgraded on an ongoing basis without significant increases in cost levels over time.

4.3 In the longer term, PON-based networks can be upgraded to deliver much higher speeds and capacity with very limited incremental investment as demand grows

Over time, the emergence of new applications that are more demanding in terms of speeds and capacity may drive growth in concurrent bandwidth and traffic. Once full-fibre networks are fully deployed, the properties of fibre network technology allow for this growth in bandwidth requirements to be managed at limited additional cost.

55 See Analysys Mason (2022), *Netflix's Open Connect program and codec optimisation helped ISPs save over USD1 billion globally in 2021* and Analysys Mason (2022), *The impact of tech companies' network investment on the economics of broadband ISPs.*

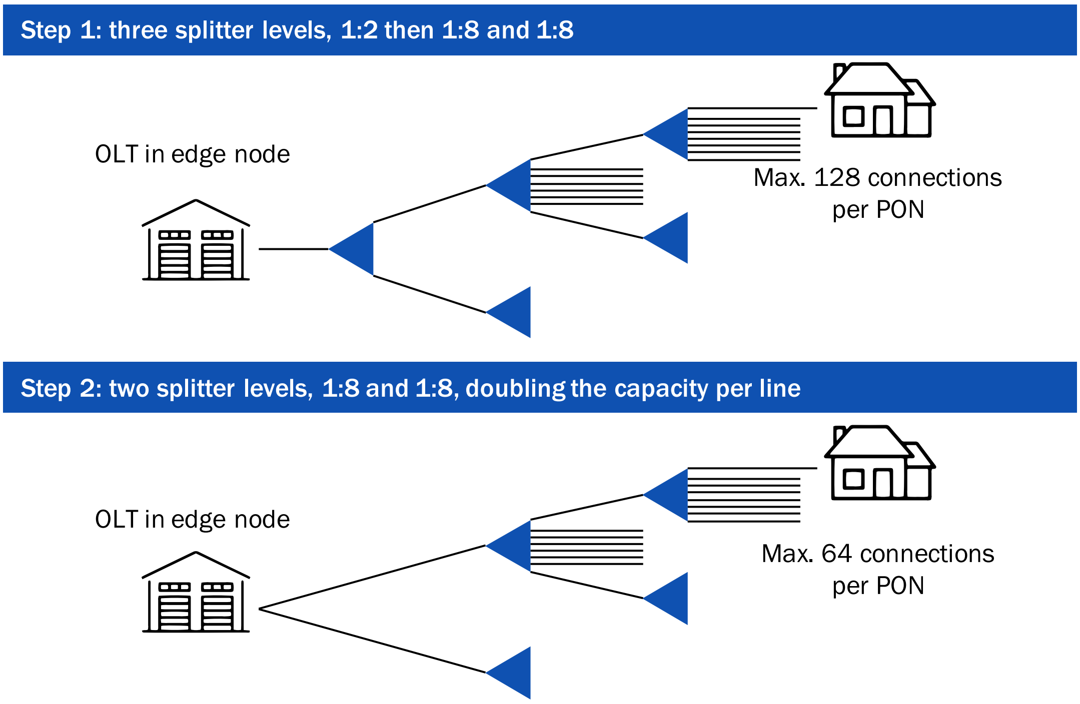
PON standards are designed to facilitate upgrades over time, given progressive and limited investment

In dedicated point-to-point fibre networks, capacity can be upgraded by deploying better optical equipment at each end of the network. This is what happens inside operators' backhaul and core networks: speed and capacity can reach hundreds of Gbit/s with dense wavelength division multiplexing (DWDM).

In PON-based networks, more co-ordination is required: the OLT and the line cards it controls serve thousands of end users. Moving from one technology (e.g. GPON) to another (e.g. XGS-PON) could require all users in a PON to be upgraded at the same time. Fortunately, standards have developed in a way that enables coexistence of a standard with the next: XGS-PON can coexist with GPON in an individual PON with combi-PON equipment (as shown in Annex B.5), and 50G-PON is designed to coexist with either GPON or XGS-PON (but not both) on an individual PON.

Many networks currently being deployed in Europe are XGS-PON native. This allows operators to use higher splitting ratios and combine a larger number of users on a single PON, without sacrificing performance compared to GPON (see Figure 4.1 above). The architecture of these networks is designed to allow splitting ratios to scale over time. For example, a recent network we have reviewed has 128 users per PON currently, served through splitters at three levels: the signal is split in two at the OLT location, then each half is split in 8, then each of the 16 resulting branches are split in 8 again to reach 128 users. As concurrent demand grows, the operator can simply bypass the first splitter and use two different OLT ports to move to a 1:64 splitting ratio, doubling the capacity per user in each PON. This is illustrated in Figure 4.3 below.

Figure 4.3: Example of an easily upgradable XGS-PON network [Source: Analysys Mason, 2023]



The costs of PON network upgrades are limited to active components, and can be incurred over time as component costs reduce and demand materialises

As discussed in Section 3.2, the initial deployment of fibre for coverage purposes involves building passive infrastructure that generally will not need to be replaced, only maintained over time, and has essentially infinite capacity.[56] Meanwhile, active equipment throughout the network and at end-user premises needs to be replaced periodically, due to degradation and obsolescence, in particular associated with electronic components.

Replacement of active equipment tends to be accompanied by large capacity increases as new generations of equipment become available, without large cost increases; the cost for new generations of equipment declines over time and generally converges with that of previous generations before replacement occurs.

Only the active equipment in the core and backhaul networks might need additional upgrades beyond periodic replacement, however these only account for a small portion of total costs (as discussed in Section 4.2).

Due to this dynamic, active equipment in the access networks will continue to require investment, and will account for a growing share of cumulative investment over time, as the network goes through more cycles of replacement and upgrades to XGS-PON, 50G-PON, and yet-to-be-defined future standards. However, these upgrades will require a much lower level of investment overall than has been taking place during the roll-out phase of full-fibre networks.

Overall, the transition from legacy technologies to fibre currently involves large upfront deployment costs in order to make fibre availability ubiquitous across Europe. **This transition is progressing well, and the majority of European households now have access to full fibre**. When deployed, **passive network elements in fibre networks will have a very long lifespan, likely higher than the typical 40-50 year lifetimes used for accounting purposes; active equipment presents a well-established long-term upgrade profile**: through periodic replacement and upgrading of active equipment, network capacity will increase significantly over time, requiring limited and stable investment. **This significant increase in network capacity is expected to be able to handle ongoing growth in network bandwidth requirements for decades, with much lower investment required for ongoing upgrades compared to initial deployment**.

56 In the distant future, hollow-core fibre is also expected to offer a long-term upgrade path for the highest-capacity routes in core transmission networks (as discussed in Section 3.3).

