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# Working Paper

No. 10

## Sustainability:
## Modern Fixed and Mobile Networks Compared Across Different Regional Structures

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## IMPRINT

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## Management Summary

This study analyses and quantifies the energy consumption and $CO_2$ emissions associated with operating modern telecommunications access networks, both fixed broadband (FFTH) and mobile networks (4G/5G). To quantify the environmental impacts, specific bottom-up models for the fixed and mobile access network are developed and used to endogenously determine the asset-related quantities of active network elements and their respective energy consumption. The modelling task is carried out for Germany based on household and population data at municipality level from the *German Federal Institute for Research on Building and Regional Planning* (BBSR), energy consumption data from the *EU Code of Conduct on Energy Consumption of Broadband Communication Equipment* and the $CO_2$ emission factor for the electricity mix from the *German Federal Environment Agency*, in order to capture the demand for VHCN fixed and mobile access services.

Furthermore, the study investigates how different settlement structures shape the environmental footprint of telecommunications networks. Based on these findings, it is analysed whether the use of mobile networks represents a sustainable strategy for the supply of rural areas in comparison to fixed network technologies. From an environmental perspective, mobile networks, especially 5G, are considered as a possible substitute for the provision of broadband access in rural areas. The analysis shows that, from an environmental perspective, FTTH access networks perform better than mobile access networks. These findings hold for any regional structure but are even more significant for rural areas.

The analysis focuses on energy consumption and $CO_2$ emissions of network operations. Deployment-related emissions and spill-over effects induced by using ICT for eco-benefits in other sectors are beyond the scope of this analysis.

# 1 Background and focus of the study

## 1.1 Background

The telecommunications sector is recognised as a critical enabler of the green economy, enabling the digital transformation and herewith enhances sustainability across various industries. Digitalisation contributes to the efficiency of sectors such as transport, energy, and manufacturing by enabling smart grids, smart cities, and the resource optimisation. However, despite its role in promoting a green economy, the telecommunications sector is itself a significant consumer of energy and a source of $CO_2$ emissions. Due to the energy-intensive nature of electronic communications networks they noticeably contribute to global greenhouse gas emissions. According to the World Bank Group and the International Telecommunication Union (ITU), the ICT sector accounts for approximately 1,5% to 4% of global $CO_2$ emissions, with connectivity networks, data centres and consumer devices being the main contributors.[1] Growing demand for digital services, such as cloud computing and 5G, is expected to further increase energy consumption, and thus the sector's carbon footprint.

The European Union (EU) has adopted the European Green Deal and EU Taxonomy for Sustainable Activities to address the challenges of climate change and promote sustainability across all sectors, including telecommunications. Launched in 2019, the European Green Deal sets a long-term goal of achieving net-zero greenhouse gas emissions by 2050. It includes a range of policies aimed at reducing emissions by at least 55% by 2030, compared to 1990 levels.[2] The Green Deal acknowledges the sector's energy consumption and $CO_2$ emissions and calls for measures to ensure that digitalization contributes to, rather than hinders, environmental sustainability. This includes reducing emissions from network infrastructure, improving energy efficiency, and transition to renewable energy sources.

The EU Taxonomy, a classification system established in 2020, provides a framework for determining which economic activities can be considered environmentally sustainable. It aims to guide investors towards activities that contribute to environmental sustainability. While data processing, hosting, and related activities from data centres are listed activities, telecommunications, in terms of network infrastructure and services, is not yet included in the scope of the taxonomy.[3],[4]

A significant challenge in the context of telecommunications development is the roll-out of fibre-optic networks in rural areas. While fibre-to-the-home (FTTH) technology is seen as an efficient and sustainable solution for broadband connectivity, the expansion of fibre infrastructure in less densely populated regions is economically challenging due to low population density and thus high installation costs per user. The deployment of fibre in rural areas often requires substantial investment in infrastructure, predominantly driven by trenching and laying cables. To enhance the fibre rollout in rural areas, the Federal Network Agency (*Bundesnetzagentur*) and other governmental bodies in Germany have introduced various strategies, such as state aid, public-private partnerships, and regulatory incentives.

In parallel, there is an ongoing debate about whether mobile networks, particularly 5G, could serve as a viable alternative to fixed broadband in rural areas. Mobile technologies offer flexible solutions for

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1 Ayers et al. (2024). Measuring the Emissions and Energy Footprint of the ICT Sector: Implications for Climate Action. Washington, D.C. and Geneva, World Bank Group and ITU.
2 European Commission (2019). The European Green Deal (COM/2019/640 final), Brussels, 11.12.2019.
3 European Parliament & Council of the European Union (2020). Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment (EU Taxonomy Regulation). Official Journal of the European Union, L 198, 13–43.
4 European Commission (2024). EU Taxonomy Navigator, https://ec.europa.eu/sustainable-finance-taxonomy/sectors, last retrieved: 20.12.2024.

providing internet access in regions where fibre deployment may not be economically feasible. The potential of 5G as a substitute for fixed broadband is being explored, but it comes with its own set of challenges, such as ensuring adequate coverage and addressing concerns around network reliability and energy consumption.

## 1.2 Objectives of the study

The study aims to quantify the energy consumption and energy-related $CO_2$ emissions generated by the operation of both, Very High Capacity fixed broadband and mobile networks (VHCN), examining the environmental impact of the telecommunications sector. Two bottom-up models are specified to quantify the number of active network elements required to serve the German population with telecommunication access services. The derived quantities and corresponding usage figures are the basis for deriving the respective energy consumption of an FTTH fixed access network as well as of a mobile access network in Germany.

In addition, the study will investigate how different settlement structures impact the environmental footprint of telecommunication networks and their differences, depending on the technology deployed. In more detail, the study assesses the capabilities of mobile networks in terms of environmental sustainability in comparison to fixed broadband, in particular in rural regions. Given the challenges of extending fiber networks to less populated areas, mobile networks, especially 5G, are explored as a possible solution for providing broadband access in these regions. The analysis will investigate whether mobile networks can meet the demand for broadband services in rural areas from an environmental perspective, evaluating whether they can serve as a substitute for fixed broadband infrastructure, considering both energy efficiency and environmental impact.

The analysis focuses on the energy consumption and $CO_2$ emissions of network operations. Deployment-related emissions and spill-over effects induced by using ICT for eco-benefits in other sectors of the industry are beyond the scope of this analysis.

## 1.3 Scope of the analysis

### 1.3.1 Defining sustainability

Sustainability is a broad concept referring to the ability to meet present needs without compromising the ability of future generations to meet their own needs. It involves balancing **environmental**, **social**, and **economic** considerations to ensure long-term well-being and resilience.

- **Environmental Sustainability**: Conserving natural resources, reducing pollution, and maintaining ecosystems to protect biodiversity and ensure the planet's health for future generations.
- **Social Sustainability**: Promoting equity, social inclusion, and community development to ensure a fair and just society.
- **Economic Sustainability**: Supporting economic growth and stability while using resources efficiently and responsibly.

The focus of this analysis is primarily on **environmental sustainability**, with a secondary emphasis on economic sustainability, as certain key indicators – such as energy efficiency and $CO_2$ emissions – are closely interrelated and contribute to both domains. While these aspects are integral to assessing the sustainability of telecommunication infrastructures, the social dimension of sustainability relies on different indicators and requires a distinct evaluation. Consequently, social aspects of sustainability are not considered in this study.

**Target Metrics**. The analysis focuses on energy consumption (measured in kilowatt-hours, kWh) and the associated greenhouse gas emissions (measured in $CO_2$ equivalents). Network operations are assessed through electricity consumption, which is then converted into corresponding $CO_2$ equivalents. Other environmental indicators, such as water usage, resource consumption, or soil and water pollution, may be relevant but exceed the scope of this study and are therefore not included.

### 1.3.2 Delimiting phases of the product life cycle

The lifecycle of telecommunications infrastructure consists of three main phases: deployment, operation, and decommissioning. Each phase is associated with various activities and their environmental impacts.[5]

- **Deployment**: This phase includes the manufacture, distribution and installation of cables, antennas and network components. Key environmental factors include power usage during construction, digging, and material handling.
- **Operation**: The operational phase involves the ongoing maintenance and power consumption of active network components, which require energy for their function.
- **Decommissioning**: This phase encompasses the dismantling and disposal of components, including activities such as digging, waste management, and soil depollution. The specific component waste management is also part of this phase.

This study focuses on just one of the key phases of the Life Cycle Assessment (LCA) of telecommunications infrastructure: **network operation**. The analysis excludes the network deployment and network decommissioning (end-of-life) phases. As a result, the study does not consider the emissions and environmental impacts associated with the manufacturing, installation, disposal, or recycling of network components, nor does it account for any replacement investments required after the observation period.[6]

However, when comparing the $CO_2$ emissions of the deployment phase with those of the operational phase, the emissions of the operational phase during the lifespan of the network significantly exceed the emissions of the deployment phase. According to other studies, over 90% of the total greenhouse gas emissions for both fixed and mobile networks arise from the operational phase. This highlights the dominant environmental impact of network operation relative to its deployment and decommissioning stages.[7]

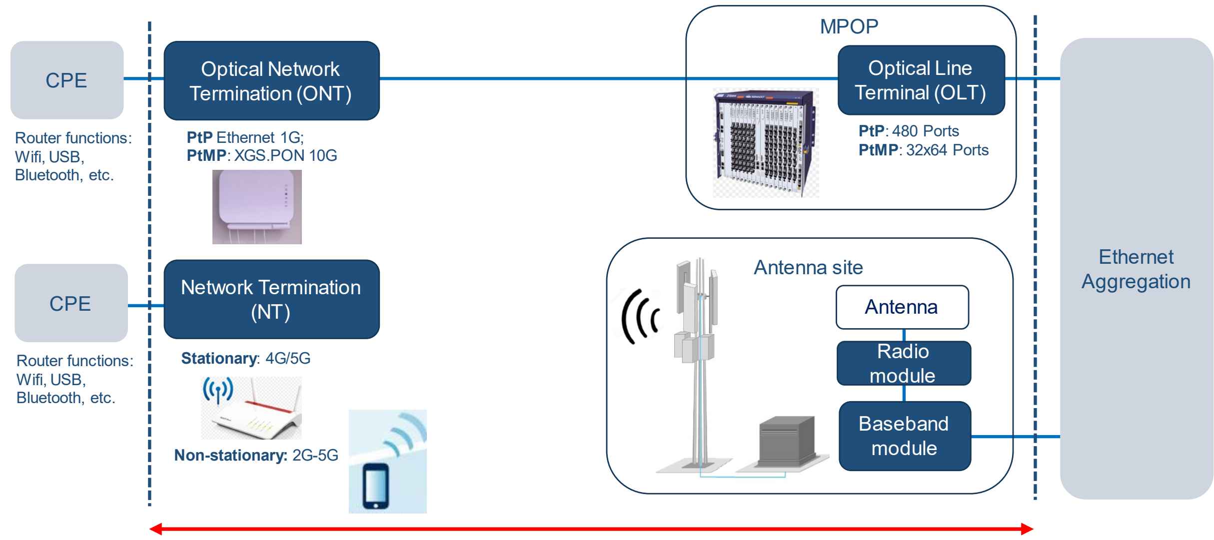
5 WIK/ Ramboll (2021). Environmental impact of electronic communications. Final report for BEREC.
6 Dismantling of active network components is a question of updating technologies due to new characteristics and of the equipment lifetime. Dismantling the access network infrastructure or leaving the lines underground is a question beyond the scope of this study.
7 Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency], and WIK/ Ramboll (2021). Environmental impact of electronic communications. Final report for BEREC.

### 1.3.3 Delimiting telecom networks

**Network Segments**. This study focuses on the **access network**, a segment of telecommunications infrastructure that establishes the direct connection between the network and end users, either through a wired or wireless connection. As the primary aim of this study is to compare the performance of modern wired and wireless access technologies, and both are undergoing significant advancements within this domain, this segment is the central focus of this analysis. In contrast, aggregation and core networks, which are already equipped with high-capacity fibre-optic technology, fall outside the scope of this analysis due to their relatively mature state.

End-user devices, such as routers and other consumer devices, which include functionalities beyond basic modem features, are also excluded from the scope of this study. These additional functionalities of Customer Premises Equipment (CPE) fall outside the boundaries of the analysis, as the study concentrates solely on the network-side infrastructure. The system boundaries of this study for both fibre and mobile access networks are depicted in Figure 1.

*Figure 1: Graphical representation of system boundaries of fibre access networks (FTTH) and mobile access networks*




Source: WIK

As illustrated in Figure 1, in fiber access networks, the connection between the end-user equipment and the nearest network node (for instance the *Metropolitan Point-of-Presence*, MPoP) occurs via fiber-optic cables. Here, the access network is commonly referred to as the *Optical Access Network* (OAN). In mobile networks, the access network is often referred to *Radio Access Networks* (RAN) and is the segment where communication occurs wireless between the mobile end device and the nearest antenna site via an air interface. The energy consumption associated with the active network components in both fiber and mobile access networks, as depicted in the figure, is the focus of this study. This includes the energy usage of components such as Optical Network Terminals (ONT), Optical Line Terminals (OLT), for fibre technologies and baseband modules and radio modules at the antenna site for mobile technologies.

**Transmission Technologies**. The analysis focuses solely on modern access technologies in fixed wired fibre and mobile networks. These include:

- FTTH (Fibre-to-the-Home) networks in both Point-to-Point (PtP) and Point-to-Multipoint (PtMP) architectures
- Current mobile access technologies (4G/ 5G and 2G if available)

Legacy technologies in fixed access networks, such as the traditional copper-based or DOCSIS technologies and other less common technologies in Germany such as satellite networks and pure Fixed Wireless Access (FWA) networks, are not included in the analysis.

The following tables summarizes the scope of this study:

*Table 1: Scope of the study – overview*

| | Within the scope of the study | Outside the scope of the study |
|---|---|---|
| Sustainability metrics | • Energy consumption<br>• CO2 emissions | • Other environmental indicators |
| Phases of the life cycle | • Network operations | • Network deployment<br>• Decommissioning (End-of-Cycle) |
| Network segment | • Access networks (OAN and RAN) including user modem | • Aggregation and core networks<br>• Data centres<br>• Consumer devices |
| Transmission technologies | • FTTH PtP 1G Ethernet<br>• FTTH PtMP XGS.PON<br>• Mobile (2G-5G) | • Copper (e.g. DSL)<br>• DOCSIS<br>• Satellite |

Source: WIK.

# 2 Understanding the role of telecom networks in the context of sustainability

Telecommunications networks are the nerve centres of a modern economy, industry and society. They connect all endpoints for communication purpose, allowing to exchange information between their sources and sinks facilitating digitalisation. Through technologies such as smart grids, smart cities, digital agriculture, and telecommuting, the telecom sector aids in the transition to a more sustainable economy. Digital solutions allow industries to optimise energy consumption, reduce emissions, and improve resource management. Studies like those conducted by the Global e-Sustainability Initiative (GeSI) have highlighted the critical role of ICT in achieving global sustainability goals, estimating that digital solutions could help reduce global emissions by up to 20% by 2030 through better efficiency in various industries.[8] Thus, telecommunication networks are enablers for more efficient use of energy and other resource consumption in nearly all facets of modern societies.

On the other hand, telecommunication networks are also responsible for significant $CO_2$ emissions generated by their own operations. These emissions primarily arise from the energy consumption associated with network infrastructure, such as data centres, base stations and network transmission equipment. The energy demands for operating these components, particularly in 24/7 operation, are substantial, and if the energy comes from non-renewable sources, they contribute to the sector's carbon footprint. In addition to energy consumption, telecoms also generate emissions through the manufacturing and disposal of equipment, adding to their overall environmental impact.

Thus, the role of telecommunication sector in context of environmental sustainability is twofold. Several studies have sought to address and quantify this relationship. One example is the EGDC Net Carbon Assessment Methodology for ICT solutions,[9] which evaluates the carbon impact of digital infrastructures and services. This methodology helps assess the "handprint" (positive environmental impact in terms of avoided emissions) and "footprint" (negative environmental impact) of telecom solutions. While telecom services reduce emissions across other sectors, the sector itself remains a significant producer of $CO_2$ emissions.

Focusing on the footprint, the $CO_2$ emissions generated by telecommunications and ICT-related activities, in terms of global $CO_2$ contributions, the ICT sector's footprint represents a significant but not overwhelming share (between 1,5% and 4%).[10]

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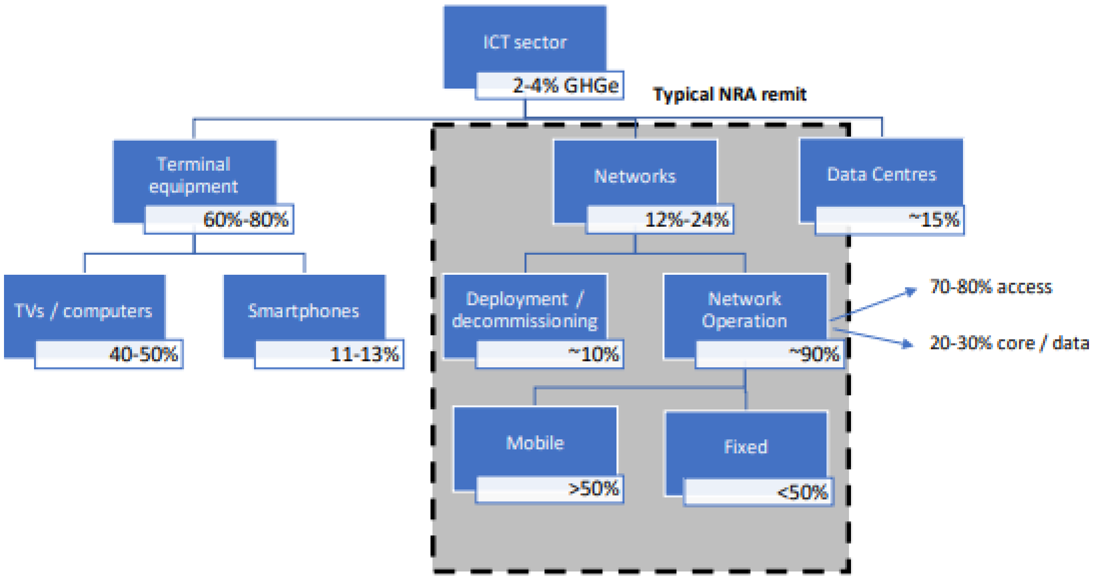
8 Global e-Sustainability Initiative (2015). #SMARTer2030 – ICT Solutions for 21st Century Challenges.
9 Green Digital Coalition (2024). Net Carbon Impact Assessment Methodology for ICT solutions.
10 Ayers et al. (2024). Measuring the Emissions and Energy Footprint of the ICT Sector: Implications for Climate Action. Washington, D.C. and Geneva, World Bank Group and ITU.

