SOCIOECONOMIC BENEFITS OF HIGH-SPEED BROADBAND AVAILABILITY AND SERVICE ADOPTION: A SURVEY

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Keywords

High-speed broadband, broadband availability, broadband adoption, fiber connections, mobile broadband, economic benefits, survey

Abstract

Ubiquitous high-speed fiber-based and mobile broadband availability is a key economic policy goal in the European Union and other developed countries. Policymakers seek to boost economic growth, productivity, and employment, especially in remote areas, through ambitious broadband targets and substantial public funding. This paper reviews the existing (empirical) literature on high-speed broadband internet and its socioeconomic impact on key outcome variables. Our main findings are that (i) the socioeconomic benefits in terms of economic growth, productivity, house prices, and education, as well as economic resilience, are high but are also subject to diminishing returns beyond a certain broadband quality level, (ii) the effects on employment are more ambiguous, (iii) the positive socioeconomic effects take hold only after broadband adoption on the demand side, but not with mere availability on the supply side, and (iv) the effects of broadband differ significantly for urban vs. rural and high-skilled vs. low-skilled workers. Based on these findings, we develop recommendations for a cost-effective and efficient broadband policy and future funding regime.

1 Introduction

The availability and adoption of the first "basic" copper and coaxial cable-based and now "high-speed" (or new) broadband internet is seen as a fundamental cornerstone for increasing long-term productivity and economic growth worldwide. High-speed wireline internet is based on fiber optic technology in access networks and, as such, has the potential for a significant increase in broadband quality, such as lower susceptibility to electromagnetic interference and higher bandwidth levels. While wireless (mobile) broadband was introduced with 3G technologies in the early 2000s, it was the introduction of 4G technology some 10 years later that enabled new mobile internet access and popular high-bandwidth services such as online gaming, HD video streaming, and videoconferencing. With 5G networks being built from 2020, another fundamental technology shift is taking place, with high promises for more network versatility, productivity gains, and product innovation (e.g., Bauer & Bohlin, 2022; Rao & Prasad, 2018). However, as the cost of deploying high-speed internet is generally much higher than for basic broadband infrastructure, it is vital to understand the socioeconomic potential of new broadband internet for businesses, employees, and households alike.

The availability of high-speed broadband infrastructure on the supply side and the migration of consumers to higher-quality broadband connections on the demand side ("adoption") are associated with significant welfare gains. For example, high-speed, fiber-based broadband internet[1] can foster the distribution and processing of large amounts of data ("big data"). Cloud computing applications provide further efficiency gains in firms. In addition, high-speed internet enables teleworking, remote health care, or home-study solutions for individuals, thereby reducing transport and transaction costs. Against this backdrop, policymakers at the national and supranational levels have set ambitious targets for broadband availability in the past. In the USA, for example, the Federal Communications Commission (FCC) published the National Broadband Plan in 2010, setting targets that "every American should have affordable access to robust broadband service" and that by 2020 "at least 100 million US households should have affordable access to effective download speeds of at least 100 megabits per second and effective upload speeds of at least 50 megabits per second" (FCC, 2010, pp. 9–10). Similarly, in the European Union (EU), the Digital Agenda for Europe of 2010 sought to ensure

[1] When we refer to both availability and adoption, we use the term "high-speed (broadband) internet" in the following.

that "by 2020, (i) all Europeans will have access to significantly higher internet speeds of more than 30 Mbit/s, and (ii) 50% or more of European households will subscribe to internet connections of more than 100 Mbit/s" (European Commission, 2010, p. 19). New targets were then formulated through the "5G Action Plan" and the European "Gigabit Society" (European Commission, 2016). They express a stronger focus on bridging the digital gap between urban and rural areas regarding the availability of the latest broadband infrastructure as by 2025 all households should have access to at least 100-Mbit/s broadband internet. However, targets for urban areas kept being set more ambitiously than for peripheral, rural areas characterized by low population density. The target of gigabit connectivity only applies to urban areas and to areas along main transportation paths (European Commission, 2016, p. 7). In 2021, additional targets were set to tackle several vulnerabilities that became more apparent during the Covid-19 pandemic. New targets to be achieved by 2030 have been included in the 2030 Digital Compass strategy, as the European Commission aims to take more action to "achieve a digitally literate population and highly skilled digital professionals" and that "more than 90% of European SMEs reach at least a basic level of digital intensity" (European Commission, 2021, Sections 3.1 and 3.3). In 2023, the European Commission proposed rules in its "Gigabit Infrastructure Act" to support the 2030 Digital Decade Connectivity Target, which aims to ensure that everyone in the EU has access to gigabit connectivity and fast mobile data by 2030 (European Commission, 2023).

In most developed countries, the ambitious broadband availability targets were coupled with massive public subsidies worth billions of euros from national and local governments through various state aid programs (Bourreau et al., 2020; Briglauer & Grajek, 2023; OECD, 2018). These subsidies were meant to induce private network operators to roll out high-speed broadband nationwide, including remote and unprofitable regions. However, subsidies may also lead to inefficient investments or to a crowding out of private investment that would have occurred without any subsidies. A reliable empirical assessment of the overall societal benefits of new broadband internet and a corresponding cost–benefit assessment are therefore of great importance for future policy decisions, including the design of targets and public subsidies, as well as for sector-specific regulation.

The main aim of this review is to provide an up-to-date and comprehensive overview of the benefits in terms of the most relevant socioeconomic impacts of wireline and wireless high-speed broadband internet, which allows us to provide reliable recommendations for future policy decisions. Moreover, by identifying existing research gaps, we want to outline an agenda for future research.