Annex A Glossary of terms used

ASDL / DSL / VSDL	Asymmetric/very-high-speed digital subscriber line refer to technologies enabling broadband internet access through standard copper telephone lines. Both technologies' performance is highly dependent on the quality and length of the copper lines; VDSL typically requires short lines and therefore is deployed together with FTTC.
CMTS	Cable modem termination system, a device located at the cable company's head end that connects cable subscribers to the internet service provider (ISP).
DOCSIS / HFC	Data Over Cable Service Interface Specification, a technology standard allowing cable TV networks, built as hybrid fibre-coaxial networks (HFC), to carry two-way data for broadband internet access. The bandwidth available for internet connectivity is shared between users on the same coaxial tree, but can be easily expanded downstream; upstream bandwidth has historically been very limited by the standard.
DSLAM	Digital subscriber line access multiplexer, a network device within the telephone exchange that deploys multiplexing techniques to connect the digital subscriber lines (DSLs) of multiple end users to a high-speed digital communications channel.
(D)WDM	(Dense) wavelength-division multiplexing, a technology that allows bi-directional communications of multiple optical carrier signals to be multiplexed over a single fibre strand by using different wavelengths.
FTTB	Fibre to the building, an architecture where copper-based telephone networks are upgraded to fibre all the way to a point on a shared property such as apartment blocks or office buildings.
FTTC	Fibre to the cabinet, an architecture where telephone networks are upgraded through a replacement of the copper line between a local exchange (i.e. an edge node or local node) and a street cabinet where the sub-loop to the end-user premises, which remains copper-based, connects.
FTTH	Fibre to the home, an architecture where the entire copper line is replaced with fibre. The term is sometimes generalised as fibre to the premises (FTTP) to reflect connectivity to non-residential premises (e.g. offices).

G.fast A DSL protocol standard deployed in the FTTC network for local loops shorter than 500m and designed to deliver between 0.1Gbit/s and 1Gbit/s, depending on the loop length. It is usually deployed together with FTTB.

GPON / XGS-PON Gigabit passive optical network, an architecture for FTTH networks where end users are connected to the network through shared fibre trees, with one fibre between the optical line termination (OLT) equipment in the edge/local node and a splitter, and multiple individual fibres connecting the splitter to the optical network termination (ONT) equipment at the end-user premises. A GPON 'tree' shares a total of 2.5Gbit/s of bandwidth between the OLT and the splitter, and its evolutions (including 25G-PON, 50G-PON and G.fast XGS-PON) enable 10Gbit/s end-user access speeds and much higher bandwidth between the OLT and the splitter.

ISP Internet service provider, a provider of internet access to end users, using mobile or fixed broadband connections, which can also provide access to enterprises. It interconnects with other ISPs via a combination of peering, partial transit and transit relationships. This interconnection with other ISPs or internet backbone providers often occurs at an IXP.

IXP Internet exchange point, a location where internet providers, including ISPs, backbones, content delivery networks (CDNs) and enterprises can meet and efficiently exchange traffic, using peering or transit arrangements. Instead of having to arrange separate circuits for each provider, which can be costly, each provider only needs one connection to the IXP (and many connections within it) to exchange traffic with all the other providers. An IXP can also help to attract content, by providing an efficient way to distribute the content.

Latency Latency is a measure of the time it takes for traffic sent from a source to be received at its destination. High latency can affect the experienced quality of the communication.

MDF Main distribution frame, a signal distribution frame or rack in the local telephone exchange with jumper wires that connect the exchange equipment to the terminations of local loops.

NTP / ONT Network termination point (or optical network termination (ONT) in fibre-based networks), the interface between an end user and a public electronic communications network. ONTs convert light signals from fibre-optic cables to electrical signals in downlink transmissions, and vice versa for uplink transmission purposes.

OLT Optical line termination, the endpoint hardware device in the passive optical network that converts the standard electrical signals coming from the core and backhaul (i.e. from the service provider's equipment) into the frequencies and framings used in the passive optical network. OLT also co-ordinates the multiplexing between the network's ONTs.

PSTN	Public switched telephone network, the conventional telephone network system that makes use of mainly copper cables, along with cellular networks, and communication satellites. The recent development in the digital telephony sector (such as Voice over Internet Protocol (VoIP), digital voice or All-IP telephony) has incentivised the telecoms industry to retire PSTN.
PtP	Point-to-Point is a fibre-based access network architecture where a dedicated fibre line with dedicated capacity is required for each end-user premises.

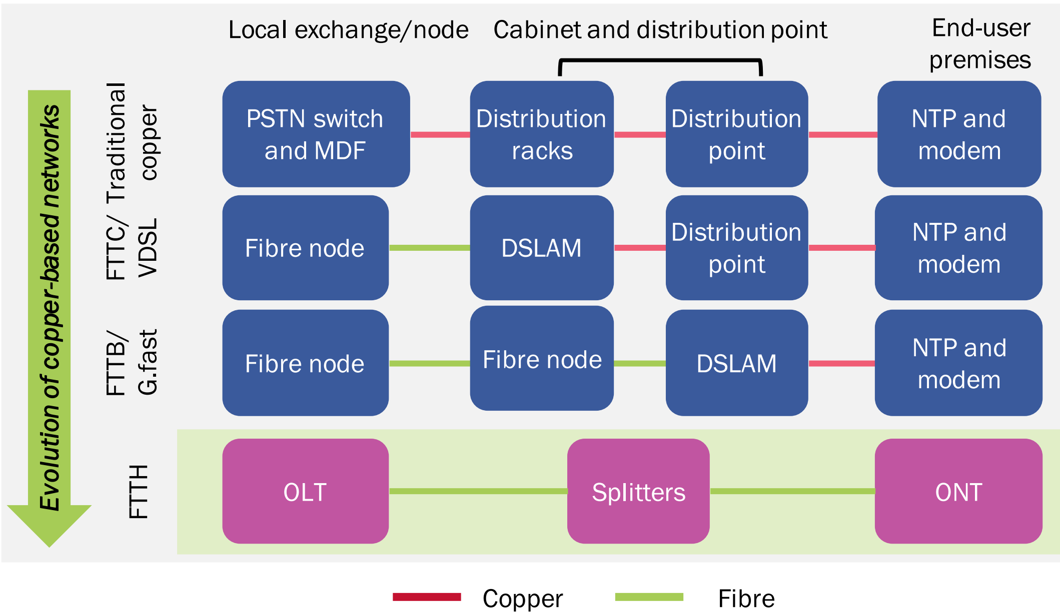
Annex B Supporting data and analysis

B.1 Contribution of established operators, public funds and financial investors to the deployment of full fibre networks in Europe

B.1.1 Networks of established operators have been evolving in a way that pushes fibre-optics closer and eventually all the way to the end users

Figure B.1 provides an overview of the evolution of copper-based telephone networks used for broadband access, towards full-fibre to the home networks.

Figure B.1: Illustrative diagram for the evolution of copper-based access networks; coax-based networks can also go through similar transitions which is not shown [Source: Analysys Mason, 2023]



Note: FTTB = fibre to the building, MDF = main distribution frame, DSLAM = Digital subscriber line access multiplexer, NTP = network termination point, CMTS = cable modem termination system

B.1.2 Investment required for fibre networks will come from both public funding and private investments

The total investment required to cover 99% of European households[57] with fibre networks could reach close to EUR300 billion.[58] In practice, it is likely that in some very-rural areas, alternative technologies such as fixed-wireless access (FWA) and satellite may be acceptable, and would likely be much more