Numerous studies have explored this relationship in detail, shedding light on how different segments of the ICT sector contribute to overall emissions. Figure 2 provides a visual overview of the contributions of different ICT sectors to total GHG emissions.

*Figure 2 CO2 Emissions in the ICT Sector: A Comparison*




Source: WIK/ Ramboll (2021). Environmental impact of electronic communications. Final report for BEREC.

Note: The percentage values refer to different scales. The ICT sector is responsible for 2–4% of total GHG emissions. Within the sector, the percentages provided represent the share of emissions attributed to end-user devices, networks, or data centres, collectively summing up to 100%. Among end-user devices, the largest shares are attributed to TVs/computers and mobile devices, while other devices are not included. Thus, network operations contribute with (2 to 4%) * (12 to 24%) *90% to the total GHG emissions ( ~ 0.1% - 0.4%).

As illustrated in Figure 3, terminal equipment, such TVs, computers, smartphones, account for the largest ICT-share of GHG emissions (between 60% to 80%), but telecommunications networks also make a notable contribution. Although their overall impact is significantly smaller, the emissions associated with network operations are particularly significant.

In Germany, total $CO_2$ emissions amounted 598 million tons in 2023.[11] The telecommunications sector's share of this is relatively modest compared to other industries, but it still represents a key area of focus for reducing emissions, particularly as demand for digital services continues to grow. As Germany pushes towards its climate targets, reducing emissions from the ICT sector will be crucial to meeting these goals.

11 Umweltbundesamt (2024). Kohlendioxid-Emissionen, 16.12.2024, https://www.umweltbundesamt.de/daten/klima/treibhausgas-emissionen-in-deutschland/kohlendioxid-emissionen#kohlendioxid-emissionen-2023, last retrieved: 19.12.2024.

# 3 Challenges in quantifying $CO_2$ emissions of fixed and mobile access networks

## 3.1 International standards

There are international standards for reporting on sustainability and environmental issues. These standards are different in their design and in their purpose. Some focus on how to quantify environmental externalities while specify standards or indicators for reporting purposes, e.g. to support environmentally sustainable investment decisions. Furthermore, some standards have relevance for all sectors, while others provide sector-specific information only. In the following, the most common standards and codes are presented:

- GHG Protocol
- ISO 14040 and ISO 14044 standards
- European Sustainability Reporting Standards (ESRS)
- Global Reporting Initiative (GRI)
- Sustainability Accounting Standards Board (SASB)
- International Sustainability Standards Board (ISSB)
- International Telecommunication Union (ITU)
- European Telecommunications Standards Institute (ETSI)
- EU Codes of Conduct (CoC)

**Purposes of the Standards**

**GHG Protocol**: This is an accounting framework primarily designed to quantify and manage greenhouse gas emissions across different sectors, including the telecommunications industry. Its main purpose is to provide a standardised method for measuring emissions and tracking reductions. The GHG Protocol helps organisations measure and manage emissions by providing a systematic approach to identifying, calculating, and reporting emissions across their operations.

**ISO 14040 and ISO 14044 standards**. These standards are designed to ensure consistency, transparency, and reproducibility in Life-Cycle-Analysis (LCA) studies. They are widely used across industries, including telecommunications, to assess the environmental impacts of products, services, and processes.

**European Sustainability Reporting Standards (ESRS)**: Part of the Corporate Sustainability Reporting Directive (CSRD), ESRS aims at enhancing transparency in sustainability reporting at the company level, addressing environmental, social, and governance (ESG) factors. It does not yet include industry-specific guidelines for telecommunications but is expected to develop them.

**Global Reporting Initiative (GRI)**: Provides globally recognised standards for sustainability reporting. GRI Standards are modular, covering a wide range of environmental and social issues, and help companies communicate their sustainability impacts in a transparent manner.

**Sustainability Accounting Standards Board (SASB)**: Focuses on providing industry-specific standards for financially material sustainability issues. For telecommunications, SASB addresses energy consumption, the environmental footprint of operations, and product end-of-life management.

**International Sustainability Standards Board (ISSB):** Focuses on providing clear, comparable, and reliable sustainability disclosures to investors, emphasising climate-related risks and opportunities. It builds on frameworks such as SASB and TCFD, with a focus on integrating sustainability reporting with financial performance.

**International Telecommunication Union (ITU):** Develops specific standards for the telecommunications sector, such as those related to energy efficiency in equipment, recycling of rare materials, and assessing environmental impacts of ICT operations. These standards are highly relevant for telecom companies seeking to reduce their environmental footprint.

**European Telecommunications Standards Institute (ETSI):** Provides standards on energy management, including KPIs for energy efficiency in ICT facilities and networks. ETSI also offers guidelines for measuring energy consumption in broadband equipment and mobile networks.

**EU Codes of Conduct on Energy Consumption of Broadband Equipment (CoC)**: These guidelines focus on improving energy efficiency in data centres and broadband equipment. The Code for Sustainable Telecommunications Networks is being developed to establish common sustainability indicators across the telecom sector, with a focus on $CO_2$ emissions, energy consumption, and resource efficiency. The final release is expected in 2025.

A detailed description of these standards is presented in the appendix to this study.

There is a wide range of international standards designed to enhance transparency, accountability, and comparability in the reporting of environmental indicators across various sectors. However, the last three standards – ITU, ETSI, and the EU Code of Conduct – are specifically tailored to address these challenges within the telecommunications sector, providing targeted frameworks for improving environmental performance in this industry.

## 3.2 Data constraints

Fulfilling reporting requirements and deriving indicators for measuring sustainability requires an appropriate data basis. This data is often not readily available.

Telecommunication companies therefore face challenges in acquiring reliable data to meet sustainability reporting requirements. A primary issue is the lack of standardised methodologies for data collection and reporting, resulting in inconsistencies that hinder comparability across the industry. This absence of uniform standards makes it difficult for stakeholders to assess and compare sustainability performance accurately. Additionally, the complex and extensive supply chains in the telecommunications sector pose challenges in tracking Scope 3 emissions, which encompass indirect emissions from both upstream and downstream activities. Collecting comprehensive data across these supply chains is often resource-intensive and requires robust collaboration with numerous partners.[12]

The dynamic nature of technological advancements further complicates data collection, as companies must continually update their reporting frameworks to align with new technologies and regulatory changes.[13] Moreover, the integration of various data sources, such as IoT sensors and cloud platforms, is essential for real-time monitoring but can be technically challenging and costly to implement. Ensuring

12 Dibra (2023). Implementing effective strategies for gathering Scope 3 data. 20.12.2023, Thomson Reuters, https://www.thomsonreuters.com/en-us/posts/esg/gathering-scope-3-data/, last retrieved: 10.12.2024.
13 Deloitte (2024). As Sustainability Reporting Becomes Mandatory, All Eyes Are on Data, 04.06.2024, https://deloitte.wsj.com/riskandcompliance/as-sustainability-reporting-becomes-mandatory-all-eyes-are-on-data-45bfc9c6?utm_source=chatgpt.com, last retrieved: 10.12.2024.

data accuracy and reliability is another critical concern, as errors can lead to misinformation and undermine stakeholder trust.

Telecommunication firms also encounter difficulties in aligning their reporting with diverse stakeholder expectations, including those of investors, regulators, and customers, each with unique information requirements.[14] The evolving landscape of sustainability regulations adds another layer of complexity, necessitating continuous adaptation to comply with varying regional and international standards. Financial constraints can impede the development and maintenance of sophisticated data collection and reporting systems.

In the research field, the Fraunhofer Institute for Reliability and Micro integration (IZM) reported in its study that expert interviews and data surveys had failed to gather the desired data on mobile networks. Respondents were unable to provide definitive statements and, therefore, chose not to participate in the survey. This indicates that energy-related technology and network planning data, at the level of granularity required, are often subject to confidentiality. Moreover, the necessary information is dispersed across various operational areas and is not centrally available.[15] Acknowledging these limitations, this study instead relies on energy efficiency measures and international standards for telecommunications networks, as established by ITU, ETSI, and the EU Code of Conduct (for further details, see Section 6.1.3), rather than company-specific data.

## 3.3 Literature review

### 3.3.1 Quantification methods

$CO_2$ emissions and energy consumption in access networks are analysed in the existing literature through various methodological approaches. Among these, the bottom-up and top-down methodologies, alongside Life Cycle Analysis (LCA) models, are well-established and widely applied frameworks.

**Bottom-Up approaches for energy and $CO_2$ quantification**

A widely used method for quantifying energy consumption and $CO_2$ emissions in telecommunications networks is the bottom-up approach. This method calculates the energy consumption of individual network components, such as modems, aggregating network equipment, or base stations, based on the distribution of connections in the field and their requirements in an efficient, real-world network. The energy consumption of these components is then aggregated to determine the total energy consumption of the network. To calculate $CO_2$ emissions, the summed energy consumption is multiplied by the $CO_2$ emission factor of the corresponding energy source.

This approach requires a significant amount of specific technical and energy-related data for each network element, making it highly data-intensive. Moreover, it relies on an optimised network structure, which may not always align with practical implementations, potentially leading to an underestimation of real-world emissions.

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**14** See for example the sustainability report of Deutsche Telekom: Deutsche Telekom (2023). CR Report 2023, https://www.cr-report.telekom.com/2023/, last retrieved: 10.12.2024.

**15** Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

Examples of environmental sustainability studies for telecommunication networks using the bottom-up approach include Stobbe et al. (2023), Obermann (2022), Ficher et al. (2021), Bieser et al. (2020), and Aleksic & Lovric (2011).

**Top-Down approach**

This method takes the actual total energy consumption of a network as the starting point and then allocates it to different network segments, such as access networks.

These user-based energy models establish a connection between user behaviour and the resulting energy consumption. Key variables, such as data rate and number of users, are crucial for modelling usage patterns, which, in turn, significantly influence the data volume, especially in mobile networks. In some models, the device inventory is also considered as an additional factor. The primary objective of these models is to calculate either the absolute energy requirement or the relative energy efficiency (e.g., Wh/GB or Wh/user) for a specific reference system, such as a telecommunications network.[16]

One of the greatest challenges in quantifying energy consumption in access networks using this approach is the heterogeneous nature of networks, particularly in countries with mixed copper and fibre-optic infrastructures. The transitional phase from copper to fibre-optic networks complicates the collection of technology-specific consumption data, such as those from technical facilities, making detailed scenario analyses significantly more challenging.

Examples of environmental sustainability studies for telecommunication networks using the top-down approach include Godlovitch et al. (2023), Breide et al. (2021), Laidler et al. (2019), Anders & Edler (2015), and Raspone et al. (2015).

**Life Cycle Analysis (LCA)**

Another method is Life Cycle Analysis (LCA). This approach considers the entire lifecycle of network components, from raw material extraction through production and operation to disposal. The LCA approach systematically examines all stages of the lifecycle, identifying and quantifying environmental impacts such as energy consumption, water usage, greenhouse gas emissions, and resource depletion. LCA enables a more holistic understanding of the environmental footprint of network systems. It allows local energy sources and infrastructure to be included in the analysis and it helps to identify the stages on the organisational level where the greatest environmental impact occurs.[17]

### 3.3.2 Overview of results

Recent studies on the quantification of $CO_2$ emissions in Fiber-to-the-Home (FTTH) and mobile access networks provide a wide range of results, often shaped by the specific methodologies and regional focus of each research effort.

Obermann (2022) provides a comprehensive comparison of internet access network technologies regarding environmental sustainability, emphasising energy consumption and $CO_2$ emissions across

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**16** Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

**17** Research Center for Energy Economics e. V. (2023). Series of articles on methods of sustainability assessment: Life Cycle Assessment.

FTTH, FTTB, FTTC, and HFC networks. Employing a bottom-up approach, the analysis measures power consumption of network components, evaluates deployment scenarios across urban and rural regions, and considers varying load levels to assess utilisation effects. The findings highlight FTTH as the most energy-efficient technology, consuming up to six times less energy than HFC networks. Additionally, implementing sleep modes in network equipment could reduce energy consumption by up to 40%.

Breide et al. (2021) provides a detailed analysis of energy consumption and $CO_2$ emissions across broadband access technologies, including FTTH differentiating it in PtP and PtMP architectures. They use network energy consumption averages derived from actual regional network nodes from six municipalities in North Rhine-Westphalia, Germany. Findings indicate that FTTH PtMP is the most energy-efficient technology, with consumption ranging between 56 kWh/year per capita, significantly lower than HFC and VDSL2, which require approximately 61 kW and 88 kW, respectively.

Stobbe et al (2023) prepared a paper under the Fraunhofer Institute frame for the German Federal Environment Agency evaluates the energy consumption and $CO_2$ emissions associated with mobile networks in Germany, focusing on both current and future scenarios. Using a life cycle inventory model, the study estimates that the energy demand of German mobile networks will increase from 2.3 TWh in 2019 to 7.5 TWh by 2030, primarily driven by radio access networks, which account for over 80% of operational energy consumption. The operational phase dominates total energy demand, contributing over 90%, while the manufacturing phase represents less than 10%.

The study by Godlovitch et al. (2023) under the European Commission framework quantifies the energy consumption and associated emissions of European telecommunications networks. Based on a top-down approach, this study uses aggregated data from the existing literature to estimate the total environmental impact of the deployment and operations of increased FTTH and full 5G coverage over time. Results predict a significant reduction in electricity intensity for data traffic, kWh per GB until 2030.

While Obermann (2022) examines the regional differences in the environmental impacts of fixed wired technologies and Stobbe et al. (2023) focuses on mobile networks, a direct comparison and modelling of both technologies has not yet been explored in the literature. This paper addresses this gap by integrating insights from both studies to quantify $CO_2$ emissions and compare them across different regional contexts. The results from these studies serve as a benchmark for comparison with the model results presented in Section 7.1.

# 4 Drivers of CO2 emissions and the role of regional differentiation

## 4.1 Differences between fixed fibre wired networks and mobile networks

The energy consumption drivers in **fiber access networks** and **mobile access networks** differ significantly due to their distinct technological characteristics and operational conditions. While both types of networks rely on transmitting data across various distances, the underlying mechanisms for transmission, power demands, and the efficiency of the systems vary considerably.

In mobile access networks, energy consumption is largely driven by radio transmissions, the frequency demand and the reach of the wireless network. Radio connections typically perform best when there is line-of-sight between transmitter and receiver. This is often not given, and the higher the distance the higher the probability of non-line-of-sight environments. The attenuation loss in mobile networks, especially in radio communications, is higher than in fibre or copper connections. Factors such as non-line-of-sight environments, as well as physical barriers like buildings, walls and insulating windows, significantly affect the quality of mobile coverage, particularly indoor coverage. The further away the antenna is from the receiver, the greater the receiver's power requirements due to these environmental challenges. Radio antennas need broadband access connections for broadband backhauling of the antenna's traffic. These backhaul fibre links need a fixed fibre network consuming power and generating $CO_2$ emissions. Radio communication is typically based on the sharing of radio emission power between a number of transmitters and receivers, each of which may require a portion of the system's total transmission power. Such sharing reduces the total transmission capacity and the quality parameters achievable (bandwidth, delay, jitter).

In contrast, fibre access networks are generally more efficient in terms of energy consumption. Fiber-optic technology, particularly in Point-to-Point (PtP) and Point-to-Multi-Point (PtMP) topologies, can cover long distances with minimal energy loss, thanks to the low attenuation of light transmitted through fiber strands. The laser-driven transmission in fibre networks is highly efficient, as it does not need repeaters and provide a huge amount of transmission capacity up to Tbit/s, supported by parallel channels (wavelength) each providing up to 400 Gbit/s (state of the art). Nevertheless, the energy demand increases as the capacity or number of wavelengths a fibre link supports increases. If they are deployed in a Point-to-Multi-Point (PtMP) topology with intermediate splitters in the field, the fibre plant must be shared between the connected users, reducing the bandwidth of the access system for each connected user. When deployed in a Point-to-Point PtP topology, the access link is not shared and provides full capacity in a high quality manner for each individual customer connected. For the purpose of this study, we assume that a fibre link for a PtP topology is operated at approximately 1 Gbps, providing this capacity symmetrically for any individual customer, in case of PtMP, we assume the system to be operated at 10 Gbps per link, and not more than 10 customers can use the link simultaneously for receiving 1 Gbps connectivity at any time.[18] In case of PtMP, the central MPoP equipment can have slightly better

18 PtP is typically deployed in form of a central Ethernet switch at the aggregation point and a Router with an Ethernet port at the customer location. PtMP requires additional technology to manage which of the customers connected to the shared fibre medium may get sending rights at a time and arrange for collisions, and vice versa, to address the receiver in the downstream direction. (See Plückebaum, et al., 2023. FTTH Punkt-zu-Multipunkt vs. Punkt-zu-Punkt – ein Vergleich aus einzelwirtschaftlicher und gesamtwirtschaftlicher Perspektive, WIK Kurzbericht, Bad Honnef, Dezember 2023, and Plückebaum, 2023. Characteristics and performance of NGA technologies, wik discussion paper no 498, Bad Honnef, May 2023).

power and emission results under certain customer scale conditions, but its respective CPE can be less efficient.[19]

In summary, the type of transmission medium is the key driver for energy consumption. Therefore, fibre and mobile networks differ to a relevant extent in terms of energy consumption. The distance and environmental conditions especially affect mobile network's performance, and how the network's capacity is allocated. Fibre networks tend to offer higher energy efficiency and performance, while mobile networks face greater challenges in terms of energy consumption due to geographical conditions and the sharing of transmission power. Fibre based access network typically do not show any relevant length or distance dependant components.[20]

As geographical conditions seem to play a relevant role in energy consumption and are considered to differ between access technologies, we further analyse differences between FTTH and mobile technologies under different regional structures.

