

Energy consumption of telecommunication access networks

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1 Introduction

The world of information and communications technologies (ICT) has changed rapidly in the last decade. The internet and its surrounding technologies became the most commonly used communication medium in people's personal and working lives. It is critical for a vast range of services – gathering information, communication and entertainment are only the main functions. Key to accessing the internet and to using its services are broadband access networks. These access networks are based on different technologies, e.g. DSL or DOCSIS, and on separate infrastructures, such as the telephone or hybrid fibre coax network. Furthermore, completely new systems, like Fibre to the Home (FTTH), were developed. State of the art access technologies can provide data rates up to several hundred Megabit per second. These technologies are available and will be further developed.

Despite the availability of highly sophisticated access technologies, the physical rollout is lagging behind. The telecommunication infrastructures in many countries were built decades ago and were not designed to transport digital data signals containing high frequencies. This leads to two different parameter sets, one for the physical infrastructure and a second for the new access technology, which uses the existing infrastructure. The problem is that these two parameter sets do not match. The telephone network for example has cable routes longer than a DSL signal can be transmitted. Consequently, the demanded resources cannot be provided to all customers. The infrastructure has to be updated or a completely new one (Fibre to the home, FTTH) has to be built, otherwise building broadband will come to a halt.

The network operators and governments have accepted the task and two methods are primarily used today to update the infrastructure:

1. To update the telephone network, the length of the copper twisted pair wire has to be shortened. Therefore, so-called Outdoor DSLAMs could be installed.
2. To update the hybrid fibre coax network, more fibre nodes could be installed to shrink the service group size.

If a completely new infrastructure is set up, a continuous fibre optic network is built. These networks are called Fibre to the Building/Home networks (FTTB/H) and connect the building/subscriber directly with the network operator's Point of Presence (PoP) via a fibre optic wire. Theoretically, the update methods will also last into FTTB/H networks. This is, however, more a plan than a fact today.

In the short-term, all of these methods are able to satisfy the data rates demanded by the subscribers. A question arises: Which of the methods should be selected?

Two important decision-making criteria should be the power consumption as well as the energy efficiency of the different access technologies. However, this is not taken into account in the political and economic considerations so far. This study is intended to provide an initial impetus for the consideration and assessment of the energy requirements of different broadband access technologies.

2 Scope

As the introduction shows, broadband internet access is already one of the key requirements for our social and economic wealth and it will be an integral part of the foundation of the global system in the near future. Therefore, broadband networks, which provide the transportation capacities for all services, are needed. These broadband networks can be separated into three major layers:

1. Core network
2. Regional networks
3. Access networks

The core network connects continents, countries and major national network nodes. It is based on fibre optic links with data rates up to several GBit/s and the least possible delay. It also provides the data exchange between the network operators (network interconnection), so that every host is reachable. The core network is constantly improved by the ICT companies and can provide the capacities needed to ensure the usage of all internet services.

The regional networks connect all access networks with the core network. From a technological perspective, these regional networks do not differ much from the core network. However, they do not provide any network interconnection between different network operators. Broadly speaking, regional networks are just connection lines.

The growing demand for internet connection bandwidth however, leads to increasing requirements placed on the regional network infrastructure. The number of regional network connections is far too small to fulfil these requirements. In this context, regional networks can represent a bottleneck in more rural areas.

An access network, also referred to as last mile, is the direct connection between the network operators' local office and a single subscriber. Usually it uses a different transmission technology and infrastructure to the regional network or the core network. In most countries the type of access network technology which

is used today depends also on which infrastructure existed in the late 1990s. In Germany and many other countries of the European Union the telephone twisted pair networks were widely spread. As a result, DSL (Digital Subscriber Line) is the most common access technology in the EU. The coax networks for television and radio broadcasting also exist in many European countries.

Since the operators implemented DOCIS and adopted their broadcast coax networks into hybrid fibre coax networks, internet connections are also available over this infrastructure. In addition to these two wired technologies, other wired and radio-based access technologies exist. However, they have not gained the importance of DSL and DOCSIS.

Since telecommunication companies like Deutsche Telekom introduced broadband connections for the mass market, especially the customers' demands on data rate is constantly increasing. To address these increasing demands, the existing technologies have been developed further. The deployment of these improved technologies however, has not progressed in every section because network operators' economic considerations prevented this. As a result, the access networks are the bottlenecks of our time.

The network operators and the European governments concentrate their efforts on building up broadband access networks. In the last decade, several billion euros – private capital and public subsidies – were invested into this sector, which causes the installed access networks to transform very rapidly.

Hence, this survey is focussing on broadband access networks and their power consumption. The following access technologies will be addressed in detail:

- VDSL2 Vectoring
- DOCSIS 3.0 in HFC networks at 864 MHz
- FTTH – PtP Ethernet
- FTTH – GPON

The regional networks and the core network are needed for all the listed access technologies and can be considered as equal in terms of energy consumption. Nevertheless, every regional network connection is taken into account by fixed values and will not be examined in closer detail.

The overall goal is to ensure comparable energy consumption figures for each access technology.

To achieve this goal, the term “access network” has to be defined.

The access network connects each subscriber to their immediate service provider. It includes the passive connection point on the subscriber’s premises, the active network termination including the connection (first hop) into the core network on the service provider’s side (see Figure 1) and all active components in between.

The needed active customer premises equipment, like modems, routers or media converter, will be examined additionally.

Access network definition

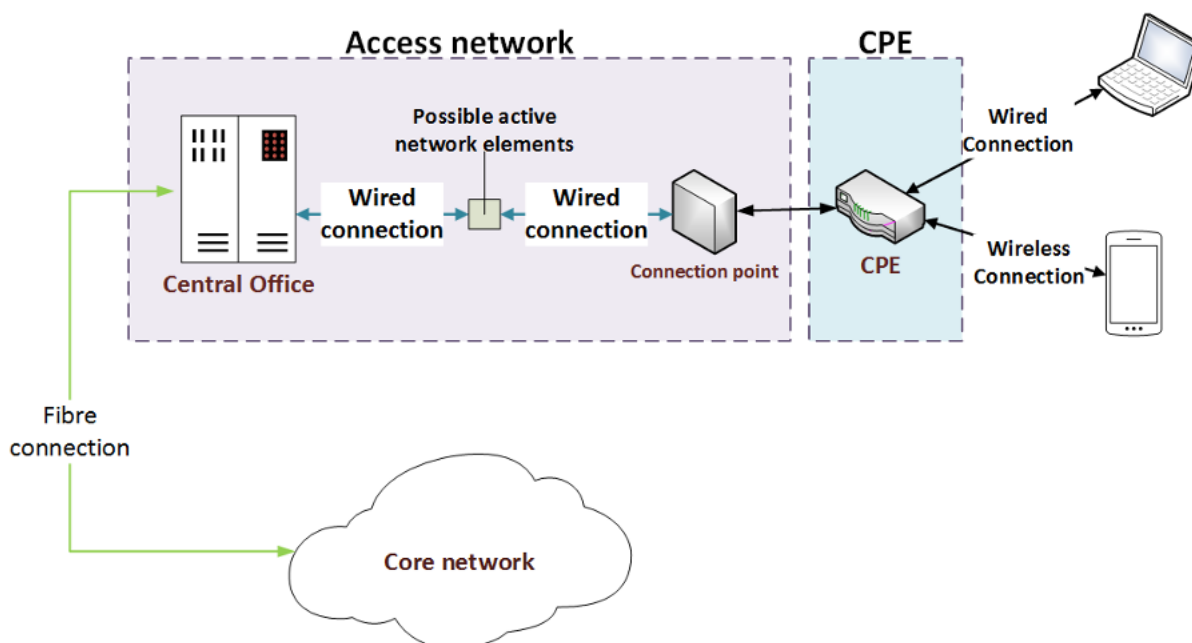


Figure 1: General definition of an access network with its components and the needed customer equipment.

Applied to the four access technologies, the following components are part of the examination:

VDSL2-Vectoring access network

- DSLAM – DSL Access Multiplexer
- Vectoring calculating unit
- Connection into the core network
- Air conditioning