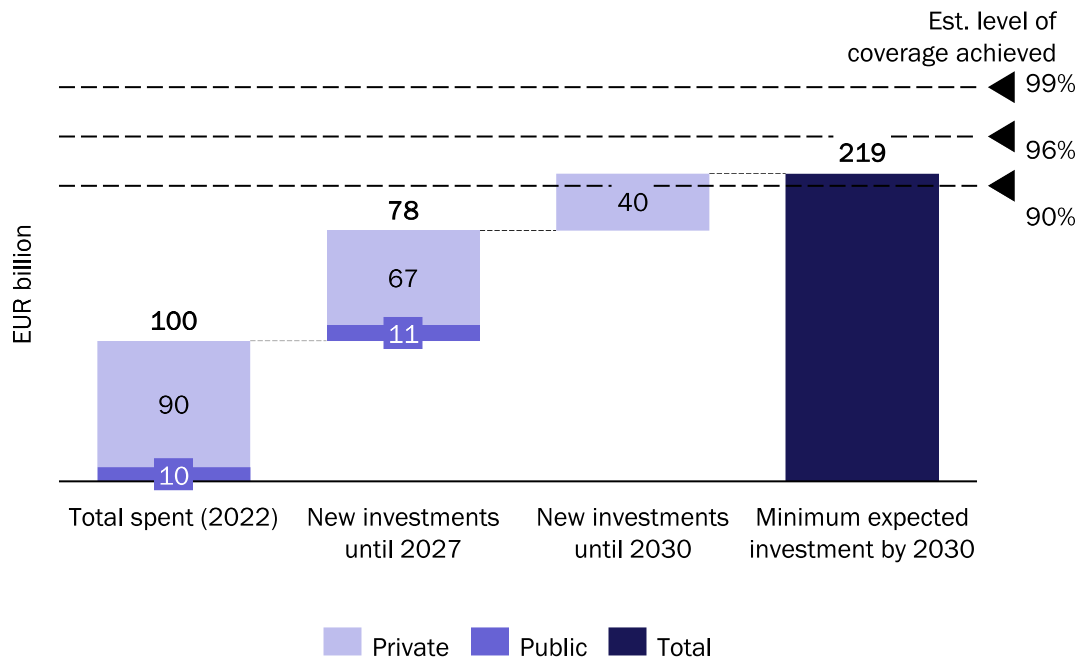
[57] ETNO (2023), *The State of Digital Communications 2023*. This figure assumes that 1% of the most rural households might be covered by other technologies, such as FWA and satellite.

[58] These figures include Norway and the UK, which are not part of the EU27.

cost effective. While public statements are not common so as to avoid discouraging investment in fibre, a few countries including Sweden and the UK have acknowledged that coverage of very remote areas may be difficult, and highlighted satellite as a fundamental solution, especially in the case of Sweden.[59] Indeed, as of 2022, the EC's DESI data showed that there was materially more very-high capacity network coverage of EU households (70%) compared to full fibre coverage (58%).[60]

Estimates published by ETNO in its State of Digital Communications Report 2023 suggest that as of 2022, over EUR100 billion has already been spent, including about EUR10 billion in public funding. New capital expenditure announced by operators adds a further EUR67 billion by 2027, and committed public funds are estimated to reach EUR11 billion between 2022 and 2027. If the private sector continued spending at the same rate until 2030, this would add a further EUR40 billion, for a total investment of ~EUR220 billion. This is shown in Figure B.2 below.

Figure B.2: Spent and committed FTTH investment to 2030 in Europe,[61] [Source: ETNO, Analysys Mason Research, 2023]



The ETNO State of Digital Communications Report 2023 further provides an indication of how much it would cost to reach different levels of coverage. Going from 90% to 99% coverage could cost around EUR80 billion, of which a quarter could come from private investment by 2030. This leaves an

59 The UK government stated that the coverage of fast broadband networks for the final 100 000 premises will be difficult and expensive; see ISPreview (2022), *Gov Ponders Approach to Gigabit Broadband in Remote UK Areas.* As part of Sweden's national broadband plan, satellite is seen as fundamental in reaching the final 2% of premises with broadband; see PTS (2022), *Sverige behöver ny bredbandsstrategi.*

60 See European Commission (2022), *Digital Economy and Society Index Report 2022 - Connectivity.*

61 EU27 plus other countries in the ETNO member footprint; these include Norway and the UK in particular.

estimated EUR60 billion required to get fibre to 99% of premises in Europe.[62] Furthermore, the EU's proposed Gigabit Infrastructure Act aims to reduce the remaining roll-out costs materially as discussed in Section 3.2.

B.1.3 Public funding will continue to be crucial in providing coverage to areas beyond large cities and other dense areas

Public funding has played an essential role in covering areas outside large cities and urban areas, where it is less economical to roll out full-fibre networks. Public funding will continue to play an essential role, as deployment is expected to shift from more economic to less economic areas. In general, less economic areas are expected to be the last to have fibre, meaning that over time, deployment will shift from urban to rural areas (where public funding is more crucial).

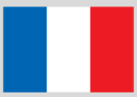
There are various forms of public (supply-side) funding available at the EU level, as well as national and regional schemes in individual countries, which include deployment subsidies and public ownership of assets. These collectively contribute to the total pipeline of public funding that has been set aside for deployment beyond 2022. Several examples of public funding sources and initiatives are shown in the case studies below, starting with the Connecting Europe Broadband Fund, an EU-level funding initiative that has already invested in several rural fibre networks across Europe.

Case study: Connecting Europe Broadband Fund

At the EU level, the Connecting Europe Broadband Fund (CEBF), with support from the European Fund for Strategic Investment (EFSI), has invested EUR183 million in eight high-capacity network projects including Asteo, Scancom, Unifiber and Rune.[63] The CEBF aims to raise funds in underserved areas across EU member states, as well as Iceland, Norway and the UK, where there are significant opportunities for profit. A future investment pipeline of EUR555 million includes funding from the European Investment Bank (EIB), the European Commission and national promotional banks.

Various EU members have also established their own broadband plans (sometimes along with digital agendas) to improve access to very high speeds across their respective countries.

Figure B.3: Examples of national broadband plans in Europe [Source: European Commission , 2023]

Country	National broadband plan	Household coverage target	Allocated funding
	'The Very High Speed France' (*France Très Haut Débit*) plan	100% high-speed broadband (minimum of 30Mbit/s) coverage by 2022 and 100% full-fibre coverage by 2025	EUR3.3 billion (EUR1.2–1.6 million spent by 2018)
	Spain's Connectivity Plan	100Mbit/s available for everyone by 2025	EUR2.32 billion

62 Noting again that this includes the UK, Norway and a few other countries that ETNO has members in. This suggests that the cost per premise for the last ~10% coverage would be over EUR3000, compared to around EUR1000 for the first 90% of households (and much less for many of those).

63 About CEBF (accessed 1 March 2023); see https://www.cebfund.eu/about.

Country	National broadband plan	Household coverage target	Allocated funding
	Germany's Gigabit Strategy	50% full-fibre coverage by 2025 and 100% full-fibre coverage by 2030	EUR12 billion for fibre networks

Along with EU-level programmes and national plans mentioned above, some countries, such as France, have also adopted unique models for fibre roll-out.

Case study: Public-private-partnership (PPP) networks in France

As part of the *France Très Haut Débit* plan, France has been split into private and public intervention zones. In public areas, public–private partnerships, or PINs (also referred to as Réseaux d'Initiative Publique (RIP)) have been introduced. Through PINs, local authorities are able to set up networks in areas without current or future expected broadband infrastructure and run them with private partners as concessions for 25–30 years. The plan aims to unlock a total investment of up to EUR15 billion from the public and private sectors, where EUR3.3 billion has already been provided by French local authorities.[64] Infrastructure operators play a crucial role: Axione has invested EUR2 billion for 25 PINs (representing roughly 20% of the RIP market),[65] Orange Concessions is managing 24 PINs,[66] Altitude Infrastructure 19 PINs[67] and XpFibre 26 PINs.[68]

The case studies above demonstrate the variety of different plans and models adopted across Europe. Public funds, as described, are expected to continue to play a crucial role in the development of fibre networks in more rural areas. Available funding is expected to increase following the revision of State-aid rules and the implementation of post-Covid-19 recovery funds for digital targets across Europe.