## 4.2 Differentiation by regional structure

In the context of telecommunications networks, regional structures refer to the spatial and organisational distribution of users and geographical and/ or socio-economic factors that determine the configuration of telecommunication infrastructure within a specific geographic area. In this paper, these structures serve as a framework for analysing how energy is consumed by various network components based on the following regional characteristics:

- geographic or administrative boundaries of the service area
- population sparsity or density
- regional usage patterns
- technological feasibility

**Geographic and administrative boundaries** define the spatial scope within which telecommunication infrastructure is deployed and managed. These boundaries determine the number of network users and can affect economies of scale, which determine the cost-effectiveness of the network operations.

**Population sparsity or density** in a region significantly influences the layout, utilisation, and energy consumption of telecommunications networks. Sparse populations in rural or remote areas, for instance, require telecommunication nodes or bases to cover larger geographical zones, which depending on the technology used, it is not always possible. This often results in a high number of nodes or bases for a relatively small number of network users, leading to a higher energy consumption per user due to the inefficiency of under-utilised infrastructure.

**Regional usage patterns** – determined by demographic, economic, and cultural factors – affect the energy profile of telecommunications networks. Areas with substantial internet or mobile data consumption, often associated with urban and economically active regions, experience higher energy demands. In regions with limited telecommunications demand, such as rural or economically disadvantaged areas,

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**19** The CPE power consumption is normally attributed to the end-customers and, therefore, falls outside the optimization objectives of network operators.

**20** Assuming, the MPoP areas size is limited below a radius of 20 km. (A copper access MPoP size in Germany today is below a radius of 7 km.) In case of larger areas an increased electrical power budget could be required for the laser transmitters covering longer access lines, instead amplifiers in the field can be deployed. Our model assumptions exclude such additional power requirement since they will not be required in Germany.

energy consumption can be dominated by idle power, as network components remain operational even when under-utilised.

**Technological feasibility**. The availability and adoption of technology varies across regions, influencing the energy efficiency of telecommunications networks. Urban or developed regions often adopt modern and newer technologies, which provide better data rates and energy efficiency per transmitted bit. Some of these technologies (for instance 5G) may offer faster speeds but have limited range and poor penetration through obstacles such as vegetation or buildings, hills etc., making them impractical in geographically extensive remote locations.

Regional structures significantly influence the resource usage efficiency of telecommunications infrastructure. The mechanisms through which regional structures affect resource efficiency vary depending on the type of network deployed, particularly when distinguishing between fixed (fibre) and mobile network technologies. The following table compares fibre and mobile access networks, examining the extent to which the identified regional characteristics influence energy consumption.

*Table 2: Regional characteristics affecting energy consumption by type of network*

| Regional characteristics | Fibre access networks | Mobile access networks |
|---|---|---|
| Geographical boundaries | Yes | Yes |
| Regional usage patterns | Yes | Yes |
| Population sparsity or density | No | Yes |
| Technological feasibility | No | Yes |

Source: WIK

The table above highlights that two regional characteristics – population density and technological feasibility – are less significant for fibre access networks thank they are for mobile access networks. Fiber networks are inherently less constrained by larger distances, making population sparsity or density in practise not a limiting factor. Similarly, technological feasibility, which refers to the extent to which transmission technologies are impacted by geographical conditions such as distances or natural obstacles, is not an issue for fibre networks. Advanced fibre access technologies, such as Ethernet over Fiber and xPON, are generally less susceptible to these limitations, enabling their deployment across a wider range of geographical conditions. In contrast, for mobile access networks, all identified regional characteristics, including population density and technological feasibility, significantly impact energy consumption, as the transmission of radio signals are inherently sensitive to geographical distance and dispersion, which directly influences the feasibility and selection of the most appropriate mobile transmission technology.

# 5 Model design

## 5.1 Concept and estimation strategy

### 5.1.1 General concept

Our strategy is to model fixed fibre and mobile access networks separately, determining their configurations and utilisation at a granular regional level to capture variations in energy consumptions across different regional structures. The model is characterized as follows:

- **Separate modelling of fibre and mobile access networks**. While fibre networks are based on fixed physical infrastructure, mobile networks rely on wireless communication. Thus, each type of network is modelled independently to reflect their fundamentally different infrastructure designs and technologies to account for distinct energy consumption patterns, operational requirements, and deployment strategies.

- **Calculations at high level of granularity**. By operating at a fine-grained scale the model captures localised regional variations in network utilisation and energy efficiency that are not apparent at national or broader scales. These regional differences include geographic boundaries as well as population size and densities, which determine the local demand for services. This level of granularity not only facilitates the differentiation of geographical characteristics but also supports sensitivity analysis to assess different deployment and usage patterns.

- **Bottom-up network dimensioning**. The network infrastructure is estimated starting from granular level of detail to determine the network equipment and base stations required to deliver fibre and mobile services across different service areas.

To implement the model, we define the service areas according to geographical boundaries based on administrative divisions established by German municipalities. Based on population, household and land area data at the municipality level, we dimension the network infrastructure required to provide coverage for both fibre and mobile services across municipalities. As a result, the estimated network infrastructure as well as the derived energy consumption and $CO_2$ emissions varies from municipality to municipality based on their different regional characteristics.

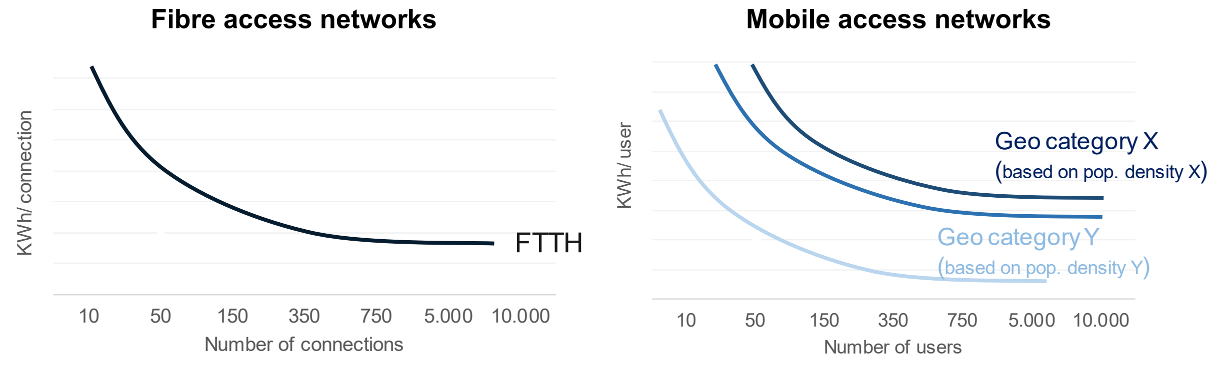
For **fibre access networks**, the model captures regional variations in energy consumption primarily based on the number of households within municipalities. The number of households approximates the total number of potential connections once fibre fully deployed and determines the number and type of fibre network equipment required to satisfy the demand in the municipality. At this stage, we differentiate between Fibre-to-the-Home (FTTH) Point-to-Point (PtP) and Fibre-to-the-Home (FTTH) Point-to-Multipoint (PtMP) topologies. These topologies typically differ in terms of equipment requirements, capacity and energy needs.

For **mobile access networks**, energy consumption is modelled based on a combination of factors, including the number of mobile internet users within each municipality, population density, and the actual frequency usage. The actual state of frequency usage is particularly important for mobile networks, as they often fully coexist with multiple generations of technology (e.g., 2G, 4G, and 5G). This coexistence in mobile access networks is often necessary to strike a balance between territorial coverage and data capacity. As mobile networks transition to newer technologies, older ones, especially based on lower frequencies, remain operational, particularly in rural areas where coverage needs take precedence over data throughput. Analogue to fibre access networks, the number of mobile internet users determine the number of base stations required. The distribution of frequencies across varying population densities impacts the propagation characteristics of the radio signal and determine this way the type and energy requirements of different base stations.

### 5.1.2 Comparing fixed and mobile networks in context of regional differentiation

To gain nuanced insights into the heterogeneous environmental impact of fibre and mobile networks, we apply the models described above and, in an additional step, simulate energy consumption across a continuum of network users, independent of the actual administrative boundaries of German municipalities. This approach enables the generation of energy curves for both fixed fibre and mobile access networks, which vary according to the number of network users and population densities. This allows for a deeper understanding and comparison of the results from a more theoretical standpoint.

*Figure 3: Graphical illustration of energy curves for FTTH and mobile access networks*




Source: WIK.

Figure 3 compares the energy consumption in both types of networks. The FTTH energy curve is represented by a single line that shows energy consumption as a function of the number of connections, while mobile networks are represented by multiple energy curves, each corresponding to different population densities as function of the number mobile users. By using a connection-to-user ratio[21] these curves can be compared in a single graph, allowing for a clear theoretical comparison, independent of local administrative constraints, of the energy consumption of two fundamentally different network types. Results of these comparisons are presented in Section 7.2.

### 5.1.3 Model overview

As mentioned in the previous section, the analysis is based on a bottom-up approach to estimate the required network infrastructure (active network elements) as well as the corresponding energy consumption and $CO_2$ emissions of fibre and mobile access infrastructure. This is done at the level of individual network elements, which are dimensioned according to demand patterns in the individual service areas. Under further consideration of averaged usage patterns and the characteristics of the considered active network elements we derive access technology specific energy consumption figures.

21 See derivation from this ratio (1.66 mobile users per household) in Section 5.2.2.1.

The model is structured around three core modules:

1. **Dimensioning access networks**: This module determines the complete inventory of technology-specific active network components required for a given service area and access network technology. It is a demand driven calculation of active network components in order to capture density patterns of the respective service area.

2. **Energy consumption of access network operations**: By using EU-wide standardised energy efficiency benchmarks for telecommunications equipment (as outlined in the most recent EU Code of Conduct),[22] energy data from specialised literature and incorporating factors such as load profiles and power saving options, this module calculates the energy consumption of various network elements.

3. **Transforming energy consumption into $CO_2$ emissions**: Finally, this module calculates $CO_2$ emissions associated with network operations by converting the calculated energy consumption into $CO_2$ emissions using $CO_2$ intensity values derived from the German electricity mix.

## 5.2 Dimensioning access networks

### 5.2.1 Fixed wired networks – Fibre-to-the-Home (FTTH)

The bottom-up network modelling approach integrates the spatial and technical characteristics of a service area to calculate the required number of network components for each technology, collectively referred to as the network inventory. In this context, a distinction is made between active and passive network elements.

#### 5.2.1.1 Active network components

The calculation of inventory requirements for active network elements is determined by two primary factors:

- **the number of active connections**, which is used to estimate the required number of network termination devices (e.g., modems) and

- **the maximum capacity of the active aggregating network elements** within a defined service area (such as a municipality). To determine the number of aggregating network elements, the service area's total demand is divided by the maximum capacity of the network nodes. If the demand, as represented by the number of active connections, exceeds the capacity of a single aggregating network element, additional elements are deployed as necessary. This approach ensures that the network infrastructure is scaled efficiently, maintaining sufficient capacity to support all active connections while avoiding underutilisation or overloading of network resources.

Since data on the number of active connections differentiated by technology is not publicly available, the total number of households is used instead, as it reflects the actual demand for active network elements. On this basis, a penetration rate of 100% homes activated is considered in the model. This

22 EU Joint Research Centre (2024). Code of Conduct on Energy Consumption of Broadband Equipment: Version 9.

method assumes a hypothetical scenario where network infrastructure of a particular technology is deployed to all households within the service area. The selected access technology determines the required devices, influencing both the central, aggregating network components and the individual network termination points at the end user's location.[23]

For this purpose, we use statistical data on the number of active connections at the municipal level based on the number of households from the German Federal Institute for Research on Building and Regional Planning (BBSR) (see Section 6.1.1).

The modelled network architecture for FTTH required different network elements depending on the selected topology and access technology applied.

The **FTTH PtP (Point-to-Point)** technology provides dedicated Ethernet connections between the Network Termination Point (ONT) at the user's premises and the Optical Line Terminal (OLT) located at the Metropolitan Point-of-Presence (MPoP). In this study, we assume PtP OLTs with 480 customer-sided ports. A port bandwidth of 1 Gbps is sufficient to deliver gigabit services to end users. Both the OLTs and the network termination points are configured with "PtP Ethernet 1G" interfaces.

The **FTTH PtMP (Point-to-Multipoint)** technology uses a particular Passive Optical Network (x.PON) architecture. A single fibre connection between the user's Network Termination (NT) and a central OLT at the MPoP is shared among multiple users via a splitter. The NT at the user's premises is connected via fibre optics to the splitter, which aggregates connections from several users, and then to the OLT, sharing a commonly used fibre strand. To ensure at least 1 Gbps per user, this study assumes FTTH PtMP devices configured with the XGS-PON 10G transmission technology. Typically, a splitter with a 1:32 ratio is used, connecting up to 32 end customers. Assuming simultaneous usage by 20% of connected customers (6.4 users), the bandwidth per user would be approximately 1.5 Gbps, comparable to the 1 Gbps available with PtP connections.

According to literature, an FTTH PtMP OLT system is assumed to have a port density of 48 ports,[24] each offering 10 Gbps. Each OLT port can support up to 32 users. With 48 ports, a single OLT can serve up to 1,536 users. The bandwidth available per user depends on the usage behaviour of customers connected to each splitter.

#### 5.2.1.2 Passive network components

Passive elements in fibre access networks are physical components that enable data transmission without amplifying or controlling electrical signals. These elements are essential components of access networks and play a significant role in infrastructure planning. The key passive elements include: fibre street cabinets and fibre ducts and cables.

Nevertheless, passive network components and other physical infrastructure, generate $CO_2$ emissions during the deployment phase. These emissions are associated with the manufacturing, transportation, and installation of these components. Unlike active network elements, passive components do not consume energy during the operation phase and, therefore, do not contribute to operational $CO_2$ emissions.

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**23** For a more detailed description of the access networks and technologies considered here, please refer to WIK Discussion Paper 498/2023.

**24** Obermann (2022). Nachhaltigkeitsvergleich Internet-Zugangsnetz-Technologien [Obermann, 2022. Sustainability Comparison of Internet Access Network Technologies].

As the scope of this study focuses on the operational energy consumption and associated $CO_2$ emissions of the telecommunications infrastructure, the determination of the number and deployment-related emissions of passive network components falls outside the scope of this analysis.

### 5.2.2 Mobile networks

For mobile access networks, this study builds upon the modelling approach presented in Stobbe et al. (2023), developed by the Fraunhofer Institute on behalf of the German Federal Environment Agency (UBA) during the period from January 2019 to November 2021. Recognising the rapid transformation of mobile networks in recent years, this study updates and refines the data employed in Stobbe et al. (2023) to accurately represent the current state of mobile network infrastructure and operations in Germany.

In contrast to fibre networks, where a single service area can effectively cover an entire municipality, modelling mobile networks involves additional considerations. It requires not only estimating the active network equipment deployed at each antenna site but also determining the number of antenna sites within each municipality. This is due to the inherent trade-off between the capacity and range of radio signals. Higher frequencies, while capable of delivering greater data throughput, have a shorter range and require a denser deployment of antenna sites. Conversely, lower frequencies can cover larger areas but provide lower capacity. Thus, dimensioning mobile access networks comprises estimating the required quantities of the following key elements:

- Antenna sites
- Active mobile network equipment

#### 5.2.2.1 Antenna sites

The starting point for determining the required number of antenna sites per geographical unit (municipality) is the actual total number of existing antenna sites in Germany. According to the latest annual report from the Bundesnetzagentur, there were 89,341 antenna sites across the country at the end of 2023.[25] The distribution of these antenna sites depends primarily on two factors: the number and concentration of mobile users and the technology employed to ensure sufficient capacity and optimal spatial coverage.

To account for these factors, we adopt the approach described in Stobbe et al. (2023), which involves back-calculating the total number of antenna sites by estimating the national **average user capacity** of a single antenna site. To estimate the average user capacity per antenna site, we require the number of mobile internet users in Germany. This figure cannot simply be equated to the number of active SIM cards, as the number of SIM cards does not directly reflect actual demand for mobile internet services. Instead, updating the approach followed in Stobbe et al. (2023), we derive the number of mobile users from age-cohort-specific data provided by DESTATIS.[26] Based on this analysis, the total number of mobile internet users in Germany is estimated to be approximately 66.8 million. Table 3 presents the derivation of the number of mobile internet users.

**25** Bundesnetzagentur (2024). Jahresbericht Telekommunikation, 16.05.2024.
**26** DESTATIS (2023). Bevölkerung in Hauptwohnsitzhaushalten. Mikrozensus Deutschland (12211-0001).