VDSL2-Vectoring customer premises equipment

- DSL-Router with modem and WLAN

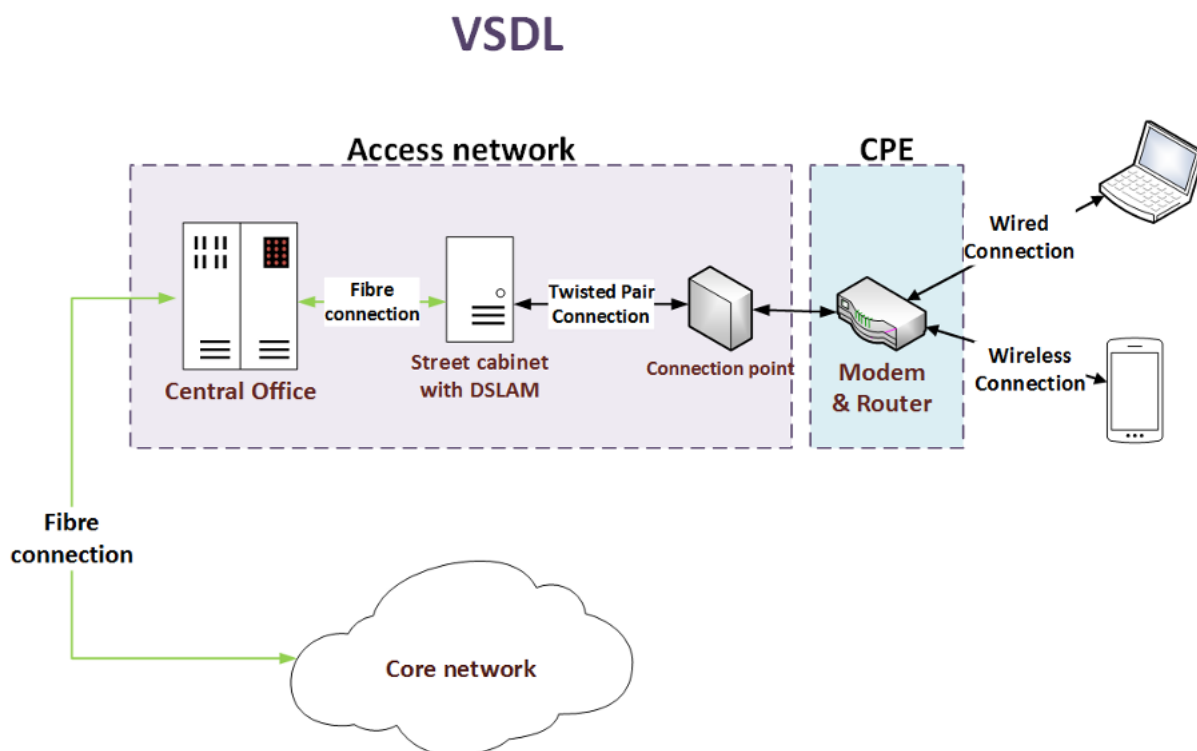


Figure 2: VDSL2-Vectoring access network and customer premises equipment.

HFC with DOCSIS 3.0 access network

- Cable modem termination system – CMTS
- Fibre node including A/B/C-Line Amplifier
- Connection into the core network
- Air conditioning

HFC with DOCSIS 3.0 customer premises equipment

- House connection amplifier
- DOCSIS-Router with modem and WLAN

Hybrid Fibre Coax Network

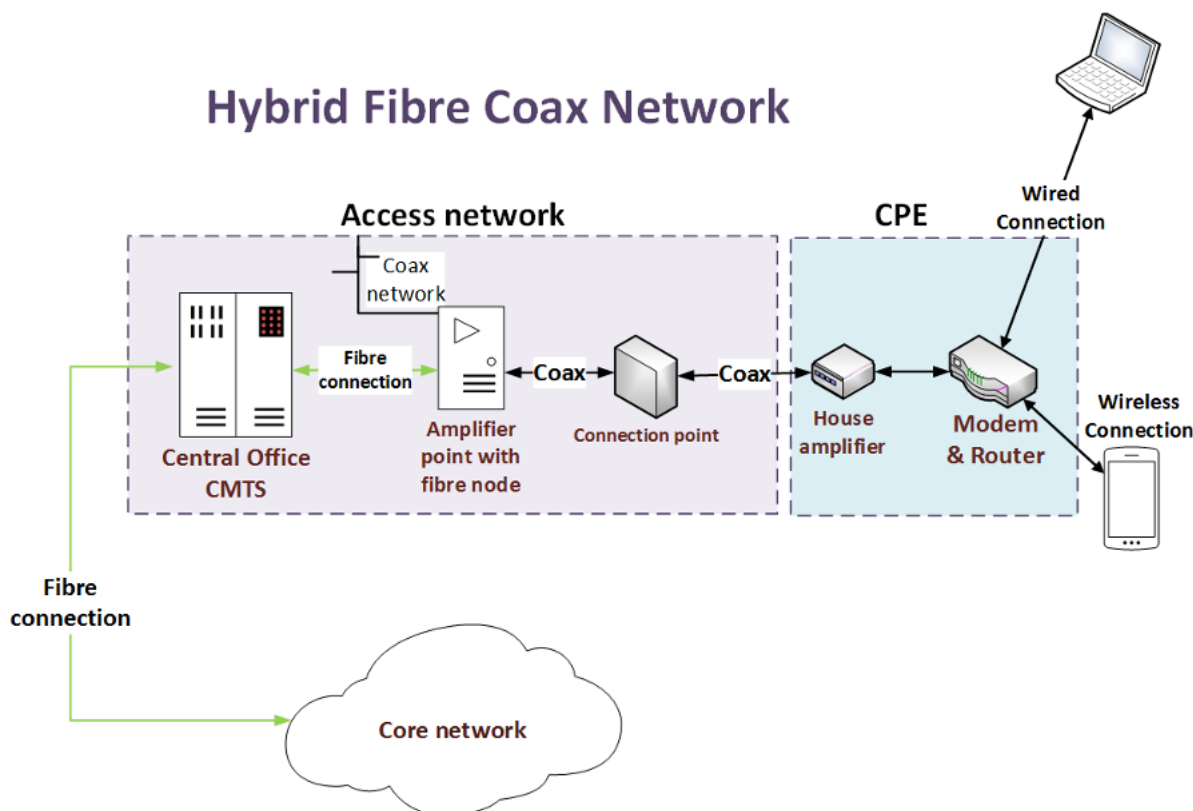


Figure 3: HFC access network and customer premises equipment.

FTTH – PtP Ethernet access network

- Optical line termination
- Central office equipment
- Connection into the core network
- Air conditioning

FTTH customer premises equipment

- Optical network unit (active)
- Router with WLAN

Fibre to the Building – Point to Point

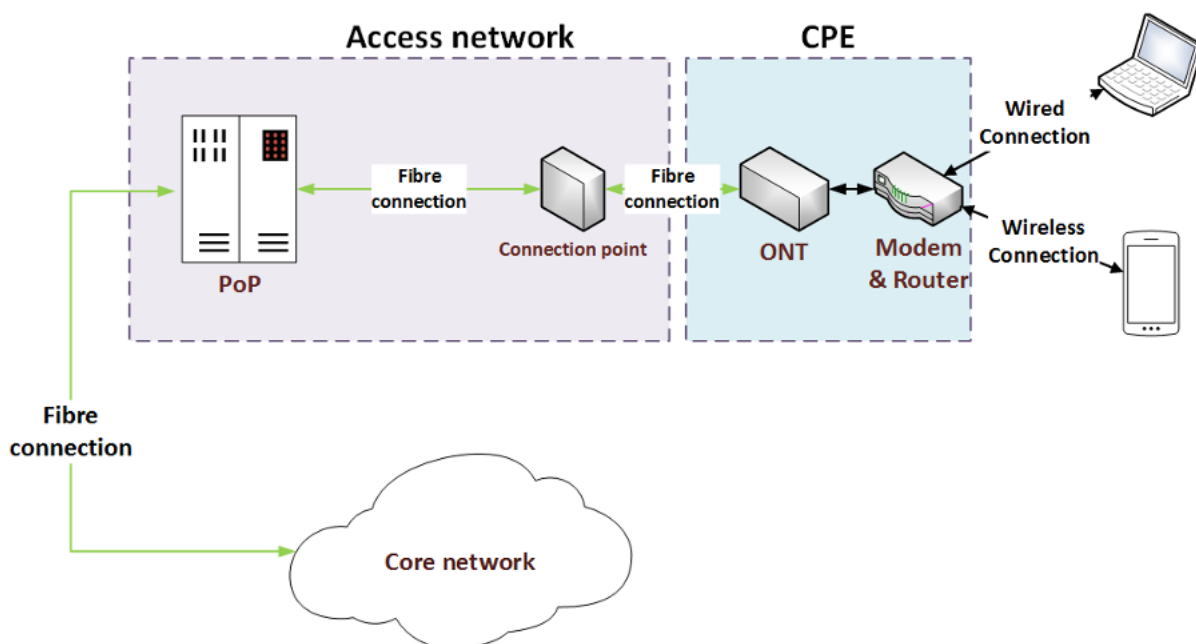


Figure 4: FTTH – Point-to-Point access network and customer premises equipment.

FTTH – GPON access network

- Optical line termination
- Central office equipment
- Connection into the core network
- Air conditioning

FTTH customer premises equipment

- Optical network unit (active)
- Router with WLAN

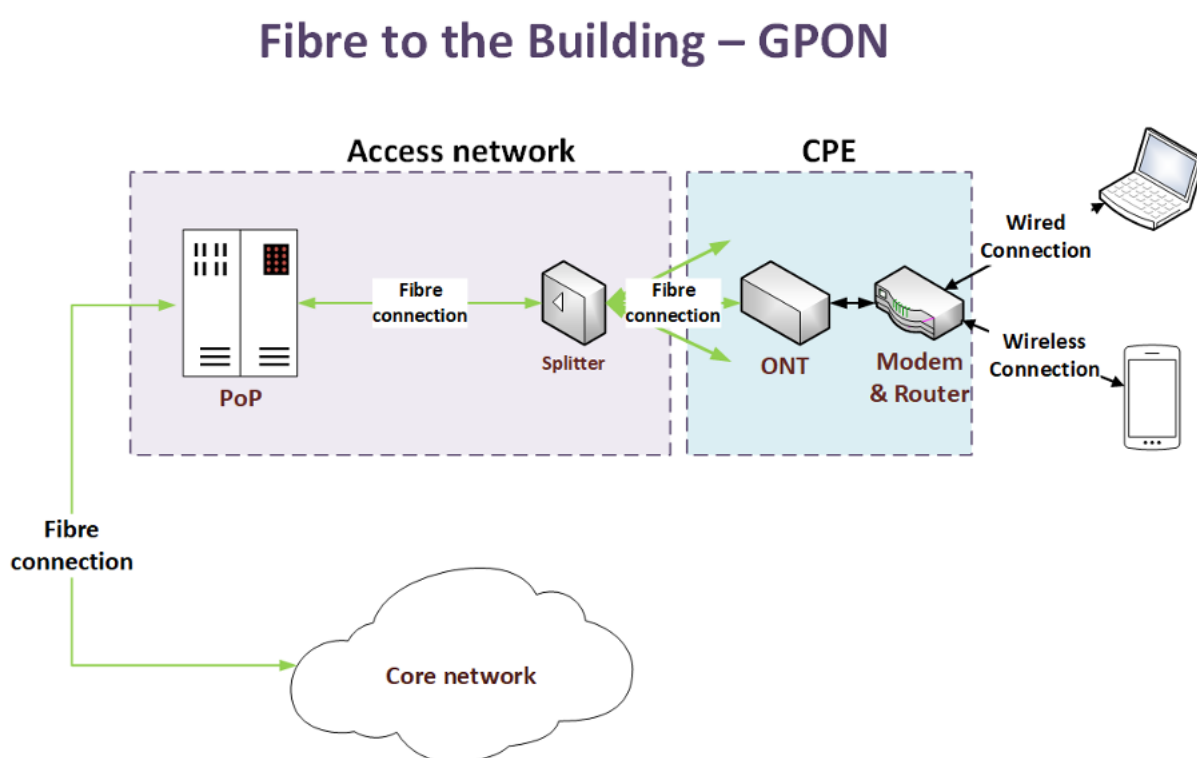


Figure 5: FTTH – GPON access network and customer premises equipment.