The study most closely related to ours is that of Abrardi and Cambini (2019). However, we include many more studies than those reviewed by Abrardi and Cambini (2019) because high-speed internet has only become available in many areas in recent years and more data are available on various outcome variables, such as economic effects on gross domestic product (GDP) and economic growth, labor market effects, and productivity. Moreover, additional studies consider effects on business creation, human capital, and real estate prices. While all of these variables are related to GDP, other important economic benefits of high-speed broadband internet are related to consumer rents derived from the use of different broadband services. Consumer rents arise from the fact that many online services require no additional payment once consumers with sufficient willingness to pay have subscribed to a broadband connection. In addition, the Covid-19 pandemic demonstrated the importance of new broadband infrastructure and digital services in times of fundamental economic crises and the closure of large parts of the traditional economy. This "resilience" effect, which is important for the economy in terms of significantly mitigating the decline in overall economic performance and subsequent faster economic recovery, is still largely unexplored but is likely to be of particularly high socioeconomic benefit. Finally, there is the ICT–electricity–energy nexus, where the overall societal impact is less clear due to several countervailing effects.

The remainder of our paper is structured as follows: In Section 2, we first provide elementary definitions underlying fixed and mobile broadband access technologies, which also define the scope of our empirical literature review, and we illustrate the main economic mechanisms that give rise to (expected) welfare gains. Section 3 then provides tabular overviews with structured information on the available empirical contributions and short summaries of their main findings. Section 4 concludes by deriving the main policy recommendations that follow from our balanced reading of the empirical literature reviewed and identifies an agenda for future research.

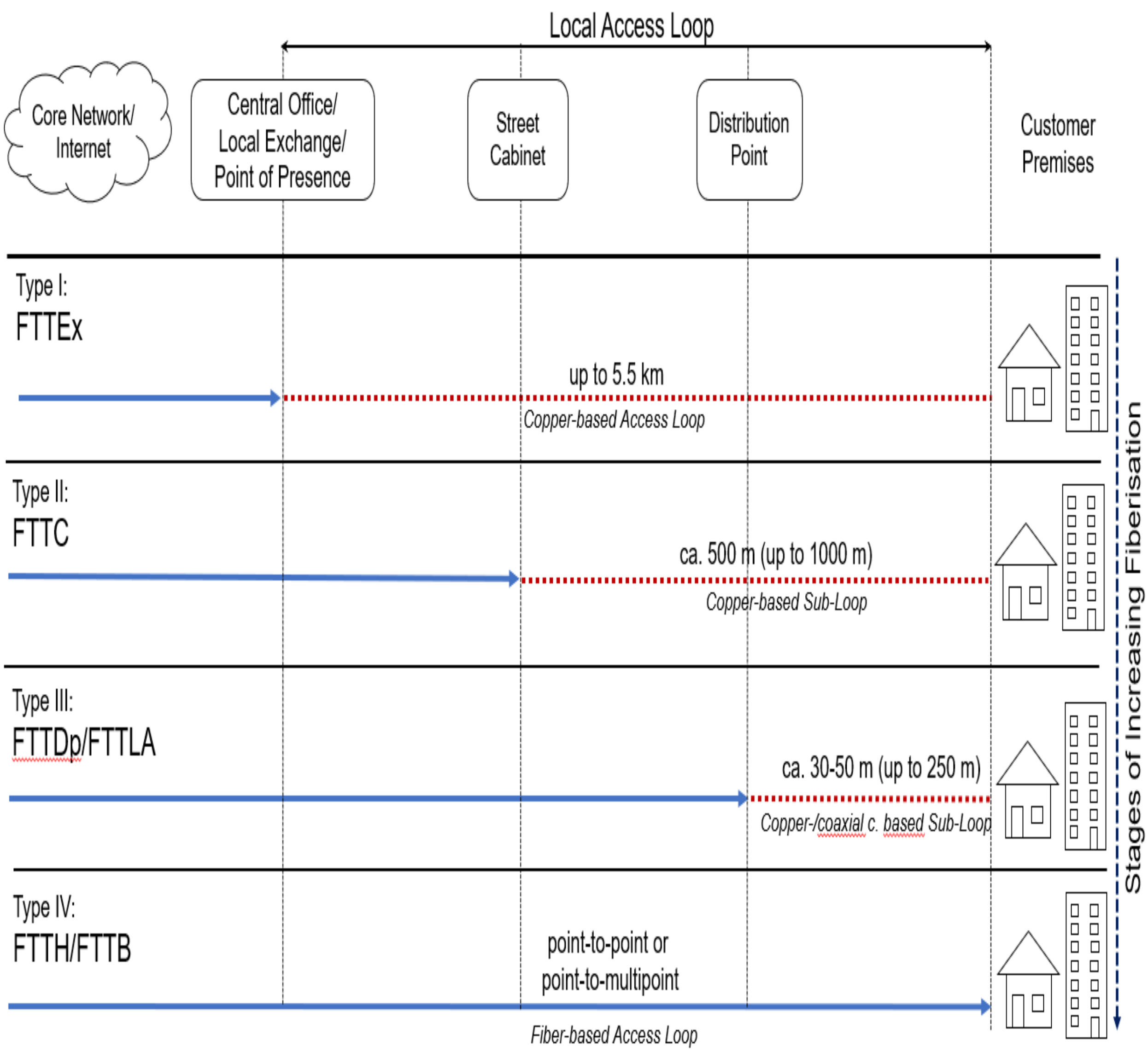
2 Definitions and economic channels

2.1 Migration from basic broadband to high-speed broadband access technologies

Fixed-line broadband: Basic broadband internet was based on legacy-based wires (twisted pair in telephone networks and coaxial cable in cable networks) in local access networks, specifically the so-called "local loop," i.e., the connection between the local exchange (in telephone networks) or head end (in cable networks) and the households or terminal ends. Over the years, more frequency bands of copper-based wires could be used for internet service. Depending on various parameters, such as electromagnetic interference, a basic broadband internet based on a copper-only local loop could deliver download data rates of up to 24 Mbit/s with ADSL (asymmetric digital subscriber line) technologies.