*Table 3: Estimation of number of mobile internet users in Germany*

| Age groups | Population | Share of mobile internet usage | Number of Internet mobile user |
|---|---|---|---|
| 0 – 5 years | 4.8 million | 72% | 3.5 million |
| 6 – 14 years | 7.2 million | 92% | 6.6 million |
| 15 –24 years | 8.4 million | 92% | 7.8 million |
| 25 – 34 years | 10.6 million | 92% | 9.8 million |
| 35 – 45 years | 10.9 million | 91% | 9.9 million |
| 45 – 54 years | 10.7 million | 86% | 9.2 million |
| 55 – 74 years | 22.5 million | 70% | 15.8 million |
| Over 75 years | 8.6 million | 50% | 4.3 million |
| Total | 83.9 million | 80% | 66.9 million |

Source: WIK based on population numbers by age-cohort from DESTATIS (2023). Bevölkerung in Hauptwohnsitzhaushalten. Mikrozensus Deutschland (12211-0001) and shares of mobile internet usage from Statista (2024). Share of people in Germany by age groups who use a mobile phone or smartphone for internet access, in selected years from 2016 to 2023 and BITKOM (2023). Kinder und Jugendliche verbringen täglich gut zwei Stunden am Smartphone. Presseinformationen 06.08.2024, Berlin and Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

By dividing the total number of mobile users (66.9 million) by the total number of antenna sites (89,341), we obtained a national average user-capacity of 748 users per antenna site.

To analyse the distribution of the 66.9 million mobile internet users across Germany, we disaggregate this figure to the municipal level. This is achieved by first calculating the average ratio of mobile internet users to households, which, based on a total of 44.2 million households, results in an average of 1.66 mobile internet users per household. Using this ratio, combined with detailed population and household data for Germany's 10,786 municipalities (for further details on the data see Section 6.1.1), we estimate the number of mobile internet users for each municipality.

This allows us to calculate the required number of antenna sites per municipality by dividing the municipality-specific number of mobile internet users by the average user capacity per antenna site (748). Consequently, municipalities with larger populations will require a higher number of antenna sites to adequately meet the communication demands of their residents. For municipalities with very small mobile user populations, this mathematical calculation may naturally yield a value under 1, suggesting that only a fraction of an antenna site is needed. However, we assume a minimum value of 0.5, representing half the capacity of a standard antenna site, as fixed infrastructure and energy consumption cannot be scaled down indefinitely. This minimum is based on the physical and technical constraints associated with operating mobile network equipment, where certain fixed costs and energy requirements persist regardless of user demand.[27,28]

Not only quantity but also the type of antenna site, along with its configuration, are relevant factors when estimating energy demands. The throughput capacity and spatial coverage of antenna sites are

27 We determined 0.5 as the cutoff by simulating the smallest feasible number of transceivers. In the model, this was derived by adjusting the number of transceivers in the rural areas (category 1) from 10.5 to 6 (one transceiver per frequency under 2,6 GHz).

28 This restriction on the smallest permissible antenna site size is a key difference between this study and Stobbe et al. (2023).

influenced by the choice of technology, which can vary across regions. To address these regional differences, Stobbe et al. (2023) classified antenna sites into six regional categories. Their analysis of a sample of antenna site configuration sheets indicated that it is unnecessary to differentiate every individual site. Instead, antenna sites can be grouped systematically into six categories based on population density. The thresholds for these categories were derived from the European Commission (2018) classification guidelines.[29] The six regional categories and their population density thresholds are as follows:

- 1 – Rural: 0 – 149 hab./ km$^2$
- 2 – Rural: 150 – 299 hab./ km$^2$
- 3 – Suburban: 300 – 749 hab./ km$^2$
- 4 – Suburban: 750 – 1,199 hab./ km$^2$
- 5 – Urban: 1,200 – 2,699 hab./ km$^2$
- 6 – Urban: from 2,700 hab./ km$^2$

Based on the defined regional categories, the following table provides an estimation of the number of antenna sites and the average antenna cell size by geographic category, derived from calculations at the municipal level.[30] The table also includes the population and area shares as well as other regional indicators to highlight the distribution of antenna sites across varying geographic conditions.

*Table 4: Modelled number of antenna sites and cell size by geographic category*

| | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| Number of municipalities | 7,121 | 1,986 | 1,196 | 291 | 179 | 13 |
| Share of population | 19% | 16% | 21% | 12% | 22% | 11% |
| Share of territorial area | 64% | 18% | 11% | 3% | 3% | 1% |
| User per antenna site | 748 | 748 | 748 | 748 | 748 | 748 |
| Cell size (average range) | 3,02 | 2,23 | 1,67 | 1,19 | 0,92 | 0,66 |
| Number of antenna sites | 19,569 | 13,676 | 18,173 | 11,460 | 20,447 | 10,255 |
| Share of antenna sites | 21% | 15% | 19% | 12% | 22% | 11% |

Source: WIK based on population and territorial data by municipality from BBSR (2023). Raumgliederungssystem des Bundesinstituts für Bau-, Stadt- und Raumforschung, 17.11.2023.

Rural regions (categories 1 and 2) account for the largest area share (82% collectively) but require relatively fewer antenna sites per unit area due to their larger cell sizes, which range from 2.23 km² to 3.02 km². These larger coverage areas result from lower population densities and reduced demand for capacity.

In contrast, urban areas (categories 5 and 6) represent only 4% of the total geographic area but require a disproportionately high density of antenna sites due to smaller cell sizes, ranging from 0.66 km² to

29 Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

30 The antenna cell size does not directly influence the model but is estimated as part of plausibility checks to validate the results. The estimation follows the methodology outlined in Stobbe et al. (2023), using the following formula: $Cell\ size = 2\ x \sqrt{\frac{2\ x\ Cell\ area}{3\ x \sqrt{3}}}$ where $Cell\ area = \frac{Municipality\ area}{3\ x\ Number\ of\ antenna\ sites}$ and number three refers to a 120° antenna sector.

0.92 km². This higher antenna site density is necessary to accommodate the larger populations concentrated in urban regions, which account for 33% of the total population.

#### 5.2.2.2 Active mobile network equipment

At antenna sites, multiple systems operating across different frequency bands are typically consolidated and configured into sectors. The range, or radio cell, and the capacity of the antenna site are determined by the mobile network equipment (or base stations), which consist of the following key components:

- antenna module
- radio module
- baseband module

**Antenna module**. Antenna modules in mobile access networks are components establishing the direct wireless connection between mobile devices and the network infrastructure. These modules form the air interface, allowing data transmission to and from mobile devices. Typically mounted on masts or elevated structures, antenna modules include multiple frequency-specific antennas that support communication across different spectrum bands. Their design and configuration play a key role in determining the efficiency and coverage of the network.

In this context, MIMO (*Multiple-Input Multiple-Output*) configurations are a technological advancement used to enhance the network's capacity and spectral efficiency. MIMO systems utilise multiple transmitters and receivers within the antenna module to simultaneously send and receive multiple data streams. These configurations, such as 2T2R (two transmitters and two receivers) or 4T4R, significantly increase the throughput of the network without requiring additional spectrum.[31]

Following Stobbe et al. (2023), antenna modules are not designed with a direct current power supply, as the transmission power is provided by the radio modules. Any optional power supply at the antenna module is considered negligible compared to the transmission power from radio modules. Therefore, the number and types of antenna modules are not modelled in this study.

**Radio module**. Within each antenna sector one or more radio units are deployed. The radio unit facilitates the conversion, processing, amplification, and distribution of radio frequency signals. More precisely, acting as the intermediary between the baseband processing unit and the antenna module, the radio module manages both the transmission (downlink) and reception (uplink) of signals. In the downlink, it converts digital signals from the baseband unit into analog radio frequency signals, amplifies them, and transmits them to the antenna module for broadcast to mobile devices. Conversely, in the uplink, it processes incoming frequency signals from the antenna and converts them back into digital signals for further processing.

Each radio unit houses individual transceivers. The radio unit is modeled by estimating the total number of transceivers at each antenna site, a value influenced by the frequency distribution at the site, which is, in turn, may vary across different geographical categories. To estimate the number of transceivers

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**31** With the introduction of Massive MIMO, which leverages large antenna arrays (e.g., 16T16R, 32T32R, or 64T64R), the network can further optimise data transmission. Massive MIMO enables advanced techniques such as beamforming and beam steering, which dynamically adjust the direction and shape of the transmitted signal to target specific devices or areas. This targeted signal delivery not only enhances the signal quality and range but also reduces energy losses by concentrating power where it is needed most. Massive MIMO is particularly effective in higher frequency bands (e.g., above 3 GHz and up to millimeter wave frequencies like 26 GHz).

for each frequency and geographical category, we rely on the most recent data from the *Bundesnetz-agentur* regarding antenna site configurations across all existing antenna sites in Germany (for further details, see Section 6.1.2). From this data, we derive the number of transceivers based on the following assumptions:

- There is one transceiver for each registered carrier frequency entry.[32]
- For frequencies above 2 GHz, we assume MIMO configurations (see rationale and description in Section 5.2.2.1), which increase the number of transceivers per frequency by a factor of three.[33]

These assumptions are validated by comparing our results with the findings of Stobbe et al. (2023) regarding the average number of transceivers per antenna site. Table 5 presents our estimates of the average number of transceivers per antenna site, derived from the total number of transceivers and antenna sites across different geographical categories.

*Table 5: Derivation of number of average transceiver per antenna site*

| | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| #Antenna site | 21.828 | 12.428 | 15.191 | 9.395 | 18.602 | 11.897 |
| #Transceiver | 395.308 | 229.296 | 277.070 | 172.928 | 554.891 | 316.133 |
| øTransceiver/ AS | 18,1 | 18,5 | 18,2 | 18,4 | 29,8 | 26,6 |

Source: WIK based on anonymized regionalized data on antenna site characteristics from Bundesnetzagentur (2024) [Database] and Bundesnetzagentur (2024). Annual report telecommunications 2023. 16.05.2024.

*Table 6: Estimates on number of average transceiver per antenna site in Stobbe et al. (2023)*

| | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| 2019 | 10,5 | 13,0 | 13,0 | 13,0 | 16,5 | 16,0 |
| 2030 (forecast) | 26,2 | 26,8 | 27,6 | 28,9 | 29,8 | 30,3 |

Source: WIK based on Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

A comparison of the results in Table 5 and Table 6 reveals that our estimation for the total number of transceivers per antenna site and geographical category for 2024 falls within the range of the figures reported by Stobbe et al. (2023) for 2019 and the forecast for 2030. Given the availability of the data at the frequency level, we extent this estimation across different frequency ranges. The table below presents the results of these extended estimations.

32 Data entries are originally differentiated by frequency, technology, main beam direction, network operator and antenna site location (yet the latter two characteristics are not visible to us, as a redacted version of the data was provided). For simplicity, we assume a 1:1 ratio, yet depending on the radio unit model, either a single frequency band or multiple frequency bands can be supported.

33 WIK expert‘s estimation.

*Table 7: Average number of transceivers per frequency and antenna site by geo class*[34]

| Frequency [MHz] | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| 700 | 2,3 | 1,7 | 1,3 | 1,2 | 1,1 | 0,9 |
| 800 | 3,4 | 3,1 | 2,7 | 2,4 | 2,1 | 1,6 |
| 900 | 6,0 | 5,5 | 5,0 | 4,5 | 4,0 | 3,3 |
| 1.500 | 0,4 | 0,4 | 0,4 | 0,3 | 0,3 | 0,2 |
| 1.800 | 3,0 | 3,8 | 4,3 | 4,5 | 4,3 | 3,6 |
| 2.100 | 2,8 | 3,6 | 4,0 | 4,1 | 10,9 | 8,5 |
| 2.600 | 0,1 | 0,2 | 0,3 | 0,6 | 3,4 | 4,4 |
| 3.500 | 0,1 | 0,2 | 0,4 | 0,8 | 3,6 | 4,2 |
| **Total** | **18,1** | **18,5** | **18,2** | **18,4** | **29,8** | **26,6** |

Source: WIK based on anonymized regionalized data on antenna site characteristics provided by the Bundesnetzagentur (2024) [Database] and Bundesnetzagentur (2024). Annual report telecommunications 2023. 16.05.2024.

The differentiation by frequency is necessary as energy consumption of radio units varies along the frequency used. Table 7 presents the average number of transceivers per frequency band and antenna site, categorized by geographical category. These figures reveal notable differences in transceiver distribution across different regions, highlighting the relationship between frequency usage and geographical heterogeneity.

A key observation is the general decline in the number of transceivers at higher frequencies, particularly in rural areas. The lower frequencies tend to provide broader coverage with lower energy requirements, making them more suitable for rural areas with larger coverage areas and lower population density. Conversely, in urban areas (specifically Areas 5 and 6), the number of transceivers increases for higher frequencies. This trend reflects the need for higher frequency bands to support the dense network traffic and higher capacity requirements typical in urban environments.

The total number of transceivers per antenna site shows a clear upward trend as the geographical classification shifts from rural to urban areas. For rural areas, the average number of transceivers per antenna site is between 18.1 and 18.5, while for urban areas, it increases significantly, reaching 29.8 for Area 5 (Urban) and 26.6 for Area 6 (Urban).

**Baseband module**. The baseband module, or baseband unit, is responsible for performing digital signal processing to enable communication between mobile devices and the network. Positioned between the radio module and the transport core network (TCN), the baseband module acts as the interface between the analog radio signals transmitted or received by the radio module and the digital data exchanged with the core network. It also implements coding and modulation techniques defined by mobile communication standards (e.g., 4G, 5G) to optimise signal transmission and ensure compatibility between devices and the network. Additionally, the baseband module coordinates multiple radio channels and antenna systems, including the interaction of neighboring radio cells, ensuring seamless connectivity and minimizing interference.

**34** In this study, we only consider macro cells. Stobbe et al. (2023) further considers outdoor and indoor micro cells, which support urban hotspots, transportation routes (category 7) or industrial applications (category 8).

In standard configurations, one baseband module typically supports approximately six transceivers.[35] By dividing the average number of transceivers per antenna site (see Table 7) by six, we can estimate the number of baseband units required per antenna site. Table 8 presents these estimates across geographical classifications.

*Table 8: Total number of estimated baseband units per antenna site by geo class*

| | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| #Baseband units | 3,0 | 3,1 | 3,0 | 3,1 | 5,0 | 4,4 |

Source: WIK based on anonymized regionalized data on antenna site characteristics from the Bundesnetzagentur (2024) [Database] and Bundesnetzagentur (2024). Annual report telecommunications 2023. 16.05.2024.

## 5.3 Energy consumption of access network operations

### 5.3.1 Fixed wired networks – Fibre-to-the-Home (FTTH)

The amount of energy consumed by each active components in FTTH network identified in Section 5.2.1 is modelled in this module. Three key parameters determine the energy demand:

**Baseline Load per Network Element** (in watt-hours): This represents the minimum load required to maintain operational readiness, independent of the number of connected users or traffic load. It reflects the baseline energy requirement of network operations.

**Energy Consumption per Port** (watt-hours/port): This parameter describes the maximum energy consumption per port that a network element can reach when fully utilised. The total consumption increases as more ports are activated.

**Utilisation Rate** (% of maximum capacity): The utilisation rate reflects the actual proportion of capacity used relative to the maximum capacity. This value depends on user behaviour, such as the intensity and duration of internet usage, and directly affects the energy consumption per port. The variability in user activities affects the data traffic handled by the network equipment, influencing how much energy is required to process the data. Higher utilisation per port leads to increased energy consumption by the network component.

- **Usage Intensity and Energy Modes**: Low power modes are operational states in which a network device reduces its functionality to a minimum to save energy. Basic functions, such as the ability to resume full operational performance when needed, remain active, while non-essential processes and performance levels are reduced. This mode significantly lowers energy consumption, particularly when active network components can transition into a power-saving mode during periods of low network traffic or inactivity.

- **Duration of Use**: The duration for which network components and modems remain in a Low Power Mode depends on several factors. The most critical factor is network utilisation. During low utilisation periods (e.g., nighttime or off-peak hours), network components can transition

35 Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

into power-saving modes. The network architecture and topology also play a role; in densely populated areas with shared network resources (for instance FTTH PtMP), idle times for individual network elements are less frequent, reducing opportunities for activating Low Power Modes.

**Power Conversion Losses**: A critical additional parameter affecting all active network elements is the power conversion loss (AC/DC loss). This loss occurs when electrical energy is converted from alternating current (AC) supplied by the grid to direct current (DC) used by network elements. Furthermore, for battery-buffered systems (e.g., uninterruptible power supplies (UPS)), storage and charging losses must also be considered. The loss factor quantifies how much energy is lost during this conversion. These losses are incorporated into the total energy consumption calculations.

**Time Period**: Another key factor is the time frame used for energy consumption calculations. In this study, energy consumption is first calculated for a typical day and then extrapolated to an annual basis. In reality, daily energy consumption varies based on numerous factors (e.g., remote work, weekends, holiday seasons, high-profile events, emergencies, and outages).

The above parameters primarily depend on the equipment used. In this study, it is assumed that generic devices are deployed, with differentiation only based on the respective fibre access technology (FTTH PtP vs. PtMP). Additionally, an average, technology-neutral user behaviour is assumed to simplify and standardise the analysis. Specific parameter values used for the calculations are detailed in the appendix to this study.

### 5.3.2 Mobile networks

In contrast to fibre networks, where systematic drivers are identified and modelled as described in the previous section, the heterogenous drivers of energy consumption for active network components of antenna sites identified in Section 5.2.2 are presented through modular components (radio module and baseband module).