3 General approach

This survey analyses the energy/power consumption of telecommunication access networks based on:

- VDSL2-Vectoring
- HFC with DOCSIS 3.0
- FTTH – Point-to-Point
- FTTH – GPON

The aim is not to generate energy consumption values for single devices of different manufacturers or normalised values per single port or user. Instead, it evaluates the overall energy consumption for each of the three access technologies at a ubiquitous rollout.

Therefore, a real region is selected, which represents a typical rural to urban settlement structure in Germany. The general target is to provide a minimum of 50 Mbit/s on every connection within this region.

To achieve this, every household, business unit, public institution etc. has to be physically connected to the particular access network.

A 100% connection rate is required.

Furthermore, each access network has to fulfil its individual technological parameters to achieve a minimum data rate per subscriber. In this survey a minimum data rate of 50 Mbit/s was chosen. 50 Mbit/s for every subscriber is a central goal of the 2018 broadband strategy of the German Federal Government. Whether this is a technologically meaningful goal remains unclear. Nevertheless,

it is nothing but the goal of the current political and economic activity to build broadband in Germany.

An individual set of parameters is required for each access technology.

According to these two simple specifications, separate network topologies for VDSL2-Vectoring, HFC with DOCSIS 3.0 and FTTH can be determined – a simplified model is used, not taking into account the actual cable route.

The network topology for VDSL2-Vectoring is based on the existing infrastructure in the chosen region. For the existing HFC network, the spatial locations of the network elements could not be obtained and FTTH networks do not exist in the chosen region. However, the HFC with DOCSIS 3.0 and FTTH networks do not suffer from length restrictions, so that the exact location of the network elements is less important.

According to this, the HFC and FTTH network design uses a green field approach.

The result of this topology determination is a quantitative estimation of active network elements and their secondary systems.

In combination with data on the energy/power consumption of the individual network element, an overall energy/power consumption can be estimated for each access technology. This method creates a supply-related energy/power consumption. In other words: “How much electrical energy is needed by every access technology to provide a minimum of 50 Mbit/s for every subscriber in the specified area?”.

4 Data basis

According to the general approach, the energy/power consumption of the different access technologies will be examined for a specific model region. Therefore, a data basis is needed, which allows a geographically referenced and statistical analysis.

First the model region has to be chosen. This region should cover rural to urban settlement structures and should include business parks as well. Furthermore, information about the existing access network should be obtainable.

All these requirements could be achieved in a region in North Rhine-Westphalia (Germany), which consists of six municipalities. Because of non-disclosure agreements, the model region had to be anonymised and the municipalities are now named A to F. This also applies to other internal information, which were provided by various companies.

Model region	Population (approx.)	Area (approx. [km ²])	Population density (approx. [Pop./km ²])
A	6,500	40	163
B	11,800	40	295
C	13,700	49	280
D	9,400	52	181
E	7,200	59	122
F	8,100	58	140
Total	56,700	298	190

Figure 6: The table shows data of the model region and its six municipalities.

All municipalities are comparatively small in their population and spatial expansion. However, these regions are typical for the German settlement structures outside the metropolitan areas like Berlin, Frankfurt, Cologne or the Ruhr valley. The population density differs between approximately 122 and 295 people per km² (see Figure 6).

As Figure 7 shows, the population density inside the regions fluctuates considerably. The population density in the inner cities is partly higher than the table in Figure 6 shows, whilst the population density drops under the mentioned number in the outskirts.

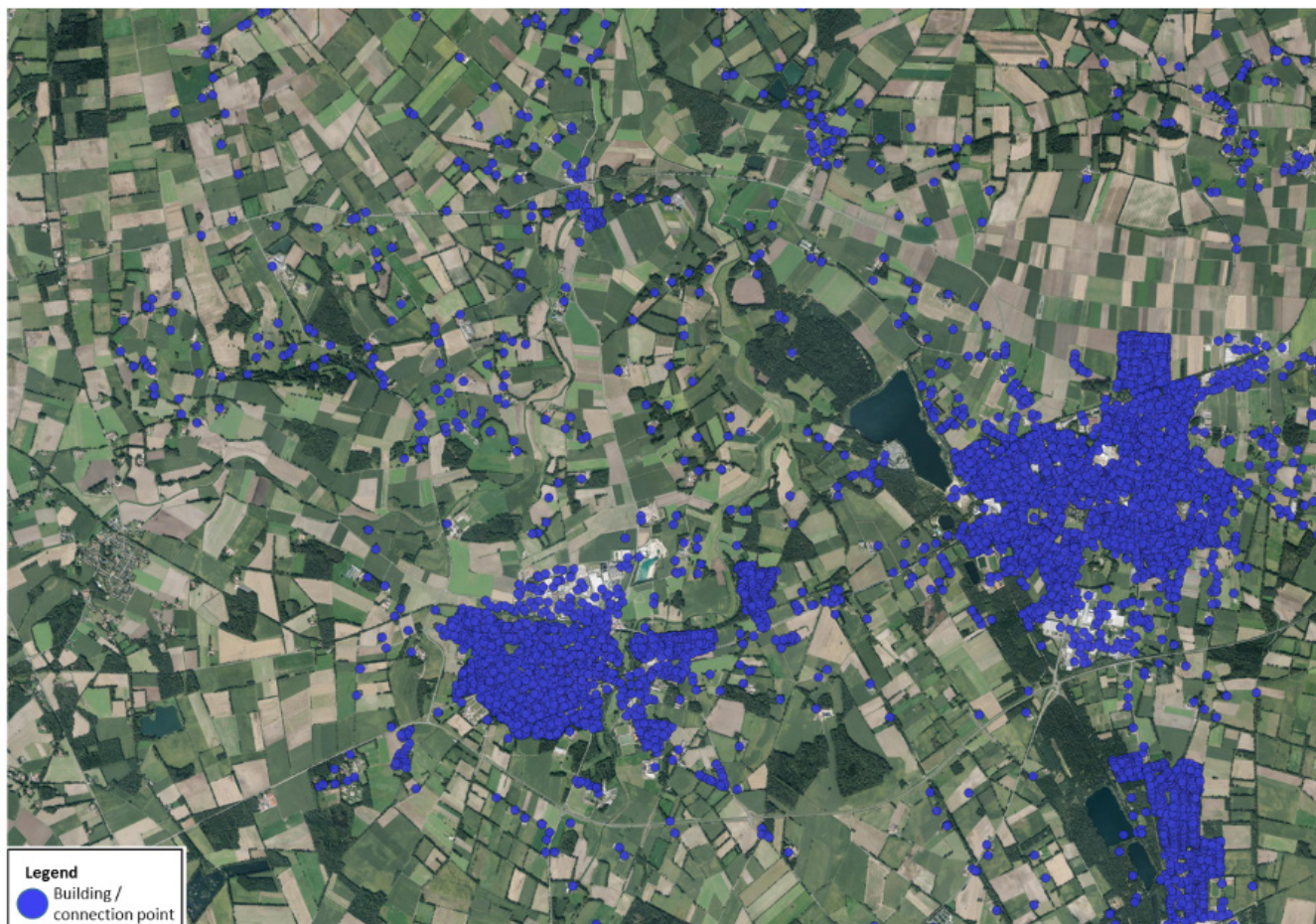


Figure 7: Example region with various population densities.

Within the model region approximately 25,000 households, companies, public administration and more (from here on referred to as subscribers) exist in 17,250 properties (from here on referred to as connection points). All these connection points have been geographically referenced (see Figure 7) and comprise the basic data for all further steps.

The next step was to integrate the access network information.

For DSL the following network elements were known:

- Central office
- Street cabinet

All of these elements have been referenced to a building or given a new individual geographical reference. Every building was assigned to the correct street cabinet. In addition, every street cabinet was allocated to its central office (see Figure 8).



Figure 8: Georeferenced buildings with allocated street cabinets.

For every connection point a set of meta data is available, which contains:

- Connection point ID
- Street cabinet ID
- City
- Street
- House number
- Number of subscribers
- Cable length
- Actual download data rate
- VDSL2 data rate
- VDSL2-Vectoring data rate

This data allows geographical as well as statistical analysis.