In further years, the length of the copper-based local loop was successively shortened due to (partial) replacement with fiber. Fiber-based infrastructure bears several advantages over copper-based infrastructure. Predominantly, fiber allows the use of more frequency bands (i.e., more bandwidth), and communication is based on optical signals, which are – unlike the electromagnetic signals in copper-based wires – not susceptible to electromagnetic interference. This allows for much higher transmission speeds in fiber-based infrastructure. Depending on the reach of the fiber into local access networks, different fiber-based high-speed broadband access scenarios (FTTx) have emerged since the early 2000s (Figure 1). Hybrid fiber in copper-wire-based access networks is referred to as fiber to the cabinet (FTTC) or fiber to the distribution point (FTTDp). This is also known as VDSL (very high-speed DSL). From an architectural point of view, FTTDp is similar to FTTC, but fiber is deployed deeper into the access network so that the remaining copper-based local loop is typically reduced to less than 250 m. Using hybrid broadband access technologies and complementary error correction techniques (e.g., vectoring or G.fast), it is currently possible to provide data rates of up to several hundred megabits per second. Technological innovations, XG.fast in particular, bring further significant performance improvements and yield data rates of multiple gigabits per second. Fiberization in hybrid fiber-coax cable networks takes place as fiber is deployed deeper into the access network and closer to the last amplifier (fiber to the last amplifier, FTTLA). With DOCSIS 3.0 technology, data rates of up to 400 Mbit/s can be provided. Current DOCSIS 3.1 technology can already provide gigabit speed levels. Further fiberization in local access loops is realized with so-called fiber to the building (FTTB) scenarios, which rely on only remaining metallic in-house cabling wiring, in particular, in buildings that were built many years before fiber roll-out. When it is also feasible to substitute metallic in-house copper lines, full fiberization is achieved, which is referred to as fiber to the home (FTTH). Even though FTTH technologies may vary in terms of their architecture and topology (either point-to-point or point-to-multipoint topologies) and there are performance limitations by components other than the fiber infrastructure, the data rates that can currently be obtained from FTTH are theoretically in the range of tens of gigabits per second (Briglauer et al., 2020; FTTH Council Europe, 2018, p. 12; Stocker, 2019; Timmers et al., 2018, p. 5).

Figure 1: Evolution of wireline broadband access technologies



Source: Briglauer et al. (2020)

Mobile broadband: The roll-out of 3G-based mobile broadband access technologies began some 22 years ago based on "Universal Mobile Telecommunications System" (UMTS) technology, which was first launched in 2001. The introduction of fourth-generation (4G) mobile broadband "Long Term Evolution" (LTE) technology, first launched in 2009, brought a significant improvement in the quality of wireless broadband networks with an increase in peak data speed levels from 42 Mbit/s with respect to its predecessor technology 3G/HSDPA+ to 300 Mbit/s peak download speed with 4G/LTE (Table 1). The 4G+ (LTE advanced)-based broadband access technologies improved spectral efficiency and enabled much higher maximum data rates almost comparable to those provided by wireline hybrid fiber technologies (FTTC/FTTDp/FTTLA). Since 2019, 5G networks have been deployed, and this technological innovation is expected to lead to further massive increases in available data rates and can provide ultra-reliable data transmission with ultra-low latencies (Stocker, 2019).

Table 1: Evolution of wireless broadband access technologies

Mobile generation	First market launch (year and country)	Mobile technology	Peak data speed (download)	Average data speed (download)
2G	1991 (Finland)	HSCSD	64 kbit/s	15–20 kbit/s
2G		GPRS	171 kbit/s	30–50 kbit/s
2G		EGPRS/EDGE	384 kbit/s	130–200 kbit/s
3G	2001 (Japan)	UMTS	2 Mbit/s	384 kbit/s
3G		HSDPA	14 Mbit/s	3–5 Mbit/s
3G		HSDPA+	42 Mbit/s	5–8 Mbit/s
4G	2009 (Norway)	LTE	300 Mbit/s	15–20 Mbit/s
4G		LTE-Advanced	1 Gbit/s	50–80 Mbit/s
4G		LTE-Advanced Pro	3 Gbit/s	60–100 Mbit/s
5G	2019 (South Korea)	NR	10 Gbit/s	150–200 Mbit/s

Source: Information available at https://commsbrief.com/mobile-data-speed-with-2g-3g-4g-and-5g-cellular-networks/; https://www.cengn.ca/information-centre/innovation/timeline-from-1g-to-5g-a-brief-history-on-cell-phones/; https://digital-strategy.ec.europa.eu/en/policies/broadband-technology-comparison#ecl-inpage-klvfy710.