B.1.4 Financial investors have made significant contributions to fibre networks, driven by the promise of stable and profitable returns

Fibre networks have attracted a wide range of external investors, including infrastructure funds, private equity firms, utility companies (especially in the Nordic countries) and institutional investors.

64 See European Commission (2022), *Broadband in France*, and Beuve, J. *et al* (2022), *Le déploiement des réseaux d'initiative publique. Quels modes de réalisation et d'exploitation pour quelle performance?*

65 Axione (2021), Animons *Le Changement* and (2018), *Bouygues Telecom, Axione and Mirova, for the first time in France, are to form a partnership to roll out a fibre optic network open to new players in the very dense area.*

66 Orange Concessions (2023), *La fibre nous relie.*

67 DC Advisory (2021), *DC Advisory advised Swiss Life Asset Managers on its minority investment in Altitude Infra THD.*

68 Mayer Brown (2021), *Mayer Brown advises Altice on structuring of the sale of part of Covage's fiber assets to Altitude.*

Major deals announced by financial investors up to the end of 2022 are expected to contribute ~20%[69] of the total private investment expected by 2027. It should be noted that this figure only includes major investments in fibre networks by financial investors. The quantum of investment is likely to be higher when accounting for smaller, unannounced deals, as well as announced deals with transaction figures that remain undisclosed. In addition to deals announced up to 2022, the pipeline of agreed and ongoing deals is estimated by some analysts to amount to ~EUR35 billion.[70] Hence, digital infrastructure assets, including fibre networks, remain an attractive investment area for institutional and private equity investors.

Investments by financial investors fall into the following three categories: carve-outs of established networks, new capital investment into greenfield fibre networks, and investment to expand non-telecoms networks to serve fibre network requirements. These three categories are discussed in more detail below.

Carve-outs of established networks

Established operators can raise money by carving out all or a portion of their existing FTTH networks to external investors, which allows them to raise capital for fibre roll-out and maintain partial ownership of a network that brings stable returns. Incumbents or cable operators that have been late to roll out fibre networks can leverage commercial partnerships to establish a fibre network, while sharing the costs and risks with external investors. As shown in Figure B.4 below, established operators have raised significant levels of capital which can help to cover a sizeable portion of the fibre capex required by the operator.

These processes may represent more limited expansion opportunities if carved-out networks are relatively mature. Hence, financial investors that seek opportunities in this category are likely to include those with a lower risk appetite, such as pension funds.

69 The total contribution from external investments is unclear as it is not possible to compile a comprehensive list of all deals. While major deals for fibre networks (EUR30 billion, 10% of total capex) can be identified more clearly, there is a further EUR53 billion (19% of total capex) invested in companies with fibre assets. It should be noted that EUR53 billion might be higher in reality as it does not include all of the smaller and undisclosed deals; it might also be lower as some investments include other elements such as retail services, hence the investment may not be entirely attributed to fibre networks only.

70 This is based on deals being tracked by specialist publications – not all these deals may conclude successfully, and new deals will occur that are not currently on those publications' radar.

Figure B.4: Examples of fibre network carve-outs [Source: Analysys Mason, Analysys Mason Research,[71] 2023]

Description	Country and year	Deal value (EUR billion)[72]
FiberCop JV has been formed from TIM's assets and TIM-Fastweb FTTH JV, with 37.5% of FiberCop's equity sold to KKR	Italy (2020)	2.9
Altice sold 49% of its FTTH to Morgan Stanley Infrastructure Partners, and formed FastFiber	Portugal (2019)	2.3
Orange Concessions was formed when Orange sold 50% of its rural FTTH networks[73] to CDS, CNP Assurances and EDF Invest	France (2021)	1.3
Bluevia was formed when Telefónica sold 45% of its rural FTTH network to Crédit Agricole Assurances and Vauban Infrastructure Partners	Spain (2022)	1.1
GlasfaserPlus JV was formed between DT pension fund IFM Investors for FTTH roll-out to 4 million rural houses	Germany (2021)	0.9
Fibre Networks Ireland was formed when eir sold 49.99% of its FTTH and copper infrastructure	Ireland (2022)	0.8
Glaspoort JV was formed between KPN and pension fund APG Group to focus on rural areas	Netherlands (2021)	0.5
Orange Polska formed a JV with pension fund APG Group, to focus on rural areas	Poland (2021)	0.3

New capital investment in greenfield fibre networks

Greenfield fibre networks refer to fibre-optic networks that are operated by new entrants, also known as alternative operators (altnets). These networks typically raise investment from external investors, which flows into new FTTH networks. These funds are used to establish new network footprints or expand coverage for recently established local fibre players. Various regional and larger-scale altnets have benefited from these investments, including but not limited to Deutsche Glasfaser in Germany, noeGIG in Austria, Open Dutch Fiber in the Netherlands and Adamo in Spain.

Altnets typically secure funding from financial investors with a higher risk appetite, such as infrastructure funds and private equity firms. Some financial investors, including KKR and EQT, have been very active in various fibre networks across Europe, but there is also a longer tail of other investors that have mostly been involved in just one or two fibre deals.

Investment to expand non-telecoms networks

Some fibre networks are being developed by utility companies (particularly in the Nordic countries) and other passive network owners that have also shown an interest in fibre networks. For example, Norlys Tele in Denmark is

71 See Analysys Mason's *FTTP valuation tracker 2023*.

72 Percentage of enterprise value for the deal.

73 These networks were formed of 24 PINs under contract with local authorities.

to serve fibre network requirements

the fibre arm of Norlys Group, formed by the merger of two utility companies (Eniig and SE). Similarly, utility firm Enel entered the Italian fibre market in 2016 with Open Fiber.

These network owners are able to leverage their existing infrastructure, such as ducts for power lines and utility poles, as well as their expertise in constructing national networks, to deploy and operate FTTH networks to diversify their services, grow revenue and increase customer loyalty.

B.2 Passive and active infrastructure investment in full fibre networks

B.2.1 The vast majority of investment in fibre networks goes towards expanding and upgrading passive access networks, which are expected to last for decades

Majority of initial fibre capex costs is required for the passive infrastructure, which generally includes civil infrastructure (assets on or in which fibre-optic cables are deployed[74]), as well as fibre-optic cables and splitters (for PON[75] architecture).

Once constructed, the passive network has a very long expected economic life. As shown in Figure B.5 below, various regulatory cost models assume long economic lifespans for these assets: 40–50 years for civil infrastructure and 20–30 years for fibre-optic cables[76] and splitters. Most operators are depreciating these assets over 40–50 years, but in practice will invest smaller amounts over time to ensure the assets remain operational for a longer period, rather than replace them per se.

Figure B.5: FTTH passive infrastructure asset lifespans in years [Source: regulatory cost models, relevant regulatory bodies, 2023]

Passive network assets[77]	Country (year in which the model was published)					
	Finland (2018)	Ireland (2020)	France (2020)	Denmark (2019)	Norway (2019)	UK (2023)
Ducts	40	40	N/A	35	50	40
Manhole	40	N/A	N/A	35	N/A	40

74 Includes ducts and manholes, poles, and in-building access points. Civil infrastructure assets do not have a finite lifespan, and can be maintained for many decades.

75 Splitters allow the signal to be distributed in each group of end users that constitute a PON. PON technology has now become a widely adopted fibre access network architecture, while PtP network architecture was favoured by early adopters of fibre networks due to the immaturity of PON. PON is a fibre-based architecture that uses passive optical splitters to allow a single fibre-optic cable to serve multiple end users (usually up to 32 or 64). In contrast, PtP access networks require a dedicated fibre with dedicated capacity for each end-user premises.