The data acquisition for HFC with DOCSIS 3.0 was far more difficult. Although the network areas could be identified in every city (see Figure 9), the spatial locations for the fibre nodes and for the CMTS (cable modem termination system) could not be obtained.

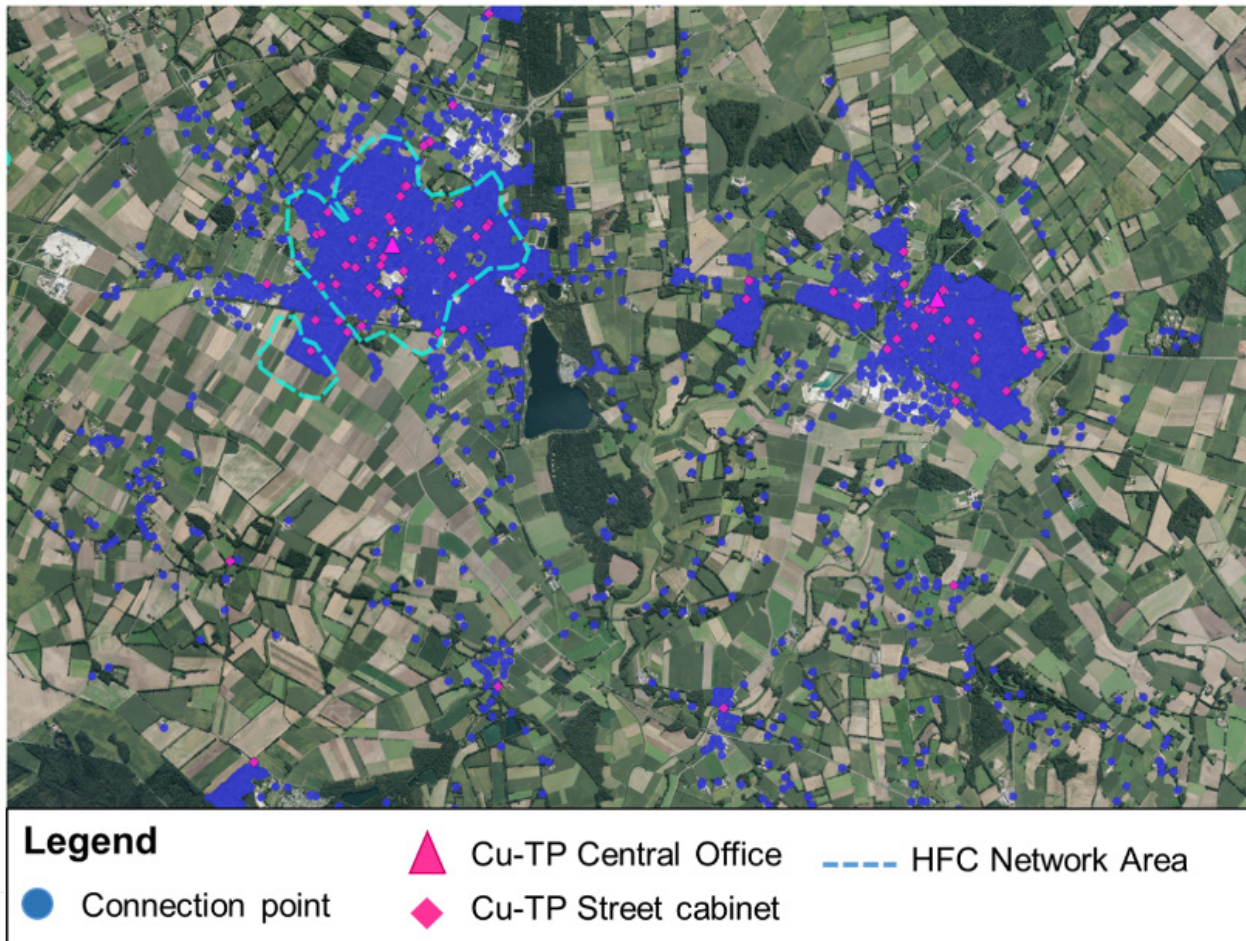


Figure 9: Example of the obtained information on HFC network areas.

Unlike the DSL access technology, HFC networks do not suffer from length restrictions. In this context, the spatial location of the fibre nodes and the CMTS becomes less important because the maximum cable length is smaller than the allowed one.

Far more important than the cable length is the service group size. It describes how many subscribers are fed from a single fibre node. All subscribers in a single service group share the available data rate so that the service group size determines the minimum data rate for each subscriber. Hence, a green field approach by varying the service group size is chosen.

Similar to the HFC networks, FTTH networks do not suffer from length restrictions. The FTTH – GPON technology has a characteristic which is similar to the HFC service group size: the splitting factor. The splitting factor also determines the minimum data rate for each subscriber. GPON is therefore also a shared medium.

Contrary to the HFC networks, a FTTH – Point-to-Point network is not a shared medium technology. Hence, there is no service group size or splitting factor. The limiting factor is however, how many cable lines can be structurally combined in a single Point of Presence.

Because of these characteristics, a green field approach with a maximum PoP size is chosen.

5 Access network modelling

5.1 DSL-Modelling

Like all DSL technologies, VDSL2-Vectoring has severe length restrictions. As Figure 10 shows, the usable data rate drops along the copper cable's length so that the minimum data rate of 50 Mbit/s can be delivered only over a few hundred metres. The telephone infrastructure, which is used by all DSL technologies, has by far longer cable lines. As a result, the demanded data rate is not available for every subscriber.

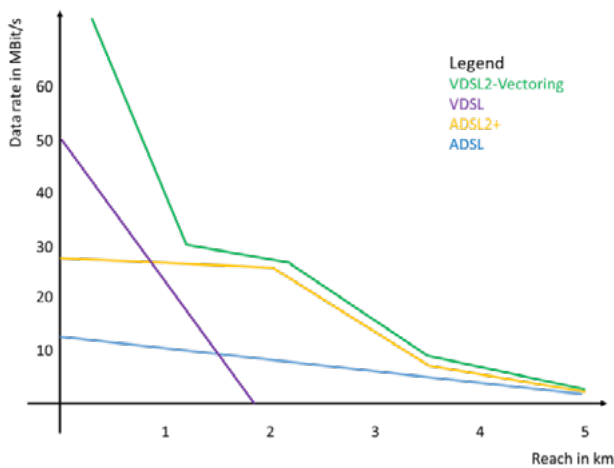


Figure 10: The graph shows the achievable data rate of the different DSL technologies respective to the reach in a simplified manner.

To provide the minimum data rate to all subscribers, the copper cable lines have to be shortened. This is done by installing new DSLAMs in the field close to the customers – typically in the existing street cabinets. In most rural areas however, installing new DSLAMs in the existing street cabinets is not enough to deliver the minimum data rate to all subscribers. Typically about 10% – 15% of the connections will not be reached. In order to provide the required data rate to the last 10% – 15% of the rural subscribers, new street cabinets with DSLAMs have to build.

All street cabinets, existing and new ones, with active DSLAM components need a power and fibre connection, which have to be built too.

To determine the power consumption of a VDSL2-Vectoring network, which is based on the existing telephone infrastructure and delivers the minimum data rate of 50 Mbit/s to every subscriber, the number of active network components has to be calculated. The calculation is carried out as follows:

1. Determine all subscribers who are provided directly from the central offices (number of central offices is known).
2. Determine all subscribers who can be supplied by installing DSLAMs into the existing street cabinets (number of existing street cabinets is known).
3. Determine new street cabinet locations which reach a maximum number of new subscribers within a certain radius until all remaining connections are assigned to a new street cabinet. (To determine the radius for the georeferenced analysis, over 235,000 data sets were statistically evaluated. A data set includes information about the actual cable length between a connection point and the street cabinet which it is assigned to, the linear distance between a connection point and its street cabinet and the achievable data rate with ADSL2+, VDSL2 and VDSL2-Vectoring).
4. Assign every street cabinet to a size class based on the number of subscribers.

After carrying out the steps one to four, the number and size of the active network elements for the VDSL2-Vectoring network in this specific region is known.

The next step is to assign power parameters to every network element so that the overall power consumption can be estimated.

5.2 HFC-Modelling

As already mentioned, HFC networks exist in the model region. The locations of the individual network's elements could not be obtained. However, this is not an obstacle. Unlike the DSL technologies, the HFC networks with DOCSIS 3.0 (864 MHz) do not suffer from length restrictions so that the exact spatial location of the individual network elements is of minor importance.

Therefore, a green field approach was chosen, based on the service group size. A service group is a group of subscribers that are fed by a single fibre node. This also means that all subscribers in a service group share the available transmission capacity – a HFC network is a shared medium.

Therefore, by varying the service group size, the exclusively usable data rate of each assigned subscriber is co-determined. At a service group size of 32 connections for example, 50 Mbit/s can be delivered to every subscriber exclusively. A larger service group size also allows to provide 50 Mbit/s, but it cannot be guaranteed for each subscriber at any given time

(shared medium). A smaller service group size on the other hand allows higher exclusive data rates for each subscriber.

As mentioned above, every service group is fed by a fibre node. Broadly speaking, a fibre node combines or separates the data signal and the TV/Radio signal and it is typically part of a bigger amplifier point which also contains coax line amplifiers (A, B, C lines) for the transmission on the coaxial infrastructure. Each fibre node is again assigned to a cable modem termination system (CMTS), which feeds the fibre nodes via a fibre optic cable, terminates the subscriber's modem connection and provides access to the core network.

Different service group sizes lead to different numbers of fibre nodes and CMTS. A typical service group consists of about 250 subscribers in active HFC networks in Germany today.