In this study, we investigate the impact of high-speed wireline and wireless internet, enabling at least 30 Mbit/s. This corresponds to the initial coverage target set by the European Commission in its Digital Agenda for Europe in 2010. Of course, much higher levels of broadband quality are now associated with high-speed broadband, but focusing only on gigabit-level networks, for example, would significantly limit our literature review to very few empirical studies. Furthermore, currently, popular digital services, such as video streaming or videoconferencing, can be used by more than one person in a household at the same time with comparatively low bandwidth requirements. In turn, we do not cover studies with wireline data download rates below 30 Mbit/s but instead refer to the findings on the causal effects of basic broadband in the previous surveys.

From the discussion above, we infer that Type II to IV FTTx technologies can deliver bandwidth levels of >30 Mbit/s and far beyond (referred to as new wireline broadband), while technologies without fiber availability in the local loop are excluded from our survey (referred to as basic broadband). The same holds for wireline technologies before the introduction of 4G mobile broadband in 2010. It was only with late 3G HSDPA technology that a peak download data speed of 42 Mbit/s was realized; the average data speed was, however, much lower, ranging from 5 to 8 Mbit/s (gray shaded area in Table 1). Therefore, we include studies of both 3G and 4 G, being aware that not all 3G technologies could guarantee bandwidth of 30 Mbit/s (referred to as new wireless broadband).

2.2 Relevant economic mechanisms

According to Bresnahan and Trajtenberg (1995), general-purpose technologies (GPTs) can be characterized by three main features: (i) potential for technical improvement, (ii) "pervasiveness," that is, applicability to all sectors of the economy, and (iii) "innovative complementarities," that is, impulses for innovations and productivity gains in other sectors. The ICT sector is indeed one of the most innovative sectors, and the diffusion of ICT across all sectors of the economy has progressed rapidly over the last two decades. The availability and adoption of (high-speed) broadband networks, that is, the "C," the infrastructural core of digitalization, affects economic output through various channels, which can best be illustrated by the aggregate production function. The latter is derived by equating total output (*GDP*) with capital and labor inputs and the state of technology and can be written in general terms as follows:

$$GDP = TFP * F\left(capital; labor; human\ capital;\ broadband_{availability}\right) \qquad (1)$$

where *TFP* represents total factor productivity given the levels of *capital*, *labor*, *human capital* and $broadband_{availability}$. In our augmented production function, we add human capital as a separate input factor because the literature on basic broadband (e.g., Akerman et al., 2015) has identified the role of skill complementarities, as ICT is a knowledge-intensive good and broadband also affects education, and thus human capital and, ultimately, GDP. We further add the physical stock of installed high-speed broadband connections, $broadband_{availability}$. Note that broadband availability is a precondition for broadband adoption ($broadband_{availability} \rightarrow broadband_{adoption}$). This means that broadband availability affects GDP through two channels: a direct and an indirect channel. The availability of broadband infrastructure has a direct effect on GDP through investment activity by network operators (network design and engineering, construction work, telecommunications equipment, and electric and metal products) and through infrastructure related multiplier effects. However, presumably much more important welfare effects arise from the indirect effect of broadband availability on broadband adoption as expressed in the following relationship and further discussed below:

$$broadband_{adoption} \rightarrow TFP;\ capital; labor; human\ capital$$

First, *TFP* is part of economic growth that is not due to changes in observable production inputs but to several unobservable variables that affect technological progress and overall efficiency. According to GPT theory, the adoption of broadband by individuals and firms increases *TFP* and thus indirectly GDP by continuously stimulating process and product innovation. For example, new broadband services enable faster distribution of large amounts of data and "big data" analytics, thereby accelerating the creation of new ideas, new products, and new businesses. In this context, for instance, cloud computing is an increasingly relevant business application. Cloud technologies provide storage capacity, processing power, development tools, and software over the internet, regardless of location. Cloud services can improve the efficiency of processes as equipment/servers, staff training, ongoing maintenance, and warranty requirements are handled by specialized service providers. Further productivity gains can be realized through more efficient business and information processes, such as better logistics management, which can optimize routes and travel times and reduce accidents and delivery. Based on IoT sensors, intelligent and collaborative robotics, AI, and machine learning, manufacturing processes are becoming more efficient (Industry 4.0). Also, a higher proportion of employees equipped with mobile broadband access solutions increase labor productivity, as shown by Bertschek and Niebel (2016).

Second, we expect welfare effects related to the actual use of new broadband services by residential consumers in their leisure time: consumers benefit from broadband adoption through easy and cheap access to, for example, e-commerce and hotel booking platforms, e-banking or telemedicine services, or e-government portals. All these digital services offer significant time savings, increasing utility and household income. High-speed broadband internet also enables extensive price comparisons to be made in the shortest possible time, leading to more efficient consumption decisions and higher real income for households. Mobile broadband allows consumers to use commuting time more effectively.

In addition, broadband access allows people to be better informed and provides access to various online job search and education platforms, ultimately leading to higher human capital accumulation and household income.

Third, broadband adoption indirectly affects GDP through its impact on the labor force. New broadband services allow for new forms of work, such as teleworking based on videoconferencing and virtual private networks, which provides more flexible work patterns for individual employees and the self-employed, which can ultimately increase the labor force. New broadband also increases the efficiency of labor markets via digital job-matching platforms. High-speed internet access is also seen as a prerequisite for the creation and management of start-ups in the digital economy. Broadband applications can also improve labor efficiency and thus act as a substitute for labor, increasing labor productivity and economic growth via capital deepening and automation while reducing employment. The impact of broadband on employment further depends on population trends and the overall state of the economy. In times of full employment, broadband adoption is unlikely to increase employment as much as in times of economic recession, when there are many unemployed people looking for work. Irrespective of the business cycle, however, access to and use of broadband applications can reduce frictional unemployment through better and faster access to information but lead to structural unemployment due to substitution effects and changes in the digital skills required by the labor market (Holt and Jamison, 2009).