76 The fibre-optic cables do not degrade materially over time but may be replaced over the course of decades. Ongoing improvements are being made to the quality of these cables, as discussed in Section 3.3.

77 Source documents include: Traficom (2017), Assessment of Pricing in the Local Loop Market; ComReg (2021), *Regulated Wholesale Fixed Access Charges Review of the Access Network Model;* Arcep (2020), *Tarifs du dégroupage*; Danish Business Authority (2017), *LRAIC Model for Fixed Networks in Denmark*; Nkom (2020), *Kostnadsmodeller og WACC;* Ofcom (2023), Corrected *Fibre Cost Model Feb 2023*.

Passive network assets[77]	Country (year in which the model was published)					
	Finland (2018)	Ireland (2020)	France (2020)	Denmark (2019)	Norway (2019)	UK (2023)
Trench	40	40	N/A	35	50	N/A
Pole	40	30	N/A	N/A	20	N/A
Fibre-optic cable	30	15/20	20/25	35	20	20
Splitter	30	N/A	20/25	20	N/A	10

N/A: not available in the published model

Passive infrastructure costs associated with the customer connection (last drop) would typically be depreciated more rapidly, over 10–15 years. Disconnection (churn) and reconnection ('win-back') of an individual customer would be much cheaper than the initial connection.

The role of passive infrastructure is to provide a medium through which optical signals can be transmitted. The capacity of ducts and poles can be expressed in terms of the number of cables they can support, and each would typically include hundreds of individual fibre strands. To all intents and purposes, this capacity is not limited to an individual network, even though there may be limitations on the number of networks that share individual ducts and poles.

The fibre-optic cable itself is housed or supported by these ducts and poles. Each individual fibre has an essentially infinite capacity when considering bandwidth and traffic: the current generation of fibre-optic cables do face some physical limitations (with capacity of multiple Tbit/s per fibre), however this is not expected to be a constraint for many decades. In access networks, the most advanced standard for active equipment is currently 50G-PON (see Sections 3 and 4), which could, in principle, offer 50Gbit/s per fibre, well below physical limits.

As mentioned previously, core and backhaul networks are mature throughout Europe. Multiple operators own or lease passive infrastructure on all the routes they require. On these routes, capacity on individual links can exceed 1Tbit/s due to traffic aggregation, and further capacity is provided by multiple fibre strands used at once in a single cable.[78]

B.2.2 Active equipment requires ongoing replacement over time, with new generations of equipment offering better performance at similar costs to previous generations

Active equipment broadly comprises the active components of a PON access network, active equipment in the core and backhaul network, and end-user equipment, as detailed further in Figure B.6.

78 This varies based on the deployment architecture, but many PONs are configured with more than 128 pairs per PON (e.g. 144) to have an option to operate 1:128 splitting ratios.

Figure B.6: List of FTTH active equipment [Source: Analysys Mason, 2023]

Network segment	Active equipment	Description	Current technology
PON access network	OLTs	Located at the first active node closest to the end user (typically in a cabinet)	• **Gigabit PON (GPON)** – offers downstream bandwidth of 2.5Gbit/s and upstream of 1.25Gbit/s; the most widely used technology in Europe and other parts of the world • **XGS-PON** – offers symmetrical bandwidth of 10Gbit/s; currently gaining significant traction particularly among altnets that want to differentiate themselves from incumbent operators • **25G-PON** – offers symmetrical bandwidth of 25Gbit/s; used in small trials and limited commercial deployment by Nokia, but not yet standardised • **50G-PON** – offers downlink bandwidth of 50Gbit/s, effective upload speeds of up to 25Gbit/s in tests so far, but may offer symmetrical bandwidth over time; not commercially deployed yet but standardised by the International Telecommunication Union (ITU) and supported by all vendors
Core and backhaul	Switches and routers	Active equipment that carries aggregated traffic and is generally replaced and upgraded over time in the normal course of network maintenance	**Core network equipment using DWDM technology** that supports bandwidth in hundreds of Gbit/s per wavelength, and its capacity-adjusted prices decline constantly
End-user equipment	ONTs and residential gateways (RGWs)	Used as routers and Wi-Fi access points for end-user devices	GPON and XGS-PON ONTs are available at different price points: the lowest-cost XGS-PON terminals are configured with a customer-facing Ethernet port at 1Gbit/s; more expensive ones offer 2.5Gbit/s or 10Gbit/s

Active equipment typically accounts for a small portion of the initial capex costs of full-fibre networks. The CPPP by the network or the CPPC is relatively similar in different networks and countries, which means that if passive investment requirements are greater, the share of investment in active equipment will be lower.

Active equipment has a shorter lifespan than passive infrastructure, and a finite capacity. Figure B.7 below shows the economic life for active equipment used in recent regulatory cost models.

Figure B.7: FTTH active equipment lifespans in years [Source: regulatory cost models, various years]

Active equipment	Economic lifetime of assets used in European regulatory network cost models
End-user equipment	4 (Ireland, 2020); 3 (Norway, 2019)
Access: OLT	8 (Greece, 2022); 7 (UK, 2023)
Core and backhaul: switches and routers	8 (Greece, 2022); 8 (Denmark, 2019)

While lifespans of active equipment are short, the performance of new equipment increases even as its price remains stable. Active equipment tends to be replaced with more modern equipment when it reaches the end of its lifespan. New equipment tends to be more efficient, offering much greater capacity for the same price or even a lower price.

These technological advances and economies of scale also contribute to improvements in subsequent generations of active equipment in terms of the bandwidth or capacity supported. Since equipment tends to be replaced when price levels have declined to that of previous generations, network operators are therefore able to increase network capacities automatically over time as part of natural replacement cycles, and at relatively stable replacement cost levels.

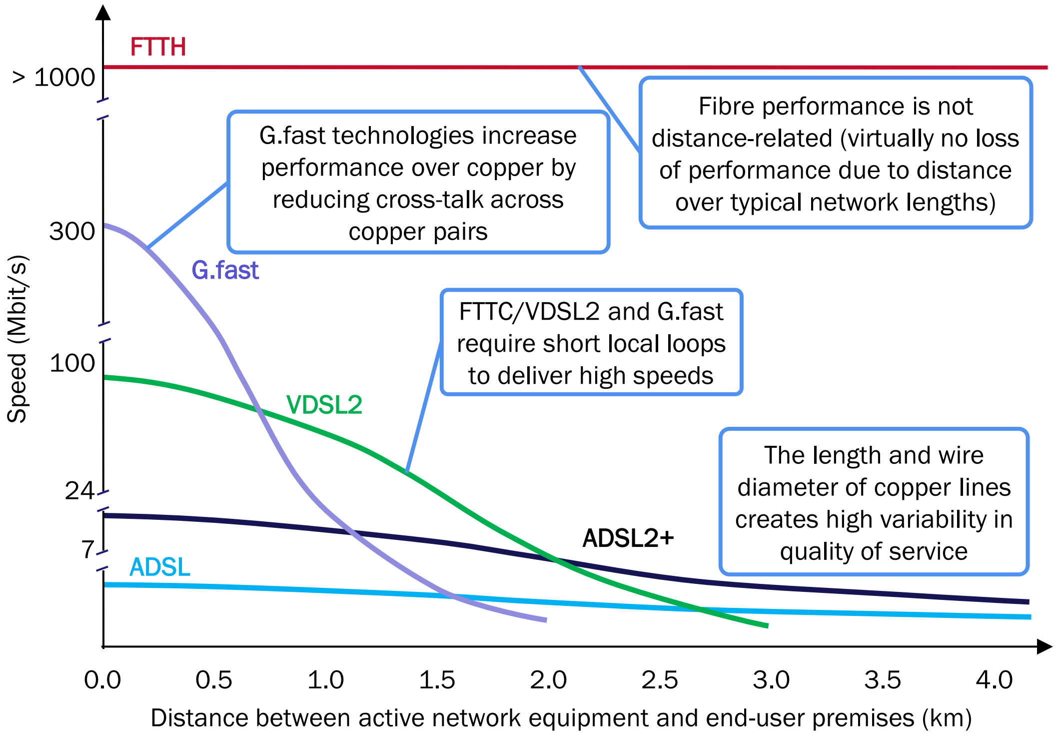
Similar replacements already take place in current-generation networks, including DSL and cable networks, and replacement capex for active equipment is unlikely to be higher in full-fibre networks than it would be if legacy networks were to remain in place.