Due to the above-mentioned characteristics, the number of network elements can be estimated by linear calculation.

5.3 FTTH-Modelling

At the start of this project, there were no FTTH/B networks in the chosen model region. Hence, a green field approach is assumed in order to utilize the technological advantages of a FTTH network. Especially the large cable lengths of a multiple of ten kilometres allow high cable connection densities in a single point of presence (PoP). This will reduce the amount of properties and will help to further raise efficiency gains, like decreasing power losses due to inefficient power supplies for the active components.

In a FTTH network, each subscriber is connected to a specific point of presence (PoP). The subscriber's modem connection is terminated at the PoP and the access into the core network is provided. Between the subscriber and the PoP there are no active components. As a result, the number of the PoPs and their efficiency will be significant for the power consumption of the whole network. This applies both to Point-to-Point and to GPON networks.

Point-to-Point

In a Point-to-Point network, each subscriber is directly connected to a specific PoP. There are no active or passive network elements between the PoP and the subscriber, which separates or merges signals. According to information from different network operators, the PoP size varies significantly. There are small PoPs with only a few cable connections (<50) and very large PoPs with up to several thousand cable connections in use (the largest reported PoP size was around 4,000 cable connections).

Due to the obtained information on the PoP power consumption, the maximum PoP size in this model is limited to 1,000 subscribers. Furthermore, the PoP size is clustered into six classes:

1. 10,000 subscribers max.	4. 250 subscribers max.
2. 750 subscribers max.	5. 100 subscribers max.
3. 500 subscribers max.	6. 50 subscribers max.

Figure 11: Used PoP size classes for FTTH – Point-to-Point.



GPON

GPON has a different network structure than Point-to-Point networks. It is based on a passive distribution network with optical splitters. The downstream signal from the PoP is passively separated into several subscriber signals by the splitter. The upstream signal is generated by merging the individual subscriber upstream signals.

The location of the splitters can be very different. For example, they can be located somewhere in the field near to the subscriber, like the street cabinets in the copper twisted pair network, or they can be located directly at the PoP – a so called GPON over Point-to-Point structure. In this study the GPON over Point-to-Point structure is considered. This allows the same network structure as for the Point-to-Point network.

This leads to two PoP sizes of 512 subscribers per PoP and 1,024 subscribers per PoP.

To determine the number of PoPs, a georeferenced analysis of the individual municipalities is carried out. An attempt is made to keep the number of PoPs as low as possible. For this purpose, the respective municipal area is divided into quadrants so that the number of subscribers per PoP reaches as far as possible the maximum PoP size.

The assignment of the customers to the respective quadrants begins in the densely populated inner cities and is then extended to the outer districts.

6 Data analysis and interpretation

The number of active network elements for the three access technologies was determined as described in Chapter 6.

6.1 Customer premises equipment

In order to be able to calculate the power consumption of the access technologies, in addition to the information on the respective access network, data on the power consumption of the customer premises equipment is also required. For this, exemplary measurements were carried out for one router device per access technology. Furthermore, technical specifications and information from equipment manufacturers and network operators were combined to determine the average power consumption of the different devices.

On all devices, the power consumption was measured in different operation modes. In the first mode, an internet connection is established, the WLAN/WiFi

network is activated and all LAN-Ports are connected to active computers, but no data is transmitted via one of the interfaces. In the second mode, only an internet connection is established. The other interfaces are switched off. An internet connection and a WLAN/WiFi network is established in the third mode. The fourth mode establishes an internet connection and LAN connections.

After these measurements each device is set to mode one and then data is transmitted first via LAN connections and then via WLAN/WiFi connections. The measured figures are shown in Figure 12 and Figure 13.

	AVM Fritzbox 7490	AVM Fritzbox 5490 Fibre
Internet connection + LAN-connections + WLAN-connection	9 W	11 W
Internet connection No LAN; No WLAN	6 W	9 W
Internet connection No LAN; + WLAN	7 W	9 W
Internet connection + LAN; No WLAN	9 W	9 W
Data transmission over LAN	9 W	11 W
Data transmission over WLAN	11 W	11 W

Figure 12: Measured figures on the power consumption of different router models in various modes of operation.

As shown in Figure 12, the power consumption of the AVM Fritzbox 7490 is, in an operational mode, somewhere between 9 watt and 11 watt. Combined with further information from technical specifications of other VDSL routers the average power consumption of VDSL2-Vectoring routers is set to 10 watt per device. As shown in Figure 13, the power consumption of the

	Technicolor TC7.200U	MikroTik Router Board RB 951G – Router without modem
Internet connection + LAN-connections + WLAN-connection	12.0 W	3.2 W
Internet connection No LAN; No WLAN	11.4 W	3.0 W
Internet connection No LAN; + WLAN	11.4 W	3.0 W
Internet connection + LAN; No WLAN	12.0 W	3.2 W
Data transmission over LAN	13 W	3.7 W
Data transmission over WLAN	13 W	4.0 W

Figure 13: Measured figures on the power consumption of different router models in various modes of operation. The MikroTik router is a router without a modem, e.g. for use behind a fibre ONT.

Technicolor TC7200 cable modem router is, in an operational mode, somewhere between 11.4 watt and 13 watt. Combined with further information from technical specifications and manufacturers cable modem routers the average power consumption of cable modem routers is set to 13 watt per device.

6.2 VDSL2-Vectoring

6.2.1 Access network

The model region consists of 25,311 subscribers and 212 street cabinets (see Figure 14), which are assigned to six central offices. By updating all 212 existing street cabinets and central offices with VDSL2-Vectoring DSLAMs, the minimum data rate of 50 Mbit/s can be

provided to 21,403 subscribers. On the other hand, at 3,908 subscribers the minimum data rate of 50 Mbit/s will not be reached. That corresponds to approximately 15% of total subscribers.

	Results for the model region in total (100% homes connected)	Number of connection points	Avg. number of connection points per street cabinet	Number of subscribers	Avg. number of subscribers per street cabinet
Street cabinets existing	212	14,096	66	21,403	101
Street cabinets new	326	2,659	8	3,908	12
Street cabinets total	538	16,755	31	25,311	47

Figure 14: Table of subscribers and connection points per street cabinet – existing and new ones.

One of the main reasons that these 3,908 connections cannot be supplied is that the cable lines between the street cabinet and the connection point are too long. To solve this problem, new street cabinets closer to the subscriber have to be built.

To estimate the number of additional street cabinets, new locations for the additional street cabinets were determined by georeferential analysis, which generates a maximum of subscribers per street cabinet within a certain radius. This analysis leads to 326 additional street cabinets. The average number of subscribers per street cabinet drops from 101 to only 12.

As a result, the financial and technical expenses per subscriber increase significantly.

This is illustrated again in Figure 15. In this figure, all street cabinets of the model region are assigned to a DSLAM size class, which reflects the maximum number of subscribers per DSLAM. 361 of the 538 street cabinets (approximately 67%) use a DSLAM with 48 ports. The average number of subscribers in this DSLAM size class is approximately 12 and significantly smaller than the possible 48 subscribers. That is not very efficient. In the higher DSLAM size classes the average number of subscribers per street cabinet is much closer to the maximum per DSLAM than in the 48 port class.

Subscribers per DSLAM by DSLAM size (100% homes connected)				
Max ports per DSLAM	Number of street cabinets	Number of connection points	Number of subscribers	Avg. number of subscribers per street cabinet
48	361	3,031	4,368	12
96	68	3,376	4,996	73
144	61	4,961	7,320	120
192	36	3,789	5,977	166
>192	12	1,598	2,650	221
Total	538	16,755	25,311	47

Figure 15: DSLAM size classes and numbers of assigned subscribers per DSLAM street cabinet.

Overall, Figure 15 shows the challenges of a rural VDSL2-Vectoring expansion – long cable lines and only few customers in a given area.

Power consumption access network (100% of homes connected)				
Street cabinet				Central office
Max. ports	VDSL2-Vectoring per street cabinet [W]	Number of street cabinets	Total VDSL2-Vectoring per street cabinet [W]	Central office per subscriber
48	195	361	70,395	0.96
96	268	68	18,224	
144	277	61	16,897	
192	254	36	9,144	
>192	291	12	3,492	
Total		538	118,152	24,299
Total power consumption VDSL2-Vectoring [W]				142,451
Total power consumption VDSL2-Vectoring [kW]				142

Figure 16: Key figures of the power consumption of street cabinets by DSLAM size.

After estimating the number of network elements, key figures for the power consumption for each DSLAM size have to be provided. This is shown in Figure 16. The used key figures were provided by different network operators and are measured values, experience values and manufacturer specifications. Firstly, it becomes clear that electrical efficiency increases with an increasing number of ports per DSLAM.

Together with the DSLAM assignment in the classes in Figure 15, a chaining of inefficiencies of a rural VDSL2-Vectoring development is shown. Not only does a large number of small DSLAM sites have to be built for very few subscribers. In addition, these small DSLAMs are

even more significantly electrically inefficient compared to the larger DSLAMs.

Beside the DSLAM itself, the connection into the core network has to be considered too. According to the final report on the development of ICT-related electricity demand in Germany¹, the access to the core network requires approximately 0.96 watts per subscriber. In total, the VDSL2-Vectoring access network has a power consumption of 142 kW in this model region – this corresponds to CO₂ emissions of approximately 482 tonnes².

6.2.2 Customer premises equipment

So that a user can actually use the access network, additional components such as modems and routers are required. This so-called customer premises equipment (CPE) also requires a power supply. The power supply is provided by the respective subscriber and is not charged to the network operator however, the power consumption for the CPE has to be included in the overall consideration, as without the CPE the subscriber into the network can establish no connection.