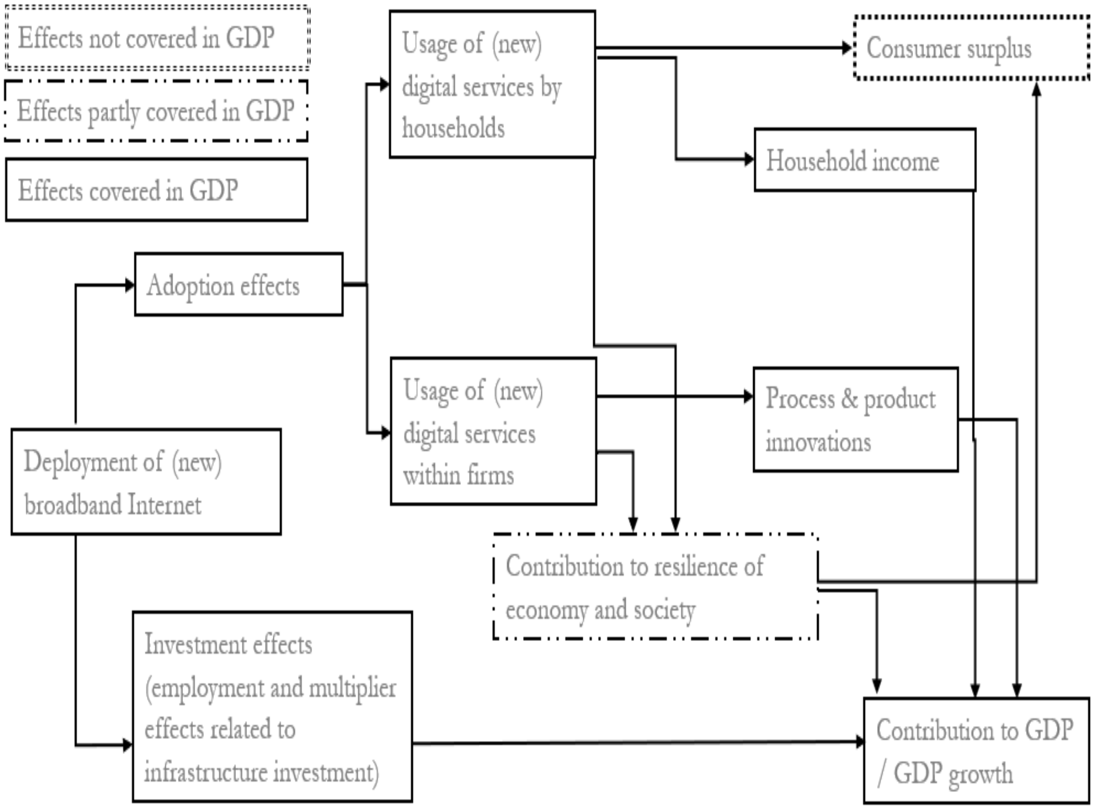
Fifth, another significant externality of new broadband infrastructure and services, as recently experienced during the Covid-19 pandemic, is the increased resilience of the overall economy and society in times of global crisis, when large parts of traditional economic sectors are affected or even shut down by governments. The availability and adoption of broadband infrastructure thus facilitate the adaptation of businesses and consumers to new situations and make them more resilient to unexpected events. According to Barrero et al. (2021a), the positive effects of the broadband infrastructure are three times higher during economic crises, such as the Covid-19 pandemic, than in normal times. The reason is that digital services helped sustain the operation of many businesses and market transactions as well as facilitated work from home, online education, health and entertainment, and social interaction when it is not possible to continue production and consumption offline. Without broad-scale availability and adoption of broadband internet, it would have not been possible to move economic and social activities online, e.g., to shift from offline to e-commerce, to take classes online, or to watch movies online instead of going to the cinema. Thus, the availability of digital services massively mitigated the decline in GDP caused by pandemic-related policies and, at the same time, provided huge benefits (or less utility losses) to consumers not captured in GDP.

In economics, total welfare is defined as the sum of producer surplus, which is included in GDP, and consumer surplus. Formally, consumer welfare is calculated as the difference between the maximum price consumers are willing to pay for a good (the reservation price) and the price consumers must pay (the market price). While consumer surplus is not included in GDP, the use of new digital services, such as highly popular search engines, online video content, or other enhanced multimedia applications, including social networks, has most likely induced substantial value for consumers in aggregate terms. For example, some consumers would probably be willing to pay for particularly popular and widely used online services, such as Google Search, Wikipedia, YouTube, and many others. However, for many of these services, there is no additional charge in monetary terms[2] once consumers have decided to subscribe to a broadband connection under a commercial contract. In turn, new digital services often create additional value for consumers, and hence their willingness to pay for more expensive high-quality broadband access connections will increase.

Figure 2 illustrates and summarizes the hypothesized effects and relationships induced by the availability of (new) broadband networks. Next to direct GDP-related multiplier effects, the indirect effects follow from broadband adoption, which allows for various business and residential uses that affect the level of household income, product innovation, technological progress and efficiency gains, total factor productivity, and ultimately GDP. Furthermore, broadband internet increases the resilience of the economy and society during major economic crises, which impacts both GDP and consumer surplus. Finally, using broadband services directly increases consumer surplus, which is not captured in GDP but represents another major socioeconomic benefit.