B.3 Performance and efficiency gains of fibre networks over and above legacy technology

B.3.1 Compared to legacy technologies, fibre exhibits better performance and is less costly to operate and maintain, while also being more energy efficient and environmentally friendly

As shown in Figure B.8 below, full-fibre networks can deliver high speeds even in areas that are far (up to 20km) from the network's 'active' node.

Figure B.8: Performance of copper and fibre access technologies for various distances between active network equipment and end-user premises [Source: Analysys Mason, 2023]



Due to their performance over long distances, fibre networks are more reliable relative to legacy networks, which is demonstrated through several examples:

- In a report published by Ofcom, it has been observed that fibre networks experience lower rates of Netflix disconnections compared to copper networks.[79]
- As early as 2012, Portugal Telecom reported that its fibre network incurred 16% fewer trouble calls[80] and 40% fewer truck rolls[81] per customer than its copper network.[82]
- High fault rates in the copper networks have also been observed by Telia in Estonia, so prominent that it has significantly contributed to the copper decommissioning in Estonian rural areas.[83]
- Resolving trouble calls is also less costly for fibre networks than for copper networks: in 2020, the Fiber Broadband Association estimated that, per customer, the cost to resolve trouble calls per

79 Ofcom (2022), *UK Home Broadband Performance*.

80 Calls generated by automated fault detection software or customer calls upon faults.

81 Occasions involving in-person visits by engineers to resolve the network faults.

82 Portugal Telecom (2012), *Enabling convergence through IT, Technology and Innovation conference, Lisbon, 29-30 October 2012*.

83 Study for FTTH Council Europe by WIK-Consult (2020), *Copper switch off: European experience and practical considerations*.

customer from a copper network's operating centre would be triple the cost required in fibre networks.[84]

Moreover, fibre networks consume less power than copper or cable-based networks, making them more energy efficient and environmentally friendly. Fibre networks can use longer cables, implying that fewer exchange sites would be required, and hence, less electricity needs to be consumed. A study commissioned by TalkTalk (in the UK) in 2022 found that its plan to reduce the number of its exchanges from 3035 to 1000 would result in a reduction in energy consumption by 85 000kWh per annum and 20 000 tonnes of CO_2 emissions.[85]

Copper-based FTTC and coax-based DOCSIS technologies consume 8–18 times more power than fibre-based GPON technology per connection (Figure B.9), when only considering network equipment.[86] A lifecycle assessment conducted by Telefónica also found that fibre (FTTH) networks use significantly less power than copper networks, resulting in lower carbon dioxide emissions (80% less per end user and 95% less per 1TB of data transmitted), as shown in Figure B.10.[87]

Figure B.9: Power used by connection by broadband access technologies [Source: Analysys Mason Research, 2021]

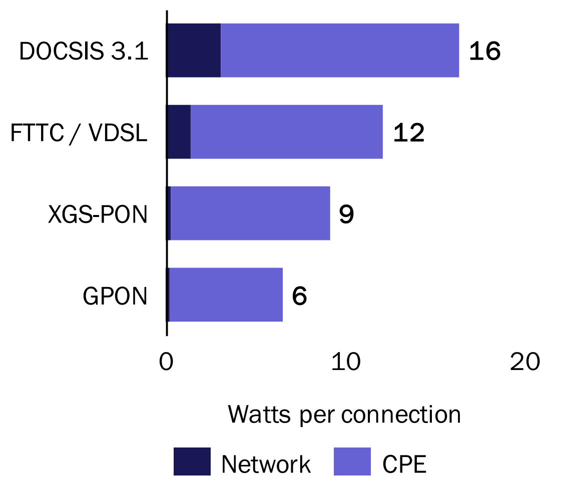
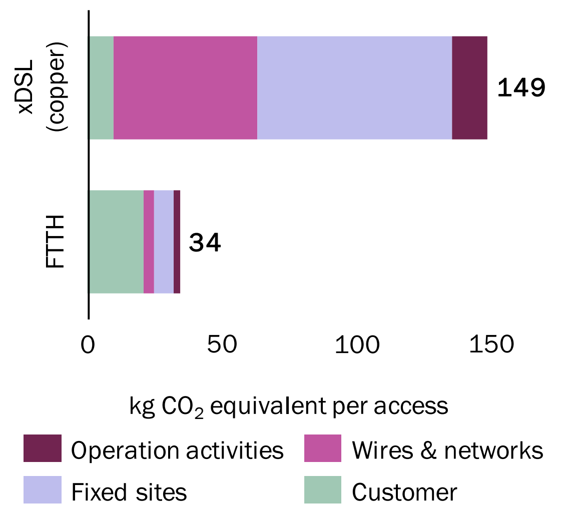


Figure B.10: Environmental impact of fixed network technologies (copper and FTTH) [Source: Telefónica, 2022]



84 Broadband Communities (2020), *To Reduce Network Operating Expenses, Choose FTTH*.

85 TelecomTV (2022), *TalkTalk finds fibre networks will cost the planet much less than copper*.

86 See Analysys Mason's *Driving down energy usage across telecoms networks: 5G RAN and beyond*.

87 Telefónica (2022), *Connectivity solutions' Life Cycle Assessment*.

B.3.2 Fibre will bring further cost savings in the medium term through simplification of network topologies, and longer-term upgradeability through the use of hollow-core fibre optics

Various regulators and/or incumbents have announced copper decommissioning programmes in various European markets. For example, in the UK, BT is expected to reduce its current footprint of ~5600 local exchanges to just ~1100 by the early 2030s.[88] In the EU27, Altice (Portugal Telecom previously) had planned to close 75% of its local nodes as of 2016 and stopped marketing voice services over the copper network to new customers in 2019,[89,90] while KPN in the Netherlands plans to decommission ~1300 of its copper exchanges.[91] The benefits of such decommissioning programmes (through reduced number of network nodes, less resources and lower costs) may be realised earlier than planned, in line with the EC's draft Gigabit Infrastructure Act which proposes to reduce decommissioning timeframes. This, in turn, will support wider European initiatives including the Digital Decade Programme and Europe's green agenda.

In the long term, hollow-core fibre could replace typical fibre optic cables for very-high-capacity core network links, providing higher bandwidth and lower latency. Unlike traditional fibre-optic cables, hollow-core fibre cables are made up of cores that are filled with air instead of fused silica (glass). Air-filled core enables higher bandwidths and lower latency than typical fibre-optic cables, by enabling the transmission of data at close to the speed of light. At present, the manufacturing of hollow-core fibre is still in its infancy, and current solutions suffer from higher attenuation than traditional fibre optics. Over time, manufacturing processes are expected to improve, and hollow-core solutions, once viable, are expected to provide an upgrade path for supporting advanced applications far into the distant future (these solutions are likely limited to very large core network links in the foreseeable future).