Today most network operators use a combined modem router unit. According to technical specifications of

different manufacturers, like AVM Fritzbox 7490 or the LANCOM 1781VA-4G, and the final report on the development of ICT-related electricity demand in Germany, the power consumption of a typical VDSL2-Vectoring CPE is about 10 watt (see also Chapter 7.1). With 25,311 subscribers and a single CPE power consumption of 10 watts, this leads to a total output of approximately 253 kW for the entire customer premises equipment in the model region.

$$25,311 \text{ CPE} \times 10 \frac{\text{kW}}{\text{CPE}} = 253 \text{ kW}$$

¹ Entwicklung des IKT-bedingten Strombedarfs in Deutschland – Abschlussbericht; Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie; Dr. Lutz Stobbe, Marina Proske, Hannes Zedel (Fraunhofer IZM), Dr. Ralph Hintemann, Dr. Jens Clausen, Dr. Severin Beucker (Borderstep); Berlin 2015

² Strom- und Wärmeversorgung in Zahlen; Bundesumweltamt; <http://www.umweltbundesamt.de/themen/klima-energie/energieversorgung/strom-waermeversorgung-in-zahlen#Strommix>; last access: 01. August 2017

6.2.3 Total power consumption VDSL2-Vectoring

Power consumption access network and customer premises equipment (CPE) (100% of homes connected)					
Street cabinet				Central office	CPE VDSL2
Max ports	VDSL2-Vectoring per street cabinet [W]	Number of street cabinets	Total VDSL2- Vectoring per street cabinet [W]	Central office per subscriber [W]	VDSL2 Vectoring per CPE [W]
48	195	361	70,395	0,96	10
96	268	68	18,224		
144	277	61	16,897		
192	254	36	9,144		
>192	291	12	3,492		
Total		538	118,152	24,299	253,110
Total power consumption VDSL2-Vectoring [W]					395,561
Total power consumption VDSL2-Vectoring [kW]					396

Figure 17: Total power consumption of the VDSL2-Vectoring access network and the CPE in the model region.

A power consumption of 396 kW corresponds to 3,465,114 kWh per year. The production of a single kilowatt-hour in Germany creates 534 grams CO₂³.

This leads to CO₂ pollution of approximately 1,850 tonnes per year.

6.3 HFC

6.3.1 Access network

As described in chapter 6, the number of fibre nodes and the CMTS must be determined for HFC networks to estimate the power consumption of the access

network. The numbers of fibre nodes and CMTS are derived directly from the service group size used.

Model region	Number of connections	Service group size						
		16	32	64	128	256	512	
A	2,884	181	91	46	23	12	6	Number of service groups
B	5,181	324	162	81	41	21	11	
C	6,160	385	193	97	49	25	13	
D	4,282	268	134	67	34	17	9	
E	3,209	201	101	51	26	13	7	
F	3,595	225	113	57	29	15	8	
Total	25,311	1,582	791	396	198	99	50	

Figure 18: Number of fibre nodes depending on the service group size.

Figure 18 shows how many fibre nodes would be needed in the individual cities and in total to provide

connections to all 25,311 possible subscribers by using different service group sizes.

³Strom- und Wärmeversorgung in Zahlen; Bundesumweltamt; <http://www.umweltbundesamt.de/themen/klima-energie/energieversorgung/strom-waermeversorgung-in-zahlen#Strommix>; last access: 01. August 2017

		Service group size						Number of service groups
		16	32	64	128	256	512	
Amplifier point with fibre node		1,584	794	399	202	103	54	
Power consumption 75% of AP [W]	45	89,100	44,640	22,410	11,340	5,760	3,015	Power consumption amplifier points [W]
Power consumption 25% of AP [W]	90							

Figure 19: Power consumption of amplifier points in a 25/75 % distribution at different service group sizes.

A fibre node within an amplifier point feeds each service group. A typical amplifier point has a maximum power consumption of approximately 90 watts and an average power consumption of approximately 45 watts. However, not every amplifier point is equipped to the maximum. A typical distribution of amplifier points in existing HFC networks is approximately 75% with an average configuration (45 watt) and approx. 25% of a maximum configuration (90 watt) (see Figure 19) – according to different equipment manufacturers.

Based on this distribution, the power consumption of the amplifier points in the different service group sizes is between approximately 3,000 watts and approximately 89,000 watts. A typical service group size today is 256 subscribers per service group, which corresponds to a power consumption of 5,760 watts. However, a data rate of 50 Mbit/s for each subscriber at all times can only be realized by a service group size of 32 subscribers or less.

		Service group size						Number of service groups
		16	32	64	128	256	512	
CMTS		1,584	794	399	202	103	54	
Max. number of service groups per CMTS chassis	72	22	12	6	3	2	1	Number of CMTS chassis
Power consumption central office per CMTS [W]	5,760	126,720	69,120	34,560	17,280	11,520	5,760	Power consumption CMTS chassis [W]

Figure 20: Number of CMTS chassis and the resulting power consumption including air conditioning etc. at the central office.

As mentioned above, every fibre node is connected to a CMTS – Cable Modem Termination System. According to information from HFC equipment manufacturers, approximately 72 fibre nodes/service groups can be connected to a typical CMTS. Based on the service group size, the number of CMTS chassis needed varies between one and 22. A typical CMTS chassis has

maximum power consumption of approximately 5,760 watts, including additional air conditioning etc. at the central office. This leads to a total power consumption the central office between 5,750 watts and 126 kW – depending on service group size.

	Service group size					
	16	32	64	128	256	512
Number of service groups	1,584	794	399	202	103	54
Power consumption amplifier points [W]	89,100	44,640	22,410	11,340	5,760	3,015
Power consumption central offices [W]	126,720	69,120	34,560	17,280	11,520	5,760
Total power consumption access network [W]	215,820	113,760	59,970	28,620	17,280	8,775

Figure 21: Total power consumption of the HFC access network – amplifier points and central office.

The overall power consumption of the HFC access network is therefore based on the power consumption of the amplifier points as well as the central office.

Depending on the service group size, the total power consumption is between 8,775 watts and approximately 216 kilowatts (see Figure 21).

6.3.2 Customer premises equipment

In order to establish a connection between a user and the internet, additional equipment is needed. Nearly every user needs a house amplifier to ensure the necessary signal level. The house amplifier is installed between the connection point (the passive network termination of the access network) and the modem. According to equipment manufacturers, the average power consumption of deployed house amplifiers is approximately 5 watts per device (see Figure 22).

Beside the house amplifier, the user needs a modem to establish a connection into the internet. Today, combined modem-router devices, like the AVM Fritzbox 6590 Cable, are used. Currently used devices have an average power consumption of approximately 13 watts (see Figure 22).

Number of subscribers		25,311		
House amplifier	Power consumption/house amplifier [W]	5	126,555	Total power consumption house amplifiers [W]
Modem & router	Power consumption/modem & router device [W]	2,659	329,043	Total power consumption modem & router devices [W]
			455,598	Total power consumption of customer premises [W]

Figure 22: Power consumption of the customer premises equipment.

As Figure 22 shows, the total power consumption of the customer premises equipment for all 25,311 subscribers is approximately 455.6 kW.

6.3.3 Total power consumption HFC

The total power consumption of the HFC access network and the customer premises equipment is

shown in Figure 23. Depending on the service group size, the power consumption is between 464 kW and 671 kW.

	Service group size					
	16	32	64	128	256	512
Number of service groups	1,584	794	399	202	103	54
Power consumption amplifier points [W]	89,100	44,640	22,410	11,340	5,760	3,015
Power consumption central offices [W]	126,720	69,120	34,560	17,280	11,520	5,760
Total consumption of customer premises equipment [W]	455,598					
Total power consumption HFC network [W]	671,418	569,358	512,568	484,218	472,878	464,373

Figure 23: Total power consumption of the HFC access network and the customer premises equipment.

A typical current service group size is around 256 subscribers per service group. The ISP (Internet Service Provider) can provide the required 50 Mbit/s with DOCSIS 3.0 at a service group size of 256; even higher data rates are possible. However, the HFC access network is a shared medium, so all subscribers within the same service group share the available transmission capacity. If the data rate of 50 Mbit/s is to be a minimum data rate per subscriber, a service

group size of 32 or fewer subscribers is needed. Otherwise, the 50 Mbit/s cannot be guaranteed to each subscriber.

A service group size of 32 leads to a total power consumption for the HFC network of 569 kW or 4,987,576 kWh per year, which is approximately 2,663 tonnes of CO₂.

6.4 FTTH – Point-to-Point and GPON

As described in chapter 6, there were no active FTTH networks within the model region. Therefore, a green field approach was chosen. In addition, the FTTH

technologies do not suffer from relevant length restrictions so that even long cable lines of several kilometres will be no restriction.

6.4.1 Point-to-Point access network

To determine the power consumption of the access network, the number of PoPs to connect each subscriber has to be estimated. This calculation is a spatial analysis, which tries to maximise the number of subscribers per PoP. This calculation leads to the numbers shown in Figure 24. As can be seen there,

36 PoPs are needed in total. 21 of the 36 are PoPs of the maximum size. The other 15 PoPs are smaller ones.

Therefore, approximately 82% of the subscribers can be reached from the biggest PoPs. An additional 10% of the subscribers are reached with PoPs of the size of 500 and 750 subscribers per PoP.

PoP size	Number of PoPs	Number of subscribers
1,000	21	20,856
750	2	1,438
500	3	1,207
250	7	1,556
100	3	254
50	0	0
Total	36	25,311

Figure 24: Number of PoPs in the model region, calculation based on their spatial location.