[2] Yet consumers often "pay" in nonmonetary terms by providing data or consuming online advertisements.

Figure 2: Economic impacts of (new) broadband networks



Source: Own presentation based on Briglauer et al. (2023a) and ITU (2012)

3 Empirical evidence

Section 3.1 first presents the available empirical contributions in compact tabular form according to the outcome variable categories discussed in Section 2.2. Section 3.2 then interprets the main results for each outcome variable obtained from a synopsis of all the studies reviewed in each category.

3.1 Literature review: tabular summaries

Several studies have examined the impact of telecommunications and basic broadband infrastructure and the adoption of related broadband services on economic development since the early 2000s, starting with studies examining the impact of narrowband voice telephony (e.g., Waverman & Röller, 2001). There is also a large body of empirical evidence demonstrating the benefits of basic broadband on economic growth, employment, and productivity in both advanced and developing economies (reviewed in Bertschek et al., 2015; Gómez-Barroso & Marbán-Flores, 2020). Early empirical contributions on the impact of new high-speed broadband are reviewed by Abrardi and Cambini

(2019) using both basic and new broadband data. While Bertschek et al. (2015), Gómez-Barroso and Marbán-Flores (2020), and Abrardi and Cambini (2019) reviewed the literature on broadband networks, thus the "C" in ICT (information and communication technologies), Cardona et al. (2013) and, more recently, Vu et al. (2020) reviewed the broader literature on ICT, including the impact of other complementary ICT hardware and software components. Finally, Jung and Gómez-Bengoechea (2022) provide a recent and comprehensive review of the drivers and impacts of digitalization focusing on firms and a wide range of firm-performance and digitalization metrics.

Tables 2-7 provide a structured overview of the currently available empirical evidence on the impact of high-speed broadband internet. The starting point of our literature search is the review by Abrardi and Cambini (2019) and our previous work published as policy reports in German (Briglauer & Schwarzbauer, 2022; Briglauer & Stocker, 2020). In view of our core research objective, to provide reliable recommendations for future policy decisions, we only included quantitative research that attempts to identify causal relationships between the respective broadband and outcome variables. We have therefore excluded other quantitative (mainly descriptive), qualitative, and simulation-based studies. In order to identify all relevant empirical articles that cover the socioeconomic impact of new broadband internet, we further searched established field journals ranked in the first quartile in the Scimago Journal Ranking (SJR) at least once during our reviewed publication period (2017–2023) in one of the subject areas "Economics, Econometrics, and Finance" or "Business, Management, and Accounting." Next, we identified additional articles with a backward search, reviewing the references of the articles published in the above-mentioned field journals. In addition to papers published in peer-reviewed journals, we reviewed recently published working papers and a few policy reports, which showed high thematic relevance and a promising identification strategy.

The columns in Tables 2–7 provide information on the authors and year of publication (column (1)), the structure of the datasets used (column (2)), the definition of the broadband variables (column (3)), the empirical methodology[3] (column (4)), and the main findings (column (5)). In the table headings,

[3] Abbreviations used in Tables 2–7 to describe empirical models: CEM, coarsened exact matching; DCDH, deChaisemartin and D'Haultfoeuille estimator; DiD, difference in difference; ECM, error correction model; ES, event study; FD, first differences; FE, fixed effects; FEC, bias-corrected fixed effects; GMM, generalized method of moments; HPM, hedonic price model; IV, instrumental variables; OLS, ordinary least square; PSM, propensity score matching; SEM, spatial econometric model; SRDD, spatial regression discontinuity design; 2SLS, two-stage least squares; 3SLS, three-stage least squares.

we have indicated the economic channels that follow from high-speed broadband internet[4] toward the respective outcome variable. All studies examining the impact on GDP were published in the last seven years (2017–2023). Overall, we reviewed a total of 42 studies,[5] only 7 of which were previously reviewed by Abrardi and Cambini (2019); none of these studies were reviewed by Bertschek et al. (2015) or Gómez-Barroso and Marbán-Flores (2020). The reviewed publications are listed in Tables 2–7 in ascending chronological order according to the year of publication.

In order to identify causal effects, almost all studies use some kind of panel data at different administrative levels (country, region, county, municipality, and – in some studies – smaller administrative units) or at firm levels, as can be inferred from the information provided in column (2). From columns (2) and (3), we further infer that most studies reviewed use data on only high-speed wireline broadband (34 out of 42) and from developed countries (32 out of 42). Some studies employ data from a larger set of countries containing both developing and developed countries.

In column (3), we describe the measurement of broadband variables and indicate whether the author(s) used wireline and/or wireless broadband data. In column (3), we further distinguish whether high-speed broadband internet is only available to households or businesses or whether the technology is being used. The actual subscription of broadband connections by consumers is referred to as the "adoption" of the technology, while the supply-side coverage of infrastructure is referred to as the "availability" of the technology. In general, the availability of infrastructure represents the investment activity of network operators, while the adoption of a technology expresses consumers' willingness to pay since only those consumers or enterprises with sufficient willingness to pay will subscribe to the broadband connection offered. The adoption of services obviously depends on the availability of the underlying infrastructure. While studies using (input-oriented) availability data are more informative from a supply-side policy perspective (i.e., regulation or public funding), studies using (output-oriented) adoption data are more informative from a welfare perspective. This distinction is also relevant because of substantial differences between the supply-side provision of high-speed broadband infrastructures and demand-side adoption (European Commission, 2022), resulting in overcapacities and demand–supply gaps. When interpreting the respective coefficient estimates, it is

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[4] In Tables 2–7, we use the variable *broadband* to refer to both the availability or adoption of new wireline or wireless broadband internet.