B.4 Historical demand for fixed networks

B.4.1 Growth in traffic demand has reverted to the relatively steady growth pattern seen prior to Covid-19 lockdowns

Historically, traffic demand had been increasing year-on-year due to growing adoption of the internet and online services. Prior to the Covid-19 pandemic, however, traffic growth rates were declining year on year, from over 40% in 2015 to less than 30% in 2019, as shown in Figure B.11. During the pandemic, traffic surged, driven by lockdowns as people stayed at home and carried out most activities, including work and studies, online. This was a significant demand shock: physical interactions were replaced with multi-way video calls, and the scope for in-home consumption of streaming media increased from a few hours a day, to the whole day for many people. Regardless of the sudden increase

88 Openreach (2022), *Exchange Exit Programme*.

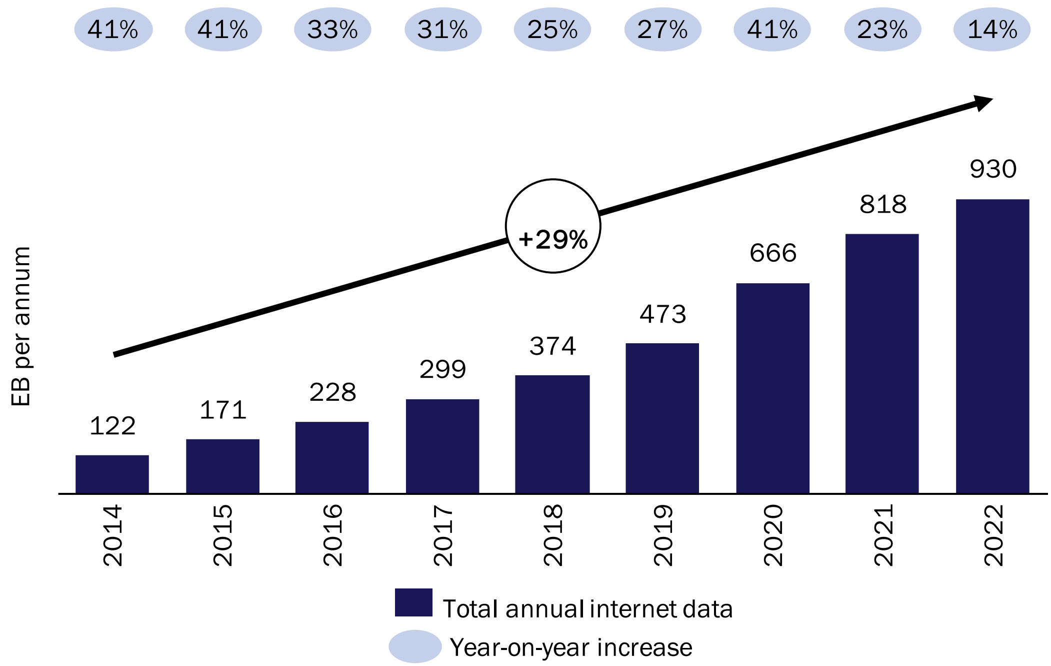
89 Portugal Telecom (2016), *An All-fiber Company in An All-fiber Country*.

90 Study for FTTH Council Europe by WIK-Consult (2020), *Copper switch off: European experience and practical considerations*.

91 KPN (2021), *Jort Wever on 'Fiber on Copper out' at KPN: 'The future is now'*.

in demand levels, no major network issues were reported.[92] Unsurprisingly, since the end of lockdowns the traffic growth has eased and total traffic growth has reverted to its historical trend: growth in traffic between 2019 and 2022 was on average 25% per annum.

Figure B.11: Total annual fixed network internet data traffic in Europe and year-on-year growth rates [Source: Analysys Mason Research, 2023]



B.4.2 Peak bandwidth requirements for existing applications are easily handled by current networks

Speed requirements by individual users depend on their online activity. Nearly everyone will, on occasion, demand as much speed as their connection can handle: for fast connections, including full-fibre access, this is currently limited to large file downloads, including OS updates and games. In these circumstances, the speed available can condition the time it takes to download files, given that their size (i.e. traffic required) is constant.[93]

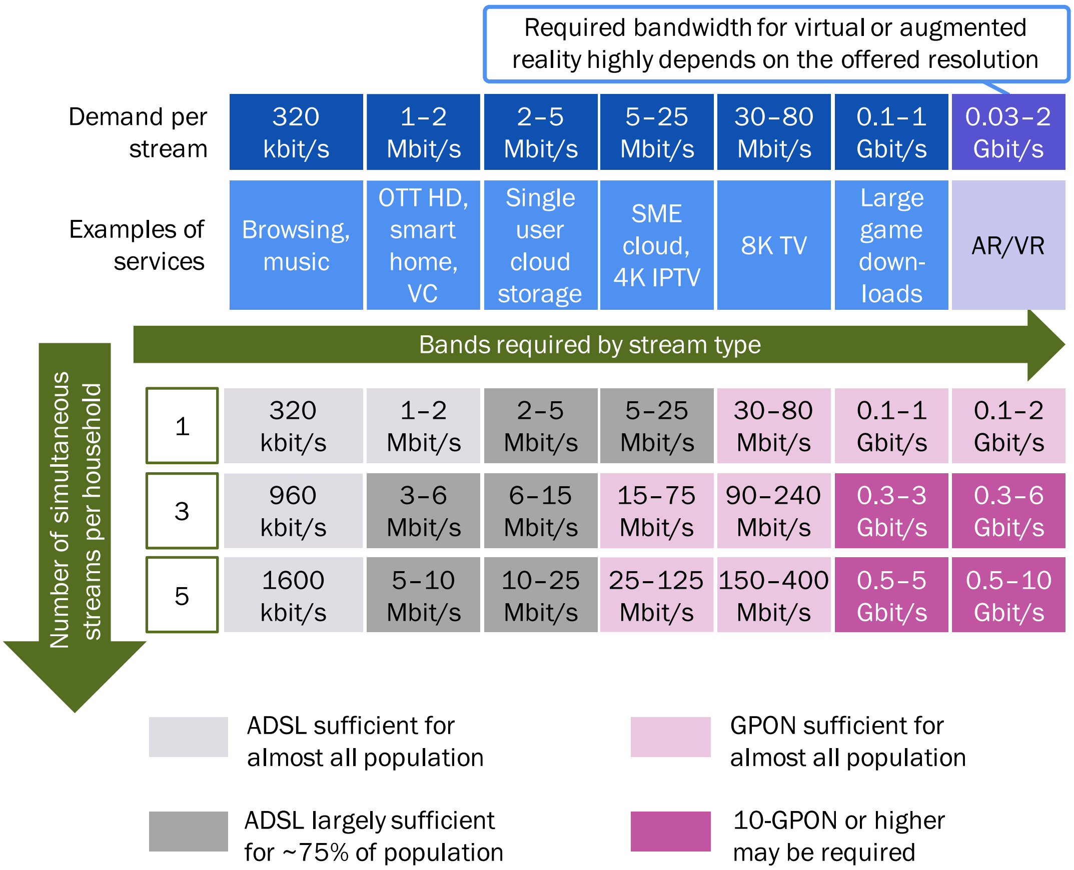
However, such requirements are sporadic for most users, and can be managed across multiple users through scheduling, which is something that content providers and ISPs collaborate on routinely. Furthermore, a degradation in download speeds simply means that a file takes longer to download, which in most cases does not impact the user experience. Other mass-market uses, in particular video streaming and cloud gaming, require good bandwidth availability over time. Overall, these use cases can demand maximum sustained peak speeds of 25–30Mbit/s per user; in practice, the vast majority of