**Radio Module.** The design and functionality of the radio module rely on several key components, many of which have significant implications for energy consumption. Among these, the power amplifier is the most energy-intensive, as it amplifies the radio frequency signal for transmission. Other components, such as filters, oscillators and mixers, also contribute to the module's overall energy consumption, albeit to a lesser extent. Overall, the total energy consumption of the radio module is influenced by several factors, including:

- Number of transceivers
- Distribution of transceiver across frequency bands and geographic categories
- Work-load

Following Stobbe et al. (2023), we multiply the frequency-specific average number of transceivers at the antenna site, as estimated in Section 5.2.2.2, by its corresponding power consumption. Additionally, variations in energy consumption due to workload must be considered. Data on power consumption per transceiver for each frequency band and workload is typically not publicly available; however, these values were estimated by Stobbe et al. (2023). We use these values to parametrize the model and report them in Table 11, Table 12 and Table 13 in the appendix to this study.

To reflect the average power consumption of frequency-specific transceivers at geographically differentiated antenna sites, we apply the following weighting factors based on average load times:

- Low workload (20% capacity utilisation): 6 hrs. per day
- Medium workload (50% capacity utilisation): 10 hrs. per day
- High workload (100% capacity utilisation): 8 hrs. per day

The resulting power consumption for each transceiver, adjusted for workload, is then summed across all frequency bands to determine the total power consumption of the radio module per antenna site of a particular geographical category.

*Table 9: Power consumption of radio units per antenna sites across geo classes*

| Workload | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| Low | 2,618 | 2,558 | 2,432 | 2,860 | 5,343 | 4,894 |
| Medium | 2,642 | 2,586 | 2,465 | 2,901 | 5,458 | 5,014 |
| High | 2,683 | 2,634 | 2,520 | 2,970 | 5,651 | 5,213 |
| Average | 2,650 | 2,595 | 2,475 | 2,914 | 5,494 | 5,050 |

Source: WIK based on anonymized regionalized data on antenna site characteristics from the Bundesnetzagentur (2024), Bundesnetzagentur (2024). Annual report telecommunications 2023. 16.05.2024 and Stobbe et al (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023.

**Baseband Module.** The energy consumption of the baseband module is closely linked to its workload, which depends on factors such as data rates, the complexity of coding and modulation schemes, and the number of transceivers it supports. The digital signal processing unit (DSP), as the core component of the baseband module, accounts for the majority of its energy consumption due to the computational demands of modulation, coding, and demodulation tasks. Additionally, memory and storage requirements, used for managing data flow and intermediate storage during signal processing, contribute to power demand, particularly as data rates increase. Thus, the total energy consumption of the baseband module is determined by the following factors:

- Number of transceivers
- Distribution of transceiver across frequency bands
- Work-load
- Cooling
- Number of baseband units
- Baseband unit's base power

We calculate the energy consumption by multiplying the frequency-specific number of transceivers at the antenna site by its corresponding energy consumption, adjusted for workload-related variations in energy consumption. The workload times are consistent with those assumed for radio units. The energy consumption per transceiver baseband unit, considering frequency and workload variations, is derived from Stobbe et al. (2023) and is reported in Table 15 in the appendix to this study. The resulting power consumption for each transceiver is then aggregated across all frequency bands to obtain the total power consumption of a baseband module. A base power consumption of 25 watts is added,[36] which is then scaled according to the estimated number of baseband units. Additionally, a cooling overhead is applied, ranging from 7% for low workload to 15% for high workload, as suggested in Stobbe et al. (2023). The final results, showing the average energy consumption of baseband modules differentiated by geographical categories, are presented in the table below.

*Table 10: Power consumption of baseband units per antenna sites across geo classes*

| Workload | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| Low | 579 | 604 | 596 | 612 | 1,576 | 1,274 |
| Medium | 651 | 686 | 683 | 708 | 1,900 | 1,549 |
| High | 771 | 823 | 828 | 869 | 2,440 | 2,006 |
| Average | 673 | 711 | 710 | 738 | 1,999 | 1,633 |

Source: WIK based on anonymized regionalized data on antenna site characteristics from the Bundesnetzagentur (2024) [Database], Bundesnetzagentur (2024). Annual report telecommunications 2023, 16.05.2024 and Stobbe et al (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023.

**Total energy consumption per antenna site**. Estimated energy consumptions from the radio module and the baseband module are then added and, as in fixed wired networks, power conversion losses (AC/DC losses) are estimated and included in the calculations. As Stobbe et al. (2023), we assume a power conversion loss of 15%. Results are presented in Table 11.

*Table 11: Total power consumption of antenna sites across geo classes*

| Workload | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| Average | 4,002 | 3,988 | 3,844 | 4,398 | 9,093 | 8,090 |

Source: WIK based on anonymized regionalized data on antenna site characteristics from the Bundesnetzagentur (2024) [Database], Bundesnetzagentur (2024). Annual report telecommunications 2023, 16.05.2024 and Stobbe et al (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023.

## 5.4 Transforming energy consumption into $CO_2$ emissions

The energy consumption resulting from the operation of the presented access network technologies encompasses all active, energy-relevant network components during regular operation. $CO_2$ emissions from network operations are calculated using the following formula:

$$CO2\ (network\ operation) = Energy\ consumption\ (kWh) \times CO2\ eq/kWh$$

**Energy Consumption**: This refers to the amount of energy required to operate the network components of an access technology over a given time period, measured in kilowatt-hours (kWh). These values are calculated for each access technology as described in Section 5.3.

36 Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

**$CO_2$-equivalents per kWh**: This factor indicates how much $CO_2$ emissions (in grams) are released from generating one kilowatt-hour of electricity ($CO_2$-eq/kWh). It depends on the energy source used for electricity production (e.g., coal, natural gas, renewables) and varies according to the national energy mix. A higher share of renewable energy reduces the $CO_2$-equivalent value. For Germany, the emission factor for electricity production is sourced from the German Federal Environment Agency (Umweltbundesamt, 2023).[37] In 2023, this factor was 445 g $CO_2$-eq/kWh.

To calculate the $CO_2$ emissions caused by network operations, the energy consumption is multiplied by the $CO_2$-equivalent per kWh.

37 Umweltbundesamt (2024). Entwicklung des $CO_2$-Emissionsfaktors für den Strommix in Deutschland in den Jahren 1990 bis 2023 [Federal Environment Agency (2024). Development of the $CO_2$ Emission Factor for the Electricity Mix in Germany from 1990 to 2023].

# 6 Data and model assumptions

## 6.1 Data sources

### 6.1.1 Household data for network dimensioning

For purposes of this study, we use municipality-level data from the spatial classification dataset of the German Federal Institute for Research on Building and Regional Planning (BBSR).[38] This dataset entails census-based information on population, territorial area and number of households for each municipality in Germany by the end of 2023. We use this dataset to estimate the network user driven quantities of different network elements, dimensioning them bottom-up at the municipality level for both fixed and mobile access networks (see Chapter 5).

### 6.1.2 Data on frequency use at mobile antenna sites

To model the existing mobile access network in Germany, information regarding actual capacities at the antenna sites are required. This is best approximated by capturing the number and distribution of used frequencies per antenna site. For this purpose, we turn to the *Bundesnetzagentur* for data on the registered antenna sites and their configurations. This data is regularly collected by the German telecommunications regulator as part of its regulatory responsibilities and is not publicly available. Specifically for this study, we requested the data in an anonymized form, categorized into six geographical regions, to reflect non-location-specific figures of registered carrier frequencies per antenna site.[39]

We utilise this data for two main purposes: first, to estimate the number of antenna sites per geographical category (ranging from rural to urban), and second, to determine the number and distribution of frequency-specific transceivers across these geographical categories.

For the first purpose, we used the distribution of antenna sites provided in the raw data from the Bundesnetzagentur and applied it to the total number of antenna sites (89,341) reported in their annual telecommunications report for 2023.[40] This approach allows us to estimate the number of antenna sites within each geographical category. The following table illustrates this procedure and the resulting estimates.

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**38** BBSR (2023). Raumgliederungssystem des Bundesinstituts für Bau-, Stadt- und Raumforschung, [Dataset: BBSR raumgliederungen-referenzen-2022.xlsx],17.11.2023.

**39** This dataset differs from the one used by Stobbe et al. (2023), who employed the *'EMF antenna location database*,' which compiles individual data sheets with detailed information on the configuration of the antenna site. They claim that due to the impossibility to aggregate this data, a systematic analysis was not feasible, and a sample-based evaluation was necessary. In contrast, this study uses a more condensed dataset, which provides information on antenna locations for all registered carrier frequencies across Germany.

**40** Bundesnetzagentur (2024). Annual report telecommunications 2023, 16.05.2024.

*Table 12: Number and distribution of antenna sites across geo class*

| Geo class | Raw data on number of antenna sites | Distribution [%] | Estimated number of antenna sites |
|---|---|---|---|
| 1 Rural | 29,833 | 24% | 21,828 |
| 2 Rural | 16,985 | 14% | 12,428 |
| 3 Suburban | 20,761 | 17% | 15,191 |
| 4 Suburban | 12,840 | 11% | 9,395 |
| 5 Urban | 25,424 | 21% | 18,602 |
| 6 Urban | 16,260 | 13% | 11,897 |
| N/A | 52 | | - |
| Total | **122,155** | **100%** | **89,341[1]** |

Source: WIK based on anonymised regionalized data on antenna site characteristics by Bundesnetzagentur (2024) [Database] and [1]Bundesnetzagentur (2024). Annual report telecommunications 2023, 16.05.2024.

The second objective, determining the number and distribution of frequency-specific transceivers, is based on the assumption that the number of transceivers is proportional to the frequency bands used at each antenna site. The dataset provides information on the number of carrier frequencies used by frequency band, antenna site, technology, main beam direction, and other factors, all matched to specific geographical categories. This data offers valuable insights into the number and distribution of frequencies employed across different antenna sites. The raw distribution of used frequencies at antenna sites across various geographical regions is presented in Table 13.

*Table 13: Distribution of frequencies across geo class*

| Frequency [MHz] | 1 Rural | 2 Rural | 3 Suburban | 4 Suburban | 5 Urban | 6 Urban |
|---|---|---|---|---|---|---|
| 700 | 13% | 9% | 7% | 6% | 6% | 6% |
| 800 | 19% | 17% | 15% | 13% | 12% | 10% |
| 900 | 33% | 30% | 27% | 25% | 23% | 22% |
| 1400 | 2% | 2% | 2% | 2% | 2% | 2% |
| 1800 | 16% | 21% | 24% | 25% | 24% | 23% |
| 2000 | 16% | 19% | 22% | 22% | 20% | 19% |
| 2600 | 1% | 1% | 2% | 3% | 6% | 10% |
| 3600 | 1% | 1% | 2% | 4% | 7% | 9% |
| **Total** | 100% | 100% | 100% | 100% | 100% | 100% |

Source: WIK illustration of the anonymised regionalized data on antenna site characteristics from Bundesnetzagentur (2024) [Database].

### 6.1.3 Data on energy consumption for wired broadband equipment

#### 6.1.3.1 EU Code of Conduct on Energy Consumption of Broadband Communication Equipment

The EU Code of Conduct on Energy Consumption of Broadband Communication Equipment[41] is a framework developed by the European Commission to voluntarily reduce the energy consumption of telecommunications networks and promote more sustainable practices within the industry. It provides

**41** EU Joint Research Centre (2024). Code of Conduct on Energy Consumption of Broadband Equipment: Version 9.

guidelines and maximum energy consumption limits that network operators and manufacturers can use to optimise the energy efficiency of their network components without compromising performance or service quality. The Code aims to ensure energy-efficient operation across different parts of the network infrastructure, particularly in access networks.

Signatories to the EU Code of Conduct (CoC) voluntarily commit to ensuring that at least 90% of their deployed network equipment complies with the specified energy consumption limits.

The EU Code of Conduct (2024) covers a broad range of broadband equipment used in telecommunications networks. Nearly all network components across different access technologies are represented in terms of energy consumption. These components can be categorized into two groups:

- Customer Premises Equipment (CPE)
- Network Equipment

**Customer Premises Equipment** (CPE). The energy consumption of CPE is differentiated based on its functionality, with separate limits specified for the maximum energy consumption of various features:

- Core CPE functionalities such as network processing and storage
- WAN/Uplink interface, which supports connections using technologies like Ethernet, PON, xDSL, G.Fast, DOCSIS, or 4/5G
- Additional CPE functionalities, including Wi-Fi, powerline, USB, or Bluetooth

This study focuses solely on the modem functionality of the CPE. Accordingly, the energy consumption of the core CPE functionalities and the WAN/Uplink interface is considered, while the energy use of additional functionalities is excluded, as these depend on individual user needs and are not managed by network operators.

**Network Equipment.** In the EU Code of Conduct, network equipment refers to devices used by operators to deliver and manage broadband services. These devices are equipped with a certain number of ports to connect customers within a service area. Key network components for this study comprise Optical Line Terminals (OLT) for FTTH networks.

Energy consumption is specified in watts per network component and watts per port, based on standardised testing conditions according to ETSI EN 303 215.[42,43] Testing is conducted on fully configured devices, meaning all ports are active, and the devices operate at maximum configuration. The EU Code of Conduct (2024) differentiates energy consumption by:

- **Transmission technology** (e.g., PtP Ethernet, XGS.PON, G.PON), as energy demands vary between technologies

**42** ETSI EN 303 215 (2014). Environmental Engineering (EE) Measurement methods and limits for power consumption in broadband telecommunication networks equipment. V1.2.11 (2014-12).

**43** With regard to environmental conditions such as room temperature, humidity, and operating voltage, measurements must also be conducted under varying load profiles based on real user traffic scenarios. Components that are not directly related to network operations, such as AC/DC converters, batteries, or cooling systems, are excluded from the measurement.

- **Port density** (number of ports per device), with higher port density typically leading to greater energy efficiency per port due to better resource sharing

- **Maximum bandwidth capacity per port** (e.g., 1 Gbps or 10 Gbps)

- **Operating modes or power modes**, the operating modes of network equipment depend on network load and range from full-load (maximum utilisation) to low-load (reduced activity) and stand-by (inactive). For customer premises equipment (CPE), operating modes are categorised into the normal operating mode (on-state) and the standby mode (ready-state). In the on-state, the device actively transmits user data, whereas in the ready-state, no data transmission occurs, but the device remains ready to transmit data without requiring reconfiguration or manual intervention.

#### 6.1.3.2 Manufacturer Data Sheets

In addition to the EU Code of Conduct on Energy Consumption of Broadband Communication Equipment (2024), this study also uses manufacturer-provided information on network elements in access networks. Technical specifications and energy consumption data from manufacturers such as Cisco, Huawei, and Nokia were consulted. Some data sheets provide detailed information on the energy consumption and power requirements of devices, including maximum and typical power demands for individual modules. However, due to the inconsistent formatting of data across manufacturers, a systematic evaluation was not feasible. Instead, these data sheets were used for sample-based validation of energy figures as defined in the EU Code of Conduct (2024).

Where detailed energy data for individual modules was available,[44] the focus was on identifying the baseline energy consumption of key network elements, such as OLTs. The baseline energy consumption refers to the fundamental energy requirement of a network element when operating without active customer interfaces, essentially reflecting its idle energy usage.

The analysis of baseline energy consumption involved a detailed breakdown of individual modules, as specified in the manufacturers' technical documentation. Key modules include:

- CXU (Convergence/Cross-Connection Unit) or Switching Matrix
- Fan/Chassis
- CIU (Control and Interface Unit)
- PM_UPL (Power Management Unit/Power Supply)

These modules were identified as fixed, energy-relevant components that continuously consume power regardless of the utilisation intensity of the devices.

The baseline energy consumption values for the analysed network elements used in this study are provided in Section 5.3.

**44** Cisco ME 4600 Series Optical Line Terminal Datasheet..

### 6.1.4 Data on $CO_2$ equivalent

To calculate $CO_2$ emissions from energy consumption, the emission factor provided by the German Federal Environment Agency (Umweltbundesamt, 2023)[45] was used, which specifies a value of 445 g $CO_2$-eq/kWh for electricity generation in Germany. This emission factor is based on the average $CO_2$ intensity of Germany's electricity mix and is commonly applied in environmental studies to quantify carbon emissions associated with energy use.

Germany's electricity mix relies on primarily on renewable energy (51,8%) and fossil-based energy (44,5%).[46] There has been an increase of the share of renewable energy over time, yet $CO_2$ emissions persist, particularly from fossil fuel-based energy sources in the mix. The value of 445 g $CO_2$-eq/kWh is therefore applied as an average emission factor for the operation of network elements and does not account for temporal variations in generation or individual consumption patterns.

## 6.2 Model assumptions

### 6.2.1 Network dimensioning

#### 6.2.1.1 Fixed wired networks

As part of this study, assumptions were made to facilitate the bottom-up network modelling of the German access network, simplifying the representation of a hypothetical fibre network either FTTH PtP or FTTH PtMP with 100% homes activated. These assumptions pertain to both the structure of the network and the geographical distribution of its components. The key assumptions are as follows:

**Uniform Equipment and Generic Network.** It is assumed that all network segments utilise uniform and standardised equipment. This means that the same type of devices is deployed for each access technology at all relevant network transition points (e.g., Optical Line Terminals, OLT) and network termination points (Network Termination).

This assumption is made to simplify the complexities associated with heterogeneous infrastructure components and to reflect the expectation that standardisation of network elements within the network will lead to operational and technical efficiency gains. These efficiencies come from network scaling and streamlined maintenance processes. Additionally, this assumption is crucial for ensuring the traceability of energy consumption and $CO_2$ emission calculations, as uniform equipment allows for consistent and transparent determination of consumption values.[47]

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**45** Direct GHG emissions of electricity consumption with supply chains (Umweltbundesamt, 2024. Entwicklung des $CO_2$-Emissionsfaktors für den Strommix in Deutschland in den Jahren 1990 bis 2023 [Federal Environment Agency, 2024. Development of the $CO_2$ Emission Factor for the Electricity Mix in Germany from 1990 to 2023]).