The different PoP sizes are therefore important, since the energy efficiency increases with the subscriber

density per PoP. In other words, the power consumption per subscriber decreases with increasing subscribers per PoP. As the table in Figure 25 shows, the power consumption per subscriber with 10 watts is more than four times higher in a small 50 subscriber PoP than with 2.3 watts in a 1,000 subscriber PoP. This is especially a result of secondary systems like the air conditioning or the power supply. These systems operate much more efficiently at higher subscriber densities. The power consumption for the optical transmission in all PoP sizes is around 1.5 watt. The data on the power consumption for the different PoP sizes are measured consumption figures of operating FTTH networks from different network operators. In total, the power consumption for the 36 PoPs in the model region is about 64.4 kW. This corresponds to CO₂ emissions of approximately 301 tonnes.

Power consumption access network				
PoP size	Power consumption (incl. air conditioning) per subscriber [W]	Number of PoPs	Number of subscribers	Total power consumption P [W]
1,000	2.30	21	20,856	47,969
750	2.60	2	1,438	3,739
500	3.20	3	1,207	3,862
250	4.50	7	1,556	7,002
100	7.20	3	254	1,829
50	10.00	0	0	0
Total		36	25,311	64,401

Figure 25: Power consumption of the FTTH – Point-to-Point access network.

6.4.2 GPON access network

GPON has a different network structure than Point-to-Point networks. It is based on a passive distribution network with optical splitters. The downstream signal from the PoP is passively separated into several subscriber signals by the splitter. The upstream signal is generated by merging the individual subscriber upstream signals.

The location of the splitters can be very different. For example, they can be located somewhere in the field close to the subscriber, like the street cabinets in the copper twisted pair network or they can be located directly at the PoP – a so-called GPON over Point-to-Point structure. In this study, the GPON over Point-to-Point is considered. This allows the same network structure to be assumed as in the previous chapter.

The use of splitters allows a very high density of subscribers in a PoP. Today splitting factors of 1:128 are possible. This means that 128 subscribers can be

connected to a single GPON-port. However, with GPON the subscribers at a single splitter have to share the maximum transmission capacity of the GPON-port – today approximately 2.5 GBit/s downstream and 1.25 GBit/s upstream. To realise the minimum data rate of 50 Mbit/s per subscriber a splitting factor of 1:32 or less is needed. Typically, the PoPs (OLT) are modular today and have GPON modules with approximately 16 GPON ports per module. It follows that the 36 PoPs determined (see Point-to-Point) can be mapped into two PoP size classes (512 subscribers and 1,024 subscribers), see Figure 26. In that configuration the power consumption for the access network is approximately 18.6 kW, according to information of equipment manufacturers. This corresponds to annual CO₂ emissions of 87 tonnes. It has to be considered that the minimum data rate per subscriber in this configuration is approximately 78 Mbit/s downlink and 39 Mbit/s uplink.

Power consumption access network				
PoP size	Power consumption (incl. air conditioning) per subscriber [W]	Number of PoPs	Number of subscribers	Total power consumption P [W]
1,024	0.68	23	22,294	15,160
512	1.15	13	3,017	3,470
Total		36	25,311	18,629

Figure 26: Power consumption of the GPON access network.

The energy efficiency of GPON is a multi-dimensional optimisation problem. The more GPON-ports are required, the higher the overall power consumption. However, the power consumption per GPON-port typically drops due to efficiency gains in highly densified PoP configurations. A high splitting factor – number of subscribers per GPON-port – reduces the power consumption per subscriber. Nevertheless, the minimum data rate per subscriber is reduced also.

The overall power consumption (including cooling, switching etc.) of a GPON-port is, according to manufacturers' information, between approximately 11 watts and 35 watts. An optimised GPON-PoP with a power consumption of 11 watts per GPON-port and a splitting factor of 1:5 (theoretically) has the same power consumption per subscriber as the Point-to-Point technology. The minimum data rate per subscriber however is only 500 Mbit/s in downstream and 250 Mbit/s in upstream.

6.4.3 Customer premises equipment

Like the previous technologies, the FTTH technologies require customer premises equipment to establish a connection to the internet. This equipment must implement three process steps:

1. Convert the optical signal into an electrical signal
2. Establish a connection
3. Provide the connection to the user's devices

An implementation of all three steps in a single device would be ideal. However, the steps one and two are typically realized in a separated device, the so-called optical network termination (ONT). Connected to the ONT is a standard router device, often a DSL or cable device like an AVM Fritzbox 7490. The integrated modem is not necessary but needs a minimum power supply.

Power consumption CPE			
Subscribers	Power consumption per ONT [W]	Power consumption per router [W]	Total power consumption CPE P [W]
25,311	3.5	10	341,699

Figure 27: Power consumption of the customer premises equipment.

As the Figure 27 shows, the ONT requires approximately 3.5 watts⁴. A difference between GPON and Point-to-Point devices could not be observed. The router, because it is a standard device such as for VDSL connections, requires approximately 10 watts.

This means that approximately 13.5 watts are needed for a single set of customer premises equipment. For the model region, this results in a total power consumption of 341,669 watts.

⁴ Measured figures.

An integrated and optimised Router-ONT-Device would help to reduce the power consumption for the customer premises equipment. The AVM Fritzbox 5490 for example has an average power consumption of approximately 11 watts.

To use router devices without a modem would reduce the power consumption. A MikroTik Router Board

RB 951G for example has a power consumption between 3.2 watts and 4.2 watts.

The power consumption for the customer premises equipment can easily be reduced by using different devices.

6.4.4 Total power consumption FTTH – Point-to-Point

Power consumption access network					Power consumption CPE		
PoP size	Power consumption (incl. air conditioning) per subscriber [W]	Number of PoPs	Number of subscribers	Total power consumption access network P [W]	Power consumption per ONT P [W]	Power consumption per router P [W]	Total power consumption CPE P [W]
1,000	2.30	21	20,856	47,969	3.5	10	341,699
750	2.60	2	1,438	3,739			
500	3.20	3	1,207	3,862			
250	4.50	7	1,556	7,002			
100	7.20	3	254	1,829			
50	10.00	–	–	–			
Total		36	25,311	64,401	341,699		
Total power consumption access network + CPE P [W]							406,099

Figure 28: Total power consumption of the FTTH – Point-to-Point network in the model region.

The overall power consumption for an FTTH – Point-to-Point network in the model region is shown in Figure 28. As can be seen, the largest share of the total power consumption is generated by the customer premises

equipment – approximately 84%. In total approximately 406 kW are needed to operate the network. This leads to annual CO₂ emissions of 1,899 tonnes.

6.4.5 Total power consumption FTTH – GPON

Power consumption access network					Power consumption CPE		
PoP size	Power consumption (incl. air conditioning) per subscriber [W]	Number of PoPs	Number of subscribers	Total power consumption access network P [W]	Power consumption per ONT P [W]	Power consumption per router P [W]	Total power consumption CPE P [W]
1,024	0.68	23	22,294	15,160	3.5	10	341,699
512	1.15	13	3,017	3,470			
Total		36	25,311	18,629	341,699		
Total power consumption access network + CPE P [W]							360,328

Figure 29: Total power consumption of the FTTH – GPON network in the model region.

The overall power consumption for an FTTH – GPON network in the model region is shown in Figure 29. As can be seen, the largest share of the total power consumption is generated by the customer premises

equipment – approximately 95%. In total approximately 360 kW are needed to operate the network. This leads to annual CO₂ emissions of 1,685 tonnes.

7 Consolidation and conclusion

This survey compares the power consumption of four broadband access technologies based on a 100% of homes connected rollout within an existing model region. The model region consists of six municipalities with a population of 56,700 and 25,311 possible subscribers.

The access technologies are:

- VDSL2-Vectoring
- HFC with DOCSIS 3.0
- FTTH – Point-to-Point
- FTTH – GPON

The energy consumption was estimated by identifying the needed active components. Therefore, a spatial analysis of the model region and the obtained information on existing infrastructure was conducted, which led to the respective number of active components for each access technology.

The figures on the power consumption of the different active components are measured figures from network operators and information from different equipment manufacturers.

As Figure 30 shows, the access technologies differ considerably in the number of required active network elements and locations. The HFC network with its 794 fibre nodes and 12 CMTS needs the most active network elements. Followed by VDSL2 Vectoring with 538 active street cabinets (DSLAMs) and six central offices. FTTH has with its 36 PoPs by far the lowest amount of active network elements in different locations.

This is also reflected in the power consumption of the access networks. The power consumption of the HFC and VDSL2 Vectoring access networks is 1.8 to 2.2 times the power of the FTTH – Point-to-Point and up to approximately 7.5 times more than the FTTH – GPON access network. Expressed in figures, the HFC access network requires 114 kW, the VDSL2 Vectoring access network 142 kW, the FTTH – Point-to-Point access network 64 kW and the FTTH – GPON access network 19 kW.

	VDSL2-Vectoring	HFC	FTTH – PtP	FTTH – GPON
Active network elements in the access network	538 street cabinets + 6 central offices	794 fibre nodes + 12 CMTS	36 PoPs	36 PoPs
Power consumption access network [kW]	142	114	64	19
Power consumption CPE [kW]	253	456	341	341
Total power consumption [kW]	396	569	406	360
Total energy consumption [MWh/year]	3,465	4,987	3,557	3,156

Figure 30: Comparison of the number of active network elements and the power consumption of the examined access technologies.