92 BEREC (2021), BEREC Summary *Report on the status of internet capacity, regulatory and other measures in light of the Covid-19 crisis.*

93 The time it takes to download a file depends partly on connection speed, but also in many cases on the location of the hosted content relative to the user. Generally, if the files are available on a cache embedded in the ISP's network, the user may be able to fully utilise their access speed; if the file needs to be fetched from a server on another network, speed may be constrained by other factors.

video streams are encoded to ensure they use closer to 10Mbit/s, even for very-high-definition video. In a typical EU household hosting four people, total peak speed could reach 200–300Mbit/s, but this would require that everyone demands this maximum speed, all at the same time, across two devices each. The vast majority of users would seldom be in this situation. In a recent study for ComReg, the Irish communications regulator, we estimated that the ‘comfort speed’[94] for the top 1% of households is ~100Mbit/s.[95] Examples of typical bandwidth requirements for existing applications are provided in Figure B.12 below.

Figure B.12: Bandwidth requirements for existing applications [Source: Analysys Mason, 2023]



Note: AR/VR requirement demand is for future applications, and is an Analysys Mason estimate (not sourced from Meta).

B.4.3 Concurrent bandwidth demand has grown more slowly than traffic and has ample room to grow in full-fibre networks

The final measure of demand across a fixed broadband network is the concurrent bandwidth demanded by multiple subscribers at the same time. This can be a complex statistical question to assess, but the

94 ‘Comfort speed’ can be defined as as the amount of bandwidth that is required to support the typical usage at peak time of a high-end-user profile actively using the service.

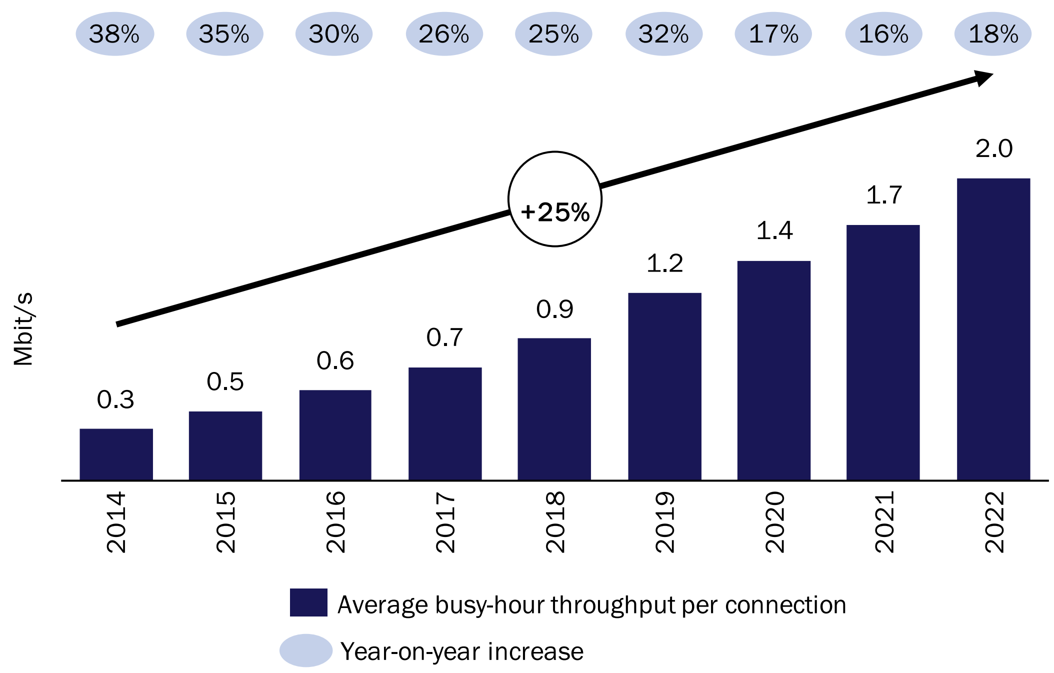
95 ComReg (2023), *ODN Sharing Report*.

more users share a given resource, the more their usage will be decorrelated, and the less it will be additive. This means that if two users stream a compressed 4K video requiring 10Mbit/s at the same time, at a speed of 100Mbit/s each, their devices will download video in fast bursts at different times from one another and buffer it. As a result, their combined usage may never add up and could be, in fact, only 10Mbit/s.

Some ISPs report aggregate usage across their entire networks. In the UK, for example, three major ISPs using primarily DSL-based technology (BT, TalkTalk and Sky), reported concurrent peak bandwidth on the busiest day of 2022 at ~3–5Mbit/s per connection. This is significantly below the peak speeds offered by DSL-based connections (~75Mbit/s) and even lower than the speeds offered by full-fibre connections (hundreds of Mbit/s and up to 1Gbit/s for these ISPs). Ofcom, the UK communications regulator, publishes a chart which shows the evolution of the peak traffic on average over a six-month period in 2021 and 2022, indicating that the peak has grown by less than 5%.[96]

Analysys Mason Research data provided in Figure B.13 shows that peak concurrent throughput across Europe per end user averaged 2Mbit/s in 2022, which is considerably lower than individual peak speed demand by individual users. Similarly, the growth of average throughput per user has been lower than the growth of total internet traffic, and did not exhibit the same growth as traffic during the Covid-19 pandemic. This suggests that the main driver of traffic was more spread-out usage across the day during pandemic lockdowns.

Figure B.13: Average fixed network busy-hour throughput per user in Europe [Source: Analysys Mason Research, 2023]



96 Ofcom (2022), *Connected Nations 2022*, page 25.

In DSL-based networks, each copper line is dedicated to an individual end user. These lines are connected to active equipment (in a building, street cabinet or local exchange) and share backhaul capacity back to the core network. In a typical VDSL-based network, several hundred users share this backhaul, and this enables enough diversity in usage to ensure the provisioning of bandwidth is close to the 'peak of peak' requirement. In a high-demand environment (e.g. the UK), this provisioning is ~4–5Mbit/s per user.

For comparison, capacity in a PON-based network is shared between end users on an individual PON 'tree'. A typical PON will combine between 32 and 128 users, who share a total downstream bandwidth of 2.5Gbit/s for standard GPON, and 10Gbit/s for XGS-PON. This smaller number of users sharing capacity reduces statistical gains, but the bandwidth available is orders of magnitude larger than in DSL-based networks. In a standard GPON network with 64 users per PON, the provisioned bandwidth is 40Mbit/s when the PON is full – around ten times the bandwidth currently provisioned for DSL users in high-traffic European markets. This is a worst-case scenario, and the evolution of PON-based technology and architecture provides for much greater bandwidth per user, as discussed in Section 4.3.

B.5 Ease of upgrade for PON-based fibre networks

Upgrading an existing PON-based network from one standard to the next can be done by upgrading the OLT equipment to accommodate current and next-generation users. As users migrate to higher-speed products or their ONT equipment becomes obsolete, the architecture can be simplified to accommodate only the new standard, and in time evolve to the next standard in the same way. This is illustrated in Figure B.14 below, with a combined XGS-PON/GPON OLT providing capacity to both types of ONTs.

Figure B.14: Evolution path of PON-based full-fibre networks [Source: Analysys Mason, 2023]