**46** Umweltbundesamt (2024). Entwicklung des $CO_2$-Emissionsfaktors für den Strommix in Deutschland in den Jahren 1990 bis 2023 [Federal Environment Agency (2024). Development of the $CO_2$ Emission Factor for the Electricity Mix in Germany from 1990 to 2023].

**47** We assume that the underlying equipment complies with the limits set by the CoC. Actual energy consumption may also fall below these limits. In reality, there may also be deviations above the specified values. Fundamentally, using CoC values to model a state-of-the-art efficient network represents more of an upper-bound estimate of energy consumption.

**No Overbuild of Routes or Active Network Components.** For the purposes of this study, it is assumed that there will be no overbuild of existing routes or active network components. Overbuild, where parallel network structures are constructed alongside existing infrastructure, typically results in inefficiencies and higher costs due to redundant infrastructure, increased material usage, and heightened energy consumption. This study is based on the principle that existing routes and network components are utilised, with new construction occurring only in areas lacking existing infrastructure.

Of course, there are also other aspects, which are determined by the actual conditions of the coverage areas, influence the technology comparison, for which we haven't accounted for. For example, the topology of a region can make the expansion of fixed network technologies more difficult due to rocks, whereas mountains that can serve as antenna locations can make coverage in the area more favourable.

#### 6.2.1.2 Mobile networks

The following assumptions[48] are used for the dimensioning of mobile access networks:

**Use of Regionally Differentiated Antenna Sites (Six Regional Types)**. This assumption takes into account the need for region-specific planning of mobile network infrastructure. It is based on the premise that different regions – such as urban, suburban, and rural areas – require tailored network configurations due to varying population densities, coverage needs, and data demands. Based on Stobbe et al (2023), six distinct regional classifications are defined and considered sufficient to effectively capture relevant regional variations in antenna site configurations (see section 5.2.2.1).

**Generic Mobile Access Networks**. In Germany, three major parallel and overlapping mobile networks are operated nationwide by Deutsche Telekom, Telefónica Deutschland, and Vodafone Deutschland.[49] Stobbe et al. (2023) compared mobile network operators in terms of customer base, number of antenna sites, and frequency spectrum and found a relative comparability of the existing three network operators. This allows to model and extrapolate a generic nationwide mobile network without modelling each network individually.

**Overlapping Mobile Networks of the Three Active Network Operators.** Mobile networks in Germany are operated by the aforementioned three network providers. This assumption acknowledges that, especially in densely populated urban areas, each operator tends to deploy its own infrastructure, resulting in overlapping mobile networks. Unlike fixed wired access networks, mobile access networks operate through an air interface, where overlapping antenna coverage is an inherent feature of wireless communication. This overlapping infrastructure includes network equipment which are typically not shared by operators but are located in close proximity to each other. The overlap of networks is considered in the model, recognising that each operator's independent infrastructure deployment leads to increased density of mobile network elements, influencing coverage and overall network capacity.

**Consideration of the Existing Technology Mix (Brownfield Approach).** The Brownfield approach refers to the evaluation of existing network infrastructure rather than starting from scratch with a hypothetical new deployment. This assumption involves considering the mix of technologies already in place, such as 4G and 5G networks, and how they coexist within the same antenna sites. The model assumes

**48** Radio emission aspects are beyond the scope of this study.
**49** As of December 8, 2023, 1&1 Mobilfunk GmbH operates its own public mobile network (Bundesnetzagentur, 2024. Daten zur Mobilfunkversorgung der 1&1 Mobilfunk GmbH. Pressemitteilung 14.03.2024).

that newer technologies were integrated with the pre-existing infrastructure, leveraging the existing sites while upgrading their capacity to accommodate newer technologies.

**One Transceiver per Technology, Frequency Band, Main Beam Direction, Network Operator, and Location.** This assumption simplifies the model by assuming that each combination of technology, frequency band, beam direction, network operator, and antenna location corresponds to one dedicated transceiver. In practice, this means that for each distinct configuration – whether it is a particular frequency band (e.g., 700 MHz, 3.5 GHz), technology (e.g., 4G, 5G), or geographical location – there is a corresponding transceiver that manages the transmission and reception of signals. While real-world deployments may have diverse configurations, this assumption provides a straightforward way to model and estimate network capacity and energy consumption.

### 6.2.2 Energy consumptions

#### 6.2.2.1 Fixed wired networks

**Network Termination (Modem).** The assumptions regarding the utilisation of customer modems or network termination points are based on the duration of use in different operating modes, which is primarily determined by individual user behaviour. According to the literature, modems are active on average for 15% of the time (approximately 3.6 hours per day),[50] representing the period during which data is transmitted. For 25% of the time (approximately 6 hours, predominantly at night), they are in sleep mode, a state of reduced energy consumption. During the remaining 60% of the time,[51] modems are in the ready state, where they await data requests but do not actively transmit data.

For PtP customer modems, which only need to be active when transmitting or receiving data for an individual customer, a longer duration in sleep mode is assumed compared to other access technologies. This assumption is supported by statistics for Germany, which indicate that end users are offline for an average of 59% of the time.[52]

The energy consumption in the different operating modes is based on the limits outlined in the EU Code of Conduct (2024).

**Central equipment**. The baseline energy consumption of central equipment was specified for different network architectures based on energy data for various network modules provided in the manufacturer sheets (see Section 6.1.3). For point-to-point connections (FTTH PtP), the baseline accounts for 10% of the total energy consumption. For FTTH PtMP, the baseline proportion is slightly higher (13%). These differences reflect the specific network architectures and the way devices operate under various usage scenarios.

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**50** Lannoo et al. (2015). How Sleep Modes and Traffic Demands Affect the Energy Efficiency in Optical Access Networks.

**51** Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

**52** In 2024, the average user time spent on internet accounted 69,3 hours per week in Germany (Statista, 2024). Durchschnittliche Nutzungsdauer des Internets pro Woche in Deutschland in den Jahren 2015 bis 2024 [Statista, 2024. Average Internet Usage Time per Week in Germany from 2015 to 2024].

It is further assumed that the Low-Power Mode can only be utilised in FTTH PtP network architectures. In shared media networks (so-called "Shared Medium") such as FTTH PtMP, these energy-saving measures are less effective or not applicable. This assumption is based on findings by Kun et al. (2015) and the EU Code of Conduct (2024), which demonstrate how energy consumption and energy-saving measures vary depending on the access technology and network topology.

**MPoP**. To determine the energy consumption of Metropolitan Points of Presence (MPoP), the Power Usage Effectiveness (PUE) was used as a key factor. PUE is a metric for evaluating energy efficiency in networks, defined as the ratio between the total energy consumption of a facility and the energy actually used by network devices.

For the network components considered in this study, a PUE factor of 1.2 was applied. This means that for every unit of energy consumed by network elements, an additional 20% of energy is used for supporting systems such as cooling and power supply. A PUE of 1.2 is considered relatively efficient compared to less optimised infrastructures, where the PUE factor can be significantly higher.[53]

#### 6.2.2.2 Mobile networks

The modelling of energy consumption in mobile access networks in Germany is based on the following key assumptions regarding antenna sites and end-user devices:

**Energy Consumption of Antenna Sites**. First, it is assumed that very small antenna sites contribute at least 50% of the total energy consumption, with a minimum energy consumption threshold applied. This assumption is particularly relevant for smaller or less complex network configurations, where the operational energy requirements are proportionally high compared to their overall network capacity (see further explanations on Section 5.2.2). Furthermore, it is assumed that since the data from Stobbe at al. (2023) collected in 2019, there has been no significant change in the energy efficiency of the radio and baseband modules. This indicates a stable performance in terms of energy usage by these critical components of the network infrastructure. Additionally, the operational downtime of antenna sites, in terms of energy consumption patterns throughout the day, also taken from Stobbe at al. (2023), is assumed to have remained unchanged since 2019, meaning that energy consumption is distributed consistently across different times of the day.

**Energy Consumption of End-User Devices.** For end-user devices, two main categories are considered. Stationary devices, such as mobile-capable end-user modems with a 4G interface, are assumed to consume between 3 and 3.6 watts (W) in energy, based on the EU (2024) Code of Conduct on Energy Consumption of Broadband Equipment (see 6.1.3.1). These devices typically operate with a constant energy demand due to their role in maintaining network connectivity. Non-stationary devices, such as mobile phones and tablets, exhibit a lower energy consumption of approximately 0.4 W, as reported in the study by Kemna et al. (2020) (see details in Table 16 in the appendix to this study). This distinction between stationary and non-stationary devices is crucial for accurately estimating the total energy demand in the network, taking into account the different types of devices connected to the mobile access infrastructure.

**53** Moayeri (2024). Die immer noch unterschätzten IT-Energiekosten. Der Netzwerk Insider.

# 7 Modelling results

## 7.1 Model results for Germany

Based on the bottom-up modelled described in Chapter 5 and populated with municipality-level data and network-specific energy data outlined in Chapter 6, energy requirements for operating fibre access networks (with 100% homes activated) and the actual total energy consumption of mobile access networks for the year 2024 were estimated for Germany. Results are presented in Table 14.

*Table 14: Total energy consumption in 2024 in Germany by access technology*

| Geographical context | #Active Connections | #Mobile Internet Users | Estimated total energy consumption [in million. MWh] | | | |
|---|---|---|---|---|---|---|
| | | | FTTH PtP | FTTH PtMP | Mobile stationary | Mobile non-stationary |
| Germany-wide | 40.2 million. | 66.8 million. | 1.27 | 1.24 | 4.03 | 4.83 |

Source: WIK. Own calculations.

Table 14 estimates the energy consumptions for each technology separately. These estimates are based on the total number of active connections for fixed wired technologies, specifically, 40.2 million active connections for FTTH (Fiber-to-the-Home) Point-to-Point (PtP) and Point-to-Multipoint (PtMP), and 66.8 million mobile internet users in Germany in 2024. For mobile networks, an important distinction is made between stationary and non-stationary mobile technologies. While both rely on wireless communication between the end user and the network, the key difference lies in the user's connection: stationary mobile technologies involve devices that remain in a fixed location (e.g., fixed broadband modems), while non-stationary mobile technologies involve mobile devices, such as smartphones, that can move between locations. This distinction significantly impacts the way energy consumption at antenna sites is allocated across these technologies. Non-stationary mobile technologies (e.g. internet communication via smartphones) are based on the entire energy consumption estimated at the antenna site for the 66.8 million internet mobile users. In contrast, for stationary mobile technologies (considered a fixed wired alternative), only a fraction of the energy consumption at the antenna site is allocated. This fraction is determined by the ratio of fixed active connections (40.2 million) to mobile internet users (66.8 million).

Results displayed in Table 14 show that fibre access technologies, FTTH PtP and PtMP, consume significantly less energy than the stationary mobile-based alternatives.

We compare these results with those from similar studies found in the literature (see Section3.3). The comparison is made on a per-connection basis for fiber access networks and on a total basis for antenna sites in mobile networks. The results of this comparison are presented in Table 15.

*Table 15: Validation and comparison of results with existing literature*

| | FTTH PtP (Ethernet 1G) | FTTH PtMP (XGS.PON) | Antenna Sites |
|---|---|---|---|
| | kWh/a per connection | kWh/a per connection | TWh/a |
| WIK (2024) | 31,5 | 30,8r | 4,57 |
| Stobbe et al. (2023) | | | 3,69 – 5,14 TWh/a[1] |
| Obermann (2022) | 30,7 | 53,4 | |
| Breide et al. (2021) | 52,9 | 37,1[2] | |

Source: WIK. Own calculations.[1] Estimates 2022 – 2026. [2] Estimates for G.PON.

For FTTH Point-to-Point (PtP), the estimated energy consumption in this study is 31.5 kWh per connection per year, which is in line with Obermann (2022), which reports a slightly lower value of 30.7 kWh.[54] Breide et al. (2021) provides a significantly higher estimate of 52.9 kWh,[55] arising from potential differences in assumptions about the energy savings at the customer's modem.

For FTTH Point-to-Multipoint (PtMP), this study estimates 30.8 kWh per connection per year, which is significantly lower than Obermann (2022) estimate of 53.4 kWh.[56] This difference is explained by the choice of customer modem and assumptions about energy saving modes. Breide et al. (2021) offers a more moderate estimate of 37.1 kWh,[57] yet their study considers G.PON instead of XGS.PON for FTTH PtMP networks operations.

For mobile network antenna sites, only Stobbe et al. (2023) provides projections of energy consumption, analysing mobile network energy use in 2019. Their projections range from 3.69 TWh/a in 2022 to 5.14 TWh/a in 2026. Our estimate for 2024, 4.57 TWh/a, falls within this range.

Based on the national average energy consumption values per access technology presented above, we further disaggregate these values by component to analyse their individual contributions to overall energy consumption. This analysis is illustrated in Figure 5.

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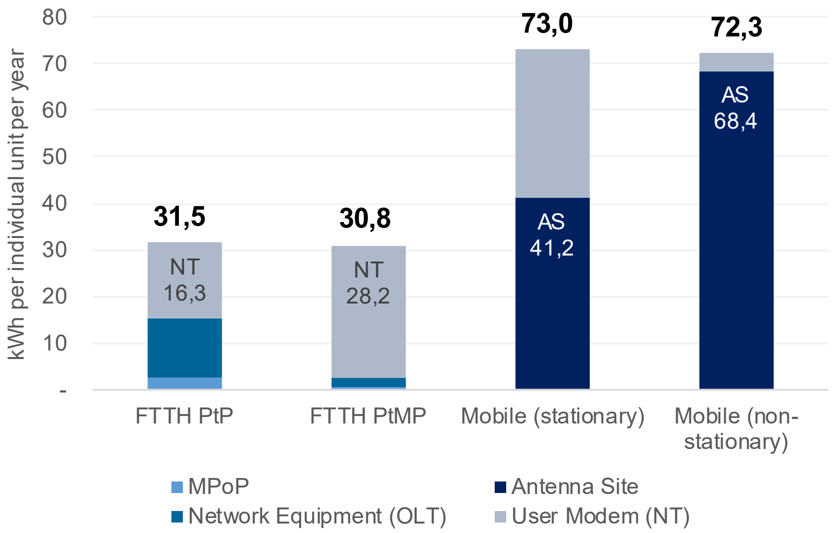
**54** Based on Obermann (2022), per connection values in kWh/a derived as follows:
3,5 W x 24 hours x 365 days / 1000.

**55** Based on Breide et al. (2021), per connection values in kWh/a derived as follows: 64,401 W / 25,311 subscribers x 24 hours x 365 days / 1000 (for the MPoP) plus 3,5 W x 24 hours x 365 days / 1000 (for the modem).

**56** Based on Obermann (2022), per connection values in kWh/a derived as follows:
6,1 W x 24 hours x 365 days / 1000

**57** Based on Breide et al. (2021), per connection values in kWh/a derived as follows: 18,629 W / 25,311 subscribers x 24 hours x 365 days / 1000 (for the MPoP) plus 3,5 W x 24 hours x 365 days / 1000 (for the modem).

*Figure 4: Contribution of network elements to average energy consumption in Germany by technology (kWh per connection or mobile user per year)*[58]




Source: WIK. Own calculations.

The graph provides a comparison of the energy consumption contributions from different network components across various technologies, including Fiber-to-the-Home (FTTH) Point-to-Point (PtP), FTTH Point-to-Multipoint (PtMP), and mobile networks (stationary and non-stationary). The energy consumption is measured in kWh per individual unit per year, illustrating how different components, such as the network equipment (OLT), user modems (NT), and antenna sites (AS), contribute to the overall energy usage.

For FTTH technologies, the network equipment (OLT) and user modem (NT) are the primary contributors to energy consumption. The relative contribution of each to the overall energy consumption depends on the chosen network topology. In the FTTH PtP (Point-to-Point) architecture, the share of energy consumption attributed to network components is higher than in FTTH PtMP (Point-to-Multipoint). In contrast, in FTTH PtMP, the majority of energy requirements come from the user modem (NT). While the overall energy consumption between FTTH PtP and FTTH PtMP is similar (31,5 vs.30,8 kWh per connection), the distribution of energy costs between the customer and the network operator can vary significantly depending on the selected network architecture. This distinction highlights how network design choices can influence both the energy efficiency and the allocation of energy costs across stakeholders.

In contrast, mobile networks show a significantly different energy consumption profile. The largest contribution to energy consumption comes from antenna sites (AS). These high energy demands are indicative of the substantial infrastructure requirements for mobile networks, particularly in antenna sites that handle wireless communications. Non-stationary mobile networks (e.g., smartphones), which are battery-operated, require significantly less energy than user modems with mobile interface. Nevertheless, these devices still depend heavily on antenna sites for signal propagation, highlighting the central role of infrastructure in mobile network energy consumption.

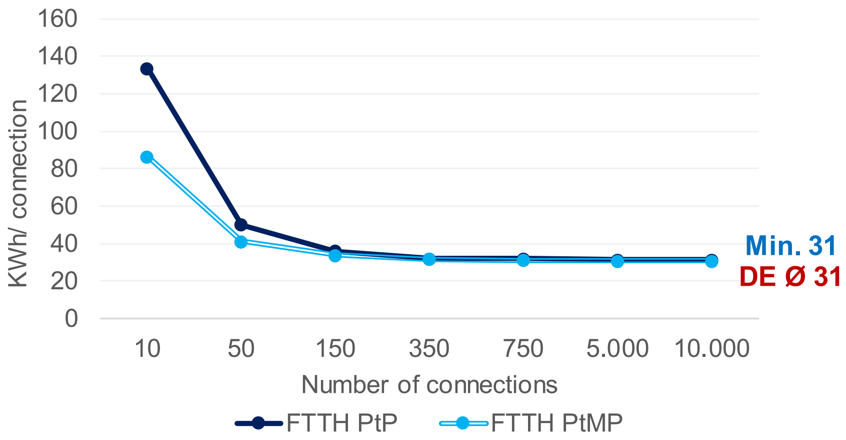
**58** From observations in practice, network measurements of access network equipment (OLT) in FTTH PtMP configurations may be lower than the 2,2 kWh/a per connection estimated in our model.