For the customer premises equipment it is somewhat different. Here the HFC network is placed last with 456 kW, the FTTH networks second with 341 kW and the VDSL2 Vectoring network is first with 253 kW. This is because an additional user device (house amplifier or ONT) is used for the HFC and the FTTH networks. Especially for the FTTH networks, the energy consumption could be reduced by optimizing the customer premises equipment.

Therefore, the total power consumption of access network and customer premises equipment differs not much between the VDSL2 Vectoring and the FTTH – Point-to-Point network – 396 kW for VDSL2 Vectoring and 406 kW for FTTH – Point-to-Point. The lowest power consumption has the FTTH – GPON network with 360 kW. The HFC network on the other hand has a by far bigger power consumption – 569 kW.

	VDSL2-Vectoring	HFC	FTTH – PtP	FTTH – GPON
Total energy consumption [MWh/year]	3,465	4,987	3,557	3,156
kWh/year per person	61	88	63	56
Compared to 4-person household [4,200 kWh/year]	6%	8%	6%	5%
CO ₂ Emission [töns/year]	1,850	2,663	1,899	1,685

Figure 31: Annual energy consumption and CO₂ emission.

The annual energy consumption can be derived from the determined power consumption, see Figure 31. If the energy consumption is normalised to the population of the model region, the per capita demand is between 56 kWh und 88 kWh per year. An average German 4-person household has an annual energy consumption of 4,200 kWh, according to the Federal Statistical Office. The energy consumption to operate one of these access networks is equal to 5% to 8% of the energy consumption of a 4-person household.

The CO₂ emissions are between 1,685 and 2,663 tons per year.

Based on these figures, the FTTH – GPON network has the most efficient access network.

The customer premises equipment of the VDSL2 Vectoring network is the most energy efficient. However, the energy efficiency of the customer premises equipment of the FTTH networks can be improved significantly.

So far, the access technologies were compared under the premise of a minimum data rate of 50 Mbit/s per subscriber. This does not take the individual performance and development capabilities of the

different technologies into account. Normalising the energy consumption to the maximum transmission volume per year can show the capabilities and the energetic performance of the different access technologies.

As shown in Figure 32, VDSL2 Vectoring, HFC and FTTH – GPON provide asymmetrical data rates for the upstream and downstream (currently offered data rates in Germany). It can also be seen that the usable data rates of VDSL2 Vectoring and HFC are significantly smaller than the data rates of FTTH technologies. That leads to a much bigger annual transmission volume of the FTTH technologies.

By normalising the respective subscriber's annual transmission volume to the specific energy consumption of each access technology, the energetic performance (annual traffic volume per 1 kWh) becomes clear. As can be seen in Figure 32 the energetic performance of the FTTH technologies is by far higher than of the other two. It is with 56 Tbyte/kWh and 47 Tbyte/kWh over 10 times as high as for VDSL2-Vectoring.

	VDSL2-Vectoring	HFC	FTTH – PtP	FTTH – GPON
Downstream data rate [Mbit/s]	100	400	1,000	1,000
Upstream data rate [Mbit/s]	40	10	1,000	500
Annual downstream volume per subscriber [Tbyte/year]	394	1,577	3,942	3,942
Annual upstream volume per subscriber [Tbyte/year]	158	39	3,942	1,971
Maximum annual traffic volume for all subscriber down + up stream [Zbyte/year]	14	41	200	150
Annual subscribers traffic volume per kWh	4 Tbyte	8 Tbyte	47 Tbyte	56 Tbyte

Figure 32: Comparison of the energy consumption normalized to the maximal annual transmission volume.

Performance related energy efficiency or energetic performance is a key figure to compare different access technologies. Nevertheless, another important figure is the number of active network elements and locations.

DSL technologies are based on the copper twisted pair telephone network. The telephone network, however, was designed to transmit audio communication signals and not high frequency data. One of the main implications is the considerable length limitations of DSL technologies – higher data rates need shorter cable length. An improvement in data rate can only be achieved by reducing the cable length. Therefore, new active network elements, so called Outdoor DSLAMs, have to be built close to the subscribers. This has to be repeated until the new infrastructure has reached the subscriber directly. This increases the number of active network elements significantly and is shown in Figure 33. Another aspect of future DSL technologies, like G.fast, is reverse powering of access network elements. In this case, the last network element, e.g. in the sidewalk, has to be supplied by the subscribers with electricity. Currently, it is still unclear who will bear the cost of reverse powering – the subscribers or the network operators.

The HFC is based on the coax television network. This network was designed for the transmission of high-frequency video signals over long distances. An implementation of data transmission was, therefore, initially unproblematic – even over longer distances.

The overall transmission capacity could also be increased by adapting the DOCSIS standards. However, it should be noted that HFC is a shared medium, in which all customers within one service group share the available total transmission capacity. At a certain point, the subscriber's data rate can only be increased by decreasing the service group size, so that fewer subscribers have to share the total transmission capacity. Because an active fibre node feeds every service group, increasing the subscriber's data rate also increases the number of active elements – see Figure 33.

FTTH technologies are based on passive distribution networks between a central office/PoP and the subscriber. That means that no active network elements are needed in the distribution network for signal transmission. Increased data rates are achieved by developing the transmission standards and exchange of the active PoP components and customer premises equipment. With GPON, a reduction in the splitting ratio may be necessary in special cases. This will require additional splitters in the distribution network, but these are also passive and do not require any power supply. However, if the splitting ratio is reduced, further GPON ports are required in the PoP but the number of active network elements is not modified during the capacity increase in FTTH networks Figure 33.

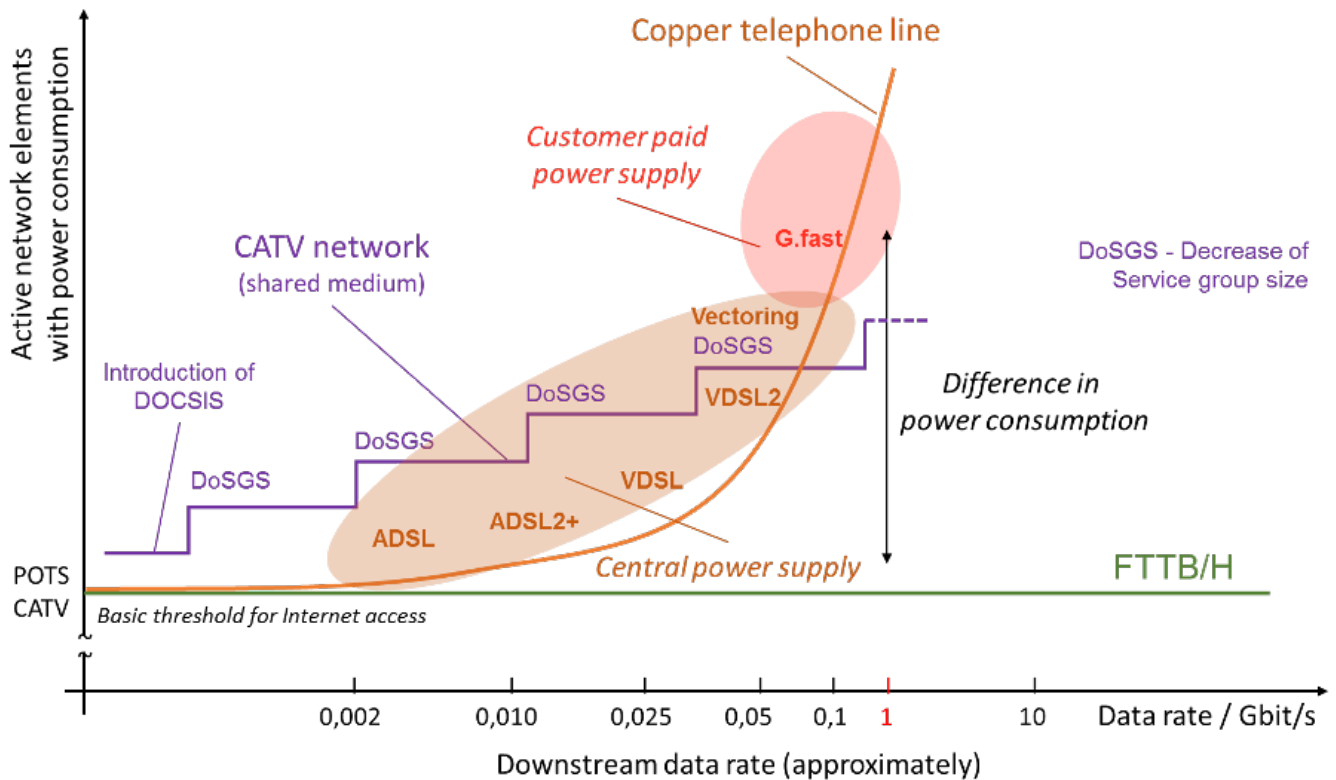


Figure 33: Number of active network elements based on the achievable data rate.

All access technologies require a minimum number of network elements to realise internet access for the subscriber (basic threshold). However, the number of active network elements and network structure develops very differently when the data rate is increased.

Figure 33 is used to illustrate the development of the active network elements in relation to the data rate for the respective technologies. It becomes clear that the copper-based technologies, xDSL and HFC, have a significant increase in active network elements. This increase only ends when each customer is directly connected via fibre (FTTH/B). FTTB/H technologies

on the other hand will not need additional active networks elements because of the physical advantages of the fibre optic distribution network. It is designed for high-frequency signal transmission and has no significant length restrictions with regard to access networks.

The FTTH technologies are the only ones that do not need to adapt their network structure in the medium to long term in order to be able to map future developments with regard to the data rate.

The only prerequisite is that the FTTH networks are optimally planned and built on the basis of their technological characteristics.

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