[5] Studies where authors examine different outcome variables are counted more than once.

important to bear in mind that the estimates of the welfare effects of high-bandwidth availability are an imperfect proxy variable for the adoption variables and the resulting welfare gains and that the respective estimates may differ significantly depending on the broadband data used. In particular, availability represents the "intention-to-treat effect", whereas actual adoption represents the "average treatment effect". The former effect is often diluted because of noncompliance issues, such as nonadopting consumers. Low adoption rates imply overcapacities on the supply side, and hence empirical models based only on broadband availability data generally underestimate the actual welfare gains (Abrardi & Cambini, 2019; Czernich, 2014).

Finally, we define the respective broadband quality measures used in column (3). There are two main approaches to measuring high-speed broadband in the empirical literature (Briglauer & Grajek, 2023). One stream of the literature focuses on measuring the impact of specific quality characteristics, such as actual downlink speeds provided to end-users. Obviously, there are other relevant broadband quality parameters, such as latency, jitter, packet loss, or symmetry, but for reasons of data availability almost all empirical studies in this stream of literature referred to downlink bandwidth (or speed) levels. Another stream of the literature measures high-speed broadband in terms of the underlying network architectures and fiber-optical/mobile broadband technologies as described in Section 2.1. Whereas measures based on lower or upper broadband speed or bandwidth levels provide a predefined quality interval,[6] measures based on network architectures provide a broader and more flexible definition that widens as innovations occur (e.g., by using bandwidth more efficiently to allow for higher broadband speeds).

[6] A technical note: whereas Mbit/s (Gbit/s) is a measure of broadband speed, bandwidth is a characteristic of the medium used and measured in the difference between the highest frequency and the lowest frequency at which signals can be send over the medium. Thus, when referring to Mbit/s, "speed" is more appropriate as using the same medium (bandwidth) and technological advancements (such as reduction in signal to noise ratio) can lead to higher broadband speeds. The two are therefore not fully interchangeable, although they are strongly correlated, and often both terms are used interchangeably in the literature.

Table 2: Gross domestic product (broadband → GDP)

Author(s)	Dataset	Broadband data	Methods	Main results
Edquist et al. (2018)	135 countries 2002–2014	Adoption Wireless ≥256 kbit/s 3G and 4G	FE IV	On average, a 10 % increase of mobile broadband adoption causes a 0.8% increase in GDP. This economic effect gradually decreases over time. The effect of mobile broadband is smaller in OECD countries than in the rest of the world.
Bahia et al. (2019)	160 countries 2000–2017	Adoption Wireless 2G, 3G, and 4G	FE IV GMM	A 10% increase in mobile adoption raises GDP per capita between 0.59% and 0.76%. Mobile has a substantial effect on top of basic wireline broadband and is stronger for countries with a more skilled population.
Briglauer and Gugler (2019)	EU 27 countries 2003–2015	Adoption Wireline FTTx	FE IV	A 10% increase in FTTx connections leads to an (incremental) increase in the GDP of around 0.02–0.03% in the OLS estimation and 0.02–0.04% in the IV case (controlling for basic broadband).
Katz and Callorda (2020)	159 countries Quarterly data 2008–2019	Adoption Wireline 1–10 Mbit/s; 10–40 Mbit/s; >40 Mbit/s	FE	A 100% increase in download speed (for >40 Mbit/s) increases the GDP by 0.73%.
Briglauer et al. (2021)	Germany 401 counties 2010–2015	Availability Wireline Average speed level ≥2 Mbit/s to ≥50 Mbit/s	FE IV	An increase in broadband availability of 1 p.p. increases the regional GDP per capita by 0.18% (0.31% considering regional externalities across neighboring counties), and rural areas benefit more from broadband availability.
Briglauer et al. (2023a)	32 OECD states country-level 2002–2020	Adoption and availability Wireline and wireless FTTx 3G and 4G	FE IV	A 1% increase in broadband adoption contemporaneously affects GDP per capita in a range of 0.026% to 0.034%, while mobile broadband adoption increases GDP between 0.079% and 0.088%. Controlling for adoption, wireline, and wireless broadband availability does not show a significant effect.
De Clercq et al. (2023)	1348 EU regions 2011–2018	Availability Wireline ≥30 Mbit/s; ≥100 Mbit/s	FEC	An increase in coverage with broadband ≥30 Mbit/s by 1 p.p. increases GDP growth by 0.09 p.p. This effect is larger in urban areas than in rural areas. Effects exhibit diminishing returns with respect to a higher minimum bandwidth level (≥100 Mbit/s instead of ≥30 Mbit/s).