Overall, the graph illustrates that mobile networks are more energy-intensive compared to FTTH technologies and that in mobile networks, the antenna sites are the dominant contributor to energy consumption.

## 7.2 Fixed vs. mobile networks in different regional structures

In this section of the study, we move beyond the nationwide results for Germany presented earlier, which are based on estimates at the municipality level. In this part of the analysis, we simulate energy consumption across a continuum of network users, independent of the administrative boundaries of German municipalities. This allows us to generate energy curves for both fixed fibre and mobile access networks, which vary based on the number of connections, users, and population densities. The results of this theoretical analysis for fibre and mobile networks are illustrated separately in Figure 6 and Figure 7 respectively.

*Figure 5: Fibre access network – Energy curves by number of connections*

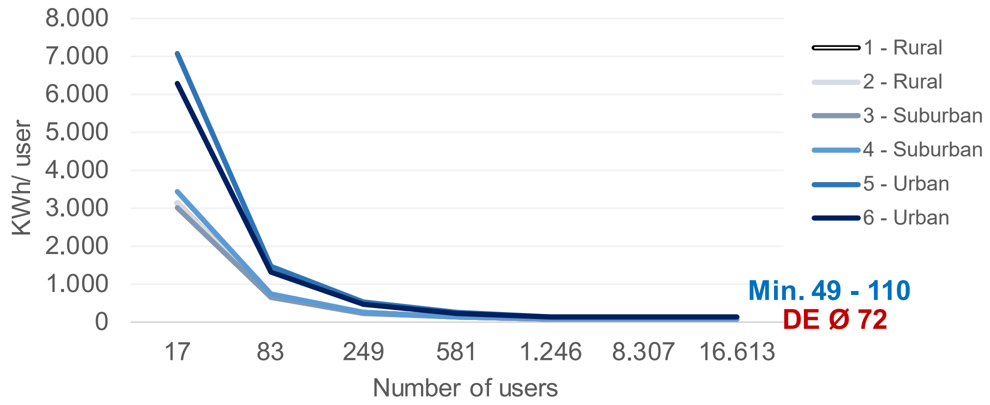



Source: WIK. Own calculations.

As depicted in Figure 6, for **fixed fibre access networks**, the average energy requirements per connection decreases as the total number of connections within the service area increases. This reduction is most pronounced at lower connection numbers, after which the decrease becomes marginal, reflecting diminishing economies of scale. Serving areas with fewer than 150 connections per MPoP exhibit significantly higher energy consumption per connection due to lower network utilisation. The energy requirements of fibre networks ranges from approximately 31 kWh per connection per year at the minimum to higher values in serving areas with a higher number of connections per MPoP. Overall, between FTTH PtP (Point-to-Point) and FTTH PtMP (Point-to-Multipoint), PtMP tend to consume less energy along the curve due to the lower base energy requirements of its central active network equipment and the higher user capacity of its network topology (see energy contribution analysis in Section 7.1).

In contrast to fibre access networks, in mobile networks population density plays a significant role, influencing energy consumption patterns. Thus, the following figure illustrates the energy curve for mobile access networks, showing how energy requirements vary with the number of mobile users and across different population density categories, ranging from 1 (rural) to 6 (urban).

*Figure 6: Mobile access network – Energy curves by number of users and population densities*




Source: WIK. Own calculations.

As illustrated in Figure 7, **mobile networks** exhibit significantly higher energy consumption per user (notice the much higher scale of kWh per user in Figure 7). This is primarily due to the high initial energy demand of antenna sites, which is disproportionately high when serving a smaller number of users. Furthermore, the overlapping infrastructure of the three mobile network providers exacerbates this effect, as users are split between three network operators, reducing economies of scale. Nevertheless, based on our estimations, a single antenna site consumed at least 18.000 to 40.000 kWh this year in Germany.[59].

As highlighted in Section 4.1.2, unlike fibre access networks, the energy consumption of mobile networks is influenced not only by the number of mobile users but also by user density and their spatial distribution within the geographical area. These factors affect antenna site configurations and capacities, leading to energy consumption variations across different population density categories. Consequently, energy consumption in mobile networks is modelled for varying numbers of mobile users within each density category. Geographical regions with a high number of mobile users in high-density urban areas demonstrate lower per-user energy consumption, as the infrastructure is utilised more efficiently, with a larger number of users being served per antenna. This efficiency compensates for the higher transmission capacities required by energy-intensive antenna sites in urban settings. In these areas, the energy consumption for mobile networks ranges from 49 to 110 kWh per user, contrasting with the national average of 72 kWh, presented in Section 7.1. Conversely, antenna sites in rural areas, despite having lower transmission capacities than their urban counterparts, exhibit much higher per-user energy consumption, reaching up to 3.097 kWh. This is due to the smaller number of users served, resulting in lower infrastructure utilisation.

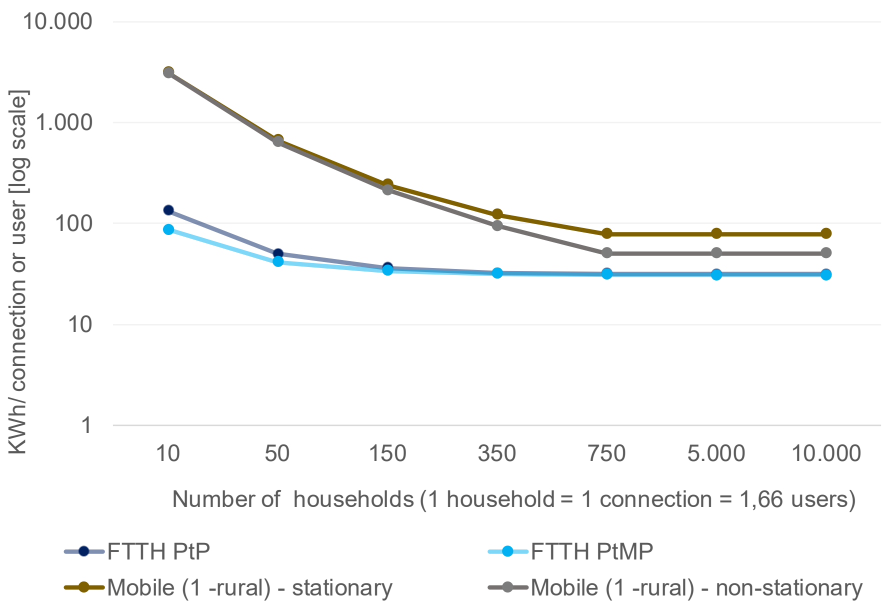
Both network types demonstrate clear economies of scale in terms of energy efficiency, albeit with distinct patterns. In fixed networks, energy efficiency improves as the number of connections increases, leveraging the centralized nature of active fibre network components. In mobile networks, average energy consumption improves with an increased number of mobile users, as base stations serve more users, thereby spreading energy demand over a larger population, and shifts upwards as densities

**59** For very smaller antenna sites, we assume an energy consumption of at least half of the national average ranging between 4.000 and 9.000 Watts per hour, depending on the antenna geographical classification (see Section 5.3.2).

increases, as more dense areas require more capacities with energy intensive modules at the antenna sites.

The following figure depicts a comparison between energy consumption (kWh / year) of fibre and mobile networks across different population sizes, presented on a logarithmic scale. The analysis encompasses both fixed (fibre) and mobile networks, with distinctions made between stationary and non-stationary mobile connections, as well as between fibre network topologies such as FTTH PtP (Point-to-Point) and FTTH PtMP (Point-to-Multipoint).

*Figure 7: Fibre vs. mobile access networks – energy consumption by population size*




Source: WIK. Own calculations.

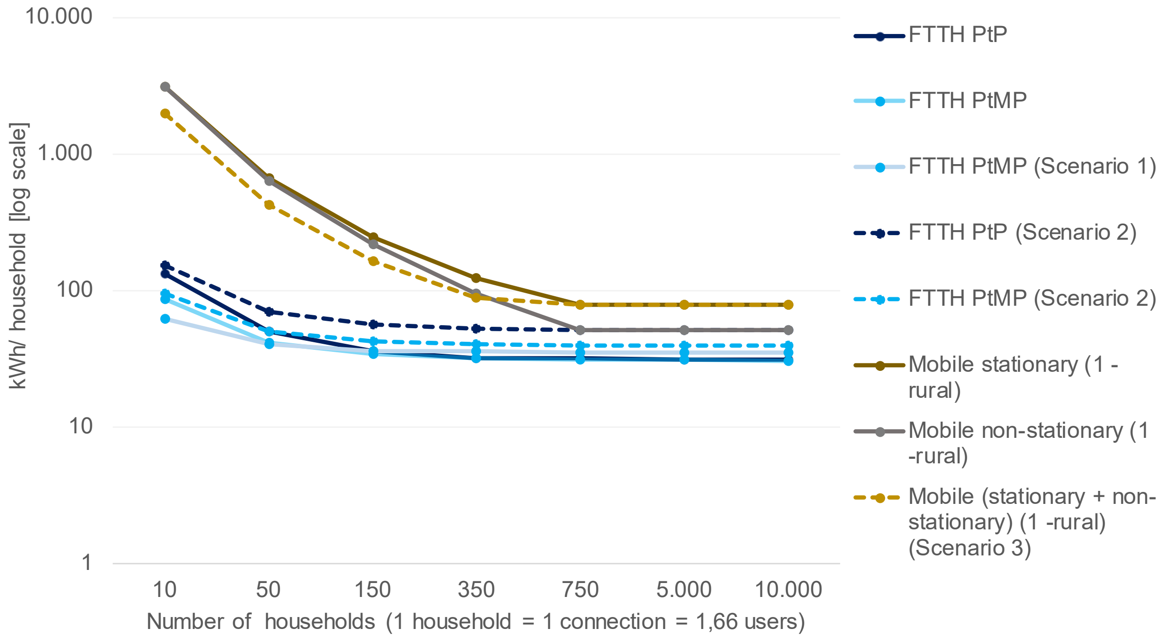
The results highlight that both fibre and mobile networks benefit from economies of scale, as energy consumption per connection decreases with increasing numbers of connections. However, fibre networks demonstrate higher energy efficiency consistently throughout all the geographical spectrum compared to mobile networks.

In rural low-density areas, mobile networks exhibit a significant energy disadvantage compared to fibre networks, primarily due to their substantially higher energy requirements per user. In these regions, the energy consumption per user for mobile networks is approximately ten times greater than that of fibre networks, underscoring the environmental inefficiency of mobile infrastructure in sparsely populated areas.

## 7.3 Sensitivity analysis

Finally, we test our baseline results for the energy consumption of fixed broadband networks (FTTH) and mobile access networks under distinct sensitivity scenarios. These scenarios aim to assess the impact of different assumptions of the two network types, particularly in rural areas, as it is the centre of dispute between FTTH and mobile-based as a fixed access substitute. The results of these sensitivity analysis are illustrated in Figure 8.

*Figure 8: Comparison of energy curves between FTTH and mobile access networks under different scenarios*




Source: WIK. Own calculations.

**Scenario 1**. This scenario focuses on the selection of network equipment, particularly the splitting ratio for FTTH Point-to-Multi-Point (PtMP) architectures. The scenario assumes a configuration of 16 instead of 48 OLT ports, and a splitting ratio of 1:16 instead of 1:32. These changes aim to reduce the power consumption associated with the network components. The rationale behind this scenario is to observe how equipment selection and the number of connections to a single fibre link can influence the energy efficiency of the network, particularly in sparsely populated areas, where the number of potential connections is limited. The results depicted in Figure 8 suggest that, in such regions, the energy advantage of FTTH compared to mobile networks becomes more pronounced, as smaller fibre network components are best suited, in terms of capacity and energy consumption in areas with fewer connections.

**Scenario 2**. In this scenario, we adjust the assumption regarding usage intensity in fibre networks. Particularly, regarding the sleep mode. In this case, either fibre network equipment is not capable of entering sleep mode, or there is an increasing demand for connectivity that keeps the network components constantly active. By removing the sleep mode benefit, this scenario eliminates the potential energy savings that are typically observed when network components are allowed to power down during periods of inactivity. As a result, the energy consumption per connection and per capita increases in both FTTH PtP and PtMP configurations, with the PtP topology seeing an energy consumption of 51 kWh per year compared to the 39 kWh of PtMP. The scenario suggests that, by adjusting these assumptions, the energy advantage of FTTH over mobile networks reduces, yet, despite this adjustment, FTTH still remains per capita significantly less energy-intensive than mobile networks.

**Scenario 3**. The use of mobile-based stationary connections in rural areas may improve network utilisation. In this case, the energy consumption per capita might be reduced by utilising mobile network stations with high available capacity, especially in sparsely populated areas where antenna sites are underutilised. Thus, in this scenario we examine the impact of sharing the energy consumption of antenna sites between stationary and non-stationary connections in rural areas. To accomplish this, the energy consumption of the antenna site is distributed across both stationary and non-stationary mobile connections in the rural area. By sharing the infrastructure, the average energy consumption per capita is expected to decrease. The results displayed in Figure 8 show a potential reduction of up to 33% in energy consumption per capita in very sparsely populated antenna sites. However, even with this improvement, mobile networks remain less energy-efficient than fibre networks.

# 8 Conclusions

Energy consumption in FTTH access networks is driven by usage and thus the number of end-users. The end-user equipment (CPE) and the corresponding number of ports in the aggregating equipment have their peculiarities with regard to energy consumption, depending on the technology deployed. The study investigated in the difference between the FTTH topologies (PtP, PtMP) and their corresponding network elements in terms of energy consumption. Both technologies have in common that power consumption per end-customer and related $CO_2$ emissions are decreasing with an increasing number of end-customers. As the number of end-customers increases, energy curves of PtP and PtMP get closer to each other. Fibre-based access networks typically do not show any components that depend on length or distance. Energy consumption is transposed into $CO_2$ emissions with a linear transformation with the application of $CO_2$-equivalents per kWh which are reflecting the national energy mix.

The energy consumption of mobile networks is not only determined by the number of users, but also by the distance which is to be covered by the antenna location. The technical reason for this finding is that radio signal becomes of weaker the longer the distance between antenna and user is, and which results in a decreasing transmission capacity. To overcome such limitations, either additional antenna segments can be installed and/or additional transmission frequencies (frequency blocks) are needed. Both strategies lead to increasing energy consumption and thus $CO_2$ emissions. Hence, serving a certain number of end-customers close to the antenna requires less energy than serving the same number of end-customers at the edge of the radio cell. However, the basic power consumption of an antenna is dominant and significantly determines the energy consumption of mobile networks. The energy required to serve additional customers only plays a minor role in this.

The model-based comparison of the energy consumption of fibre optic and mobile networks shows a significantly higher electricity consumption per end customer in mobile networks when compared to FTTH access networks. This could be shown above all for sparsely populated regions. - Although the relative advantage of FTTH over a mobile radio solution decreases as the number of end customers per MPoP increases, it remains clear even in more densely populated areas.

In summary, having focussed on $CO_2$ emissions stemming from network usage (operations) only, the findings show that FTTH access networks are environmentally superior to mobile access network operations in all population structures.

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# Appendix

*Table 16: Usage intensity – assumptions about the workload time of different operating modes of central equipment at the MPoP or antenna site by access technology*

| | FTTH PtP | FTTH PtMP | Mobile Stationary | Mobile Non-Stationary |
|---|---|---|---|---|
| Full load time (% day) | 15% | ./. | 33% | 33% |
| Low power time (% day) | 60% | ./. | 42% | 42% |
| Stand-by time (% day) | 25% | ./. | 25% | 25% |

Source: WIK's own table based on Lannoo, B. (2015). How Sleep Modes and Traffic Demands Affect the Energy Efficiency in Optical Access Networks, p. 5 and Stobbe et al (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023, p. 91.

*Table 17: Usage intensity – assumptions about the user usage time of different operating modes of network termination equipment by access technology*

| | FTTH PtP | FTTH PtMP | Mobile Stationary | Mobile Non-Stationary |
|---|---|---|---|---|
| On state time (% day) | 15% | 15% | 15% | ./. |
| Ready state time (% day) | 8% | 60% | 60% | ./. |
| Sleep mode time (% day) | 77% | 25% | 25% | ./. |

Source: WIK's own table based on Lannoo, B. (2015). How Sleep Modes and Traffic Demands Affect the Energy Efficiency in Optical Access Networks, p. 5 and 11, Stobbe et al (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023, p. 91, EU Joint Research Centre (2024). Code of Conduct on Energy Consumption of Broadband Equipment: Version 9.0 and Statista, 2024. Durchschnittliche Nutzungsdauer des Internets pro Woche in Deutschland in den Jahren 2015 bis 2024 [Statista, 2024. Average Internet Usage Time per Week in Germany from 2015 to 2024].

*Table 18: Technical specifications and energy consumption of central equipment by fibre technologies*

| | Number of ports [#] | Bandwidth [Gbps/ Port] | Full load [W/ Port] | Low power [W/ Port] | Stand-by [W/Port] |
|---|---|---|---|---|---|
| FTTH PtP OLT Ethernet 1G | 480 | 1 | 1,7 | 1,13* | 1,13* |
| FTTH PtMP OLT XGS.PON | 48 | 10 | 6,5 | ./. | ./. |

Source: WIK's own table based on EU Joint Research Centre (2024). Code of Conduct on Energy Consumption of Broadband Equipment: Version 9.0 and Obermann (2022). Nachhaltigkeitsvergleich Internet-Zugangsnetz-Technologien [Obermann, 2022. Sustainability Comparison of Internet Access Network Technologies].

*Table 19: Energy consumption of network terminations by access technology*

| | On-State [W/ Port] | Ready-State [W/ Port] | Sleep-Mode [W/Port] |
|---|---|---|---|
| FTTH PtP Ethernet 1G | 4,0 | 3,4 | 0,16* |
| FTTH PtMP XGS.PON | 4,5 | 3,4 | 0,09 |
| Mobile stationary (4G) | 3,6 | 3,0 | 3,0 |
| Mobile non-stationary(smartphone) | 0,4 | 0,4 | 0,4 |

Source: WIK's own table based on EU Joint Research Centre (2024).. Code of Conduct on Energy Consumption of Broadband Equipment: Version 9.0 and Kemna, R. et al. (2020). ICT Impact Study. Final Report. Prepared by VHK and Viegand Maagøe for the European Commission, July 2020.

*Table 20: Energy requirements of radio units by frequency and geographical category at low capacity utilisation (work-load: 20%)*

| Frequency [MHz] | 1 Rural [W/RU] | 2 Rural [W/RU] | 3 Suburban [W/RU] | 4 Suburban [W/RU] | 5 Urban [W/RU] | 6 Urban [W/RU] |
|---|---|---|---|---|---|---|
| 700 | 120,01 | 109,46 | 102,78 | 109,46 | 109,46 | 102,78 |
| 800 | 131,97 | 121,43 | 114,75 | 131,97 | 121,43 | 114,75 |
| 900 | 150,79 | 140,73 | 131,78 | 140,73 | 140,73 | 131,78 |
| 1.500 | 140,63 | 131,68 | 121,13 | 131,68 | 121,13 | 121,13 |
| 1.800 | 141,81 | 132,86 | 122,32 | 141,81 | 132,86 | 122,32 |
| 2.100 | 152,65 | 152,65 | 143,32 | 152,65 | 152,65 | 143,32 |
| 2.600 | 163,33 | 152,26 | 142,93 | 163,33 | 152,26 | 152,26 |
| 3.500 | 470,86 | 440,10 | 409,34 | 470,86 | 440,10 | 440,10 |

Source: Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

*Table 21: Energy requirements of radio units by frequency and geographical category at medium capacity utilisation (work-load: 50%)*

| Frequency [MHz] | 1 Rural [W/RU] | 2 Rural [W/RU] | 3 Suburban [W/RU] | 4 Suburban [W/RU] | 5 Urban [W/RU] | 6 Urban [W/RU] |
|---|---|---|---|---|---|---|
| 700 | 120,60 | 110,06 | 103,38 | 110,06 | 110,06 | 103,38 |
| 800 | 132,86 | 122,32 | 115,64 | 132,86 | 122,32 | 115,64 |
| 900 | 151,39 | 141,32 | 132,37 | 141,32 | 141,32 | 132,37 |
| 1.500 | 141,07 | 132,12 | 121,58 | 132,12 | 121,58 | 121,58 |
| 1.800 | 144,04 | 135,09 | 124,54 | 144,04 | 135,09 | 124,54 |
| 2.100 | 155,02 | 155,02 | 145,70 | 155,02 | 155,02 | 145,70 |
| 2.600 | 165,11 | 154,03 | 144,71 | 165,11 | 154,03 | 154,03 |
| 3.500 | 489,84 | 459,07 | 428,31 | 489,84 | 459,07 | 459,07 |

Source: Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

*Table 22: Energy requirements of radio units by frequency and geographical category at high capacity utilisation (work-load: 100%)*

| Frequency [MHz] | 1 Rural [W/RU] | 2 Rural [W/RU] | 3 Suburban [W/RU] | 4 Suburban [W/RU] | 5 Urban [W/RU] | 6 Urban [W/RU] |
|---|---|---|---|---|---|---|
| 700 | 121,59 | 111,05 | 104,37 | 111,05 | 111,05 | 104,37 |
| 800 | 134,35 | 123,80 | 117,12 | 134,35 | 123,80 | 117,12 |
| 900 | 152,37 | 142,31 | 133,36 | 142,31 | 142,31 | 133,36 |
| 1.500 | 141,81 | 132,86 | 122,32 | 132,86 | 122,32 | 122,32 |
| 1.800 | 147,74 | 138,79 | 128,25 | 147,74 | 138,79 | 128,25 |
| 2.100 | 158,98 | 158,98 | 149,65 | 158,98 | 158,98 | 149,65 |
| 2.600 | 168,07 | 157,00 | 147,67 | 168,07 | 157,00 | 157,00 |
| 3.500 | 521,46 | 490,70 | 459,94 | 521,46 | 490,70 | 490,70 |

Source: Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

*Table 23: Energy requirements of baseband units by frequency at low, medium and full capacity utilisation (work-load: 20%, 50% and 100%)*

| Frequency [MHz] | Power Consumption [W/BU] | | |
|---|---|---|---|
| | Low (20%) | Medium (50%) | Full (100%) |
| 700 | 55,38 | 63,44 | 70,16 |
| 800 | 54,03 | 60,08 | 60,08 |
| 900 | 52,02 | 55,04 | 60,08 |
| 1500 | 52,02 | 55,04 | 100,4 |
| 1800 | 60,08 | 75,2 | 90,32 |
| 2100 | 58,06 | 70,16 | 90,32 |
| 2600 | 58,06 | 70,16 | 157,52 |
| 3500 | 71,5 | 103,76 | 70,16 |

Source: Stobbe et al. (2023). Umweltbezogene Technikfolgenabschätzung Mobilfunk in Deutschland [Environmental Technology Assessment of Mobile Communications in Germany]. Final Report, 26/2023. Project UTAMO. Fraunhofer-Institut für Zuverlässigkeit und -Mikrointegration, IZM. Editor: Umweltbundesamt [German Federal Environment Agency].

*Table 24: End user mobile devices and relevant factors for estimation of their energy consumption*

| Product | Battery capacity [mAh] | Voltage [V] | Endurance Rating [h] |
|---|---|---|---|
| Apple iPhone XR | 2.942 | 3,7 | 78 |
| Samsung Galaxy A40 | 3.100 | 3,7 | 73 |
| Samsung Galaxy A50 | 4.000 | 3,7 | 50 |
| Apple iPhone 8 | 1.821 | 3,7 | 66 |
| Redmi Note 7 | 4.000 | 3,7 | 108 |
| Samsung Galaxy S10 | 3.400 | 3,7 | 79 |
| Samsung Galaxy A70 | 4.500 | 3,7 | 103 |
| Samsung Galaxy S10+ | 4.100 | 3,7 | 91 |

Source: WIK based on Kemna, R. et al. (2020). ICT Impact Study. Final Report. Prepared by VHK and Viegand Maagøe for the European Commission, July 2020

**International Standards**

**GHG protocol**

The GHG Protocol is widely recognised as the most commonly used accounting tool for quantifying and managing greenhouse gas emissions worldwide. [60] While it primarily serves as an accounting standard for GHG emissions, the other standards discussed in this report are more aligned with reporting purposes.

The GHG Protocol was developed through a collaboration between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). [61] It provides a standardised framework for businesses and governments to measure and manage their greenhouse gas emissions. This framework helps organisations identify opportunities for emission reductions, set reduction targets, and monitor progress over time.

Overall, the GHG Protocol plays a pivotal role in promoting transparency, comparability, and accountability in global greenhouse gas reporting and mitigation efforts.

**ISO 14044**

ISO 14044 provides detailed requirements and guidelines for performing a Life-Cycle-Analysis (LCA), expanding on the principles outlined in ISO 14040. This standard focuses on the specific methodology for conducting LCA, outlining the necessary steps and providing criteria for a robust and scientifically sound assessment.

It includes detailed guidelines on LCA phases: It offers comprehensive guidance on how to carry out each phase of the LCA, including inventory analysis, impact assessment, and interpretation. For LCA studies, especially those with large-scale implications, a critical review process is recommended to ensure the credibility of results. Additionally, it ensures that all stages of the LCA process are consistently followed, with transparent data and clear documentation to enhance the reliability of the study.

**European Sustainability Reporting Standards (ESRS)**

The European Sustainability Reporting Standards (ESRS) have been introduced as part of the implementation of the Corporate Sustainability Reporting Directive (CSRD) at the EU level. The CSRD succeeds the Non-Financial Reporting Directive (NFRD). While the EU Taxonomy establishes a unified understanding of "green" or "sustainable," the CSRD broadens this scope at the company level by mandating comprehensive sustainability reporting.

Companies are subject to the CSRD (and classified as "large companies") if they meet at least two of the following three criteria:

- Net turnover of €50 million or more
- Total assets of €25 million or more
- 250 or more employees

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**60** Greenhouse Gas Protocol (2024). Standards. https://ghgprotocol.org/standards#:~:text=GHG%20Protocol%20supplies%20the%20world%27s,support%20their%20missions%20and%20goals, last retrieved: 06.12.24.

**61** Greenhouse Gas Protocol (2024) What is GHG Protocol? https://ghgprotocol.org/about-us, last retrieved: 06.12.24·

Non-EU companies with an EU turnover exceeding €150 million will also need to comply. The ESRS address environmental, social, and governance (ESG) topics, as well as overarching issues. For environmental reporting, the following aspects are considered:

- Climate change
- Pollution
- Water and marine resources
- Biodiversity and ecosystems
- Resource use and circular economy

Under the CSRD, large companies must submit their first report in 2025, reflecting their environmental performance for the 2024 fiscal year. Small and medium-sized enterprises (SMEs) are required to start reporting in 2026 if they meet at least two of the following criteria:

- A balance sheet total of €4 million or more
- Net turnover of €8 million or more
- An average of 50 or more employees during the financial year

Currently, the ESRS do not include industry-specific requirements, although draft standards for various industries (including telecommunications) are under development.

**Global Reporting Initiative (GRI)**

The Global Reporting Initiative (GRI) is an independent international organisation that provides a framework for sustainability reporting, helping organisations disclose their environmental, social, and governance (ESG) impacts transparently. It sets global standards for sustainability reporting, known as the GRI Standards, which are widely recognised and used by organisations worldwide. These standards help businesses, governments, and other entities communicate their impacts on critical sustainability topics such as climate change, human rights, and corruption. GRI promotes consistency in reporting, enabling stakeholders, including investors, regulators, and the public, to assess and compare the sustainability performance of organisations.

The GRI plays a leading role in setting comprehensive reporting standards for sustainability disclosures, known as the GRI Standards. These standards are designed to be modular and globally applicable, offering organisations a structured way to report on their economic, environmental, and social impacts. The GRI Standards are divided into three main series:

- universal standards, which outline the core principles and disclosures applicable to all organisations,

- topic-specific Standards, which address specific ESG issues like climate change, waste management, human rights and labor practices and

- sector standards, which provide guidance tailored to the unique challenges and impacts of specific industries. Most of these are still under development at the moment, including the telecommunication sector.[62]

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**62** Global Reporting Initiative (2024). Reporting with the Sector Standards, https://www.globalreporting.org/standards/sector-program/?utm_source=chatgpt.com, last retrieved: 06.12.24.

**Sustainability Accounting Standards Board (SASB)**

The Sustainability Accounting Standards Board (SASB) has developed a comprehensive set of standards to guide businesses in disclosing financially material sustainability information to investors. These standards are industry-specific and focus on identifying the environmental, social, and governance (ESG) factors most likely to impact a company's financial performance. Covering 77 industries, the SASB standards are designed to ensure that disclosures are relevant, comparable, and decision-useful for investors. They emphasize materiality, helping organisations concentrate on issues that significantly affect their long-term value creation.

The standards align closely with existing financial reporting frameworks, integrating seamlessly into annual reports and other investor communications. By providing clear metrics for ESG issues, SASB facilitates consistency and comparability across industries and markets. Companies can use the standards to enhance transparency, manage risks, and identify opportunities linked to sustainability. Overall, SASB aims to bridge the gap between sustainability performance and financial value, supporting informed decision-making in capital markets.

The requirements for telecommunication companies are:[63]

- In terms of the "Environmental Footprint of Operations": Total energy consumed, percentage grid electricity, percentage renewable energy; amount of energy consumed by (a) cellular and (b) fixed networks

- In terms of "Product End-of-life Management": Materials recovered through take back programs, percentage of recovered materials that are (a) reused, (b) recycled, and (c) landfilled

**ISSB**

The International Sustainability Standards Board (ISSB) develops and maintains global sustainability disclosure standards to ensure that investors and other stakeholders have access to consistent, reliable, and comparable information about sustainability-related risks and opportunities. The ISSB standards focus primarily on the needs of capital markets, aiming to provide decision-useful insights that help investors assess an organisation's sustainability performance and its potential impact on enterprise value. The standards are built on existing frameworks such as the Sustainability Accounting Standards Board (SASB) and Task Force on Climate-related Financial Disclosures (TCFD), ensuring alignment with widely recognised reporting approaches.

By offering a cohesive framework, the ISSB standards support companies in disclosing material information on environmental, social, and governance (ESG) issues, with a particular emphasis on climate-related financial impacts. These standards are designed to work alongside jurisdictional requirements and complement broader sustainability frameworks, including those addressing societal and environmental outcomes. The ISSB adopts a building-blocks approach, allowing for integration with additional reporting frameworks to meet the needs of multiple stakeholders.

To enhance comparability and transparency, the ISSB emphasizes industry-specific guidance, ensuring that disclosures are relevant to the unique challenges and opportunities within different sectors. The

**63** SASB (2014): TELECOMMUNICATIONS, Research Brief, p. 30.

ISSB also focuses on connectivity between financial and sustainability reporting, enabling a clear understanding of how ESG factors influence a company's overall financial health.

**International Telecommunication Union (ITU)**

The International Telecommunication Union (ITU), a specialized agency of the United Nations, has developed numerous standards and recommendations aimed at promoting sustainability in the telecommunications sector. Key ITU standards related to sustainability include:

- ITU-T L.1100: Guidelines for recycling rare metals in ICT products.
- ITU-T L.1300: Best practices for energy-efficient and environmentally friendly data centers.
- ITU-T L.1310: Metrics and methods for measuring energy efficiency in telecommunication equipment.
- ITU-T L.1400 Series: Comprehensive methodologies for assessing the environmental impact of ICTs, such as life cycle assessments and carbon footprint analysis.
- ITU-T L.1500: A framework for utilising ICTs to adapt to climate change, including tools for monitoring, data collection, and early warning systems.
- ITU-T L.1600 Series: Recommendations for enhancing environmental sustainability in ICT operations, focusing on energy management, sustainable design, and resource efficiency.

These standards underline ITU's commitment to leveraging ICTs for environmental sustainability and climate resilience.

**European Telecommunications Standards Institute (ETSI)**

The European Telecommunications Standards Institute (ETSI) has established several standards aimed at advancing sustainability in the ICT sector. These standards focus on enhancing energy efficiency, minimizing environmental impact, and encouraging the adoption of renewable energy. Key examples include:

- ETSI EN 305 200-1: Energy management – Global KPIs for energy management: Defines global Key Performance Indicators (KPIs) for energy management in ICT facilities and networks, including data centers.
- ETSI EN 303 470: Measurement methods and limits for energy consumption in broadband fixed network access equipment: Provides standardised methods for measuring energy consumption in broadband fixed network access equipment and sets limits to encourage energy-efficient designs.
- ETSI TS 105 174: Assessment of mobile network energy efficiency: Offers guidelines for evaluating the energy efficiency of mobile networks, promoting energy-saving practices and the integration of renewable energy sources.

**EU Codes of Conduct**

Besides these standards, the EU Commission publishes Codes of Conduct that can serve as best practice guidelines. Two of these are already in force, while the third one is due to be finished in 2025.

- The **European Code of Conduct for Energy Efficiency in Data Centres** is an initiative developed by the European Commission's Joint Research Centre to address the growing energy consumption and environmental impact of data centres. It aims to inform and encourage data centre operators and owners to adopt best practices that enhance energy efficiency without compromising their critical functions. Participants commit to implementing energy-saving measures, monitoring energy usage, and sharing best practices to foster a culture of continuous improvement. Since its launch in 2008, over 500 data centres have joined the program, with outstanding performers recognised through annual awards.[64]

- The **European Code of Conduct on Energy Consumption of Broadband Equipment** is a framework designed to voluntarily enhance energy efficiency in broadband devices, addressing the significant rise in energy use due to increased internet traffic. It establishes maximum electricity consumption levels for broadband equipment sold within the EU, encouraging manufacturers and service providers to adopt energy-efficient designs and practices. By setting these benchmarks, the Code aims to mitigate the environmental impact of broadband infrastructure while maintaining service quality. Participants, including service providers, network operators, and equipment manufacturers, are invited to commit to these energy-saving measures, fostering industry-wide collaboration toward sustainability. The Code is regularly updated to reflect technological advancements, with Version 9.0 effective from January 1, 2024.[65]

The European Union is developing a **Code of Conduct for Sustainable Telecommunications Networks** to enhance the environmental performance of electronic communications networks (ECNs). This initiative aims to establish common sustainability indicators, focusing on energy consumption, greenhouse gas emissions, and resource efficiency, to standardise environmental impact assessments across the telecommunications sector. In 2023, the Joint Research Centre (JRC) conducted a stakeholder survey to identify and prioritize these indicators, laying the groundwork for the forthcoming Code of Conduct. The Code's official release is anticipated for the fourth quarter of 2025.

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**64** Schmitdt (2024). European Code of Conduct for Energy Efficiency in Data Centres, https://joint-research-centre.ec.europa.eu/scientific-activities-z/energy-efficiency/energy-efficiency-products/code-conduct-ict/european-code-conduct-energy-efficiency-data-centres_en?utm_source=chatgpt.com, last retrieved: 09.12.24.

**65** EU Joint Research Centre (2024). Code of Conduct on Energy Consumption of Broadband Equipment: Version 9.

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