Table 3: Employment (broadband → labor → GDP)

Author(s)	Dataset	Broadband data	Methods	Main results
Bai (2017)	USA 496 counties 2011–2014	Availability Wireline >1 Gbit/s; 1 Gbit/s–100 Mbit/s; 100 Mbit/s–3 Mbit/s; >3 Mbit/s	FD	Positive effects of broadband speed on employment in the initial publication. However, due to an error discovered by Whitacre et al. (2018), the original model specification produced no statistically significant results.
Firgo et al. (2018)	Austria 2.122 municipalities 2013–2016	Availability Wireline and wireless (aggregated) Average speed level: <2 Mbit/s to >100 Mbit/s	OLS FE SEM	A 100% increase in download speed increases employment measured at the place of work by 0.282 p.p.; the effect on employment growth in rural municipalities is 0.303 p.p., and the effect on urban employment growth is insignificant.
Balsmeier and Woerter (2019)	Switzerland 447 firms 2014-2015	Adoption Wireline FTTH, FTTC >100 Mbit/s	FD (digitalization) IV (bandwidth)	A CHF 100,000 increase in investment in digitalization is associated with about 5.8 more jobs for highly educated workers, 4 fewer jobs for mid-skilled workers, and about 2.3 fewer jobs for the low-skilled. Overall, a digital investment of CHF 100,000 created 1.6 jobs. The authors are cautious with their IV estimates.
Nordin et al. (2019)*	Sweden 9200 SAMS areas 2000–2014	Availability Wireline and wireless (aggregated) >100 Mbit/s	FE (SAMS) IV (municipality)	An increase of 10% in broadband >100-Mbit/s coverage in the whole sample leads to a 0.1% decrease in employment, whereas splitting the sample between rural and urban areas leads to an increase in employment of 0.098% in rural areas and a decrease in urban areas. FE estimates are robust in the IV model.
Katz and Callorda (2020)	159 countries (quarterly) 2008–2019	Adoption Wireline 1–10 Mbit/s; 10–40 Mbit/s; >40 Mbit/s	FE	A 100% increase in (average) download speed increases employment in all sectors by 0.23% (and by 1.53% in the service sector).
Lobo et al. (2020)	USA Tennessee 95 counties 2011–2015	Availability Wireline and wireless (aggregated) ≤100 Mbit/s ≥100 Mbit/s; ≥1000 Mbit/s	FE	Counties with >100 Mbit/s have 0.26 p.p. lower unemployment rates than counties with low broadband speed; rural counties with >100 Mbit/s have 0.39 p.p. lower unemployment rates than high-speed urban counties.

Table 3 (continued)

Authors	Dataset	Broadband data	Methods	Main results
Fabling and Grimes (2021)**	New Zealand 7500 firms 2010–2012	Adoption Wireline FTTH/B 100 Mbit/s–1 Gbit/s	OLS IV	FTTH/B adoption has a negative impact on firm employment. This reduction is observed contemporaneously and reaches its peak over a 4-year horizon (potentially due to increased outsourcing once FTTH/B is adopted in firms). Negative employment effects are observed, especially in firms with initial low computer intensity.
Campbell (2022)	USA North Carolina 5.158.485 students 2011–2019	Availability Wireline FTTx	DiD DCDH	FTTx availability increases local employment by 2.4 p.p.
Hasbi and Bohlin (2022) ***	Sweden 2000 urban areas 2009–2017	Adoption Wireline 7 broadband speed ranges with mean download speed: 33 Mbit/s	FE	Overall, there is no significant effect of different broadband speed ranges on unemployment. However, broadband is associated with an unemployment reduction for low-skilled workers in bigger cities.
Isley and Low (2022)***	USA Rural counties (population <20.000) April and May 2020	Adoption and availability Wireline and wireless ≥25 Mbit/s	IV	Higher wireline broadband availability and higher wireline broadband adoption led to higher employment rates in rural areas. A 1 p.p. increase in broadband availability increased the employment rate by 0.368 p.p. A 1 p.p. increase in wireline broadband adoption increased the employment rate by 0.869 p.p.
Abrardi and Sabatino (2023)	Italy 7485 municipalities 2019–2020	Availability Wireline FTTH/FTTC ≥30 Mbit/s, ≤1000 Mbit/s	FE IV	One additional year of access to high-speed broadband connections increases local employment by 1.3 p.p.

Notes: * Nordin et al. (2019) defined SAMS (small area for market statistics) by population density level and used a threshold of 25 per km² to indicate urban/rural areas. ** Authors do not provide a numerical interpretation of marginal effects related to dummy variables indicating fiber adoption; marginal effects appear to be high. *** Urban areas are defined as areas with contiguous buildings with no more than 200 m between houses and at least 200 residents; within these areas, the authors observe 23 million access connection speed tests. **** Authors use below 30 Mbit/s (>25 Mbit/s) threshold but include all broadband access technologies, including FTTx. Moreover, the contribution is one of the few that employs both measures for wireline and wireless technologies, as well as distinct measures for availability and adoption.

Table 4: Productivity (broadband → TFP → GDP; broadband → (GDP/labor) → GDP)

Author(s)	Dataset	Broadband data	Methods	Main results
Gal et al. (2019)	20 countries 22 industries 1.5 million firm-year obs. 2014–2016	Adoption Wireline >30 Mbit/s	ECM	A 10-p.p. increase in adoption instantaneously increases TFP growth by 1.4 p.p. After 5 years, this would imply a 5.8% (or 3.5%) higher TFP level for the average firm. The effect is, on average, more pronounced in manufacturing than service firms and more broadly in industries involving a high share of routine tasks.
Dalgic and Fazlioglu (2020)	Turkey 7000 firms (average no.) 2012–2015	Adoption Wireline Firms with >/<100 Mbit/s (0/1)	DiD PSM	High-speed broadband has a positive effect on TFP. When firms switch to a fast connection, the productivity of firms increases by 5.3 p.p.; this rate is even higher in the following period (6.5 p.p.).
Fabling and Grimes (2021)*	New Zealand 6000 firms (max. no) 2010–2012	Adoption Wireline FTTH/B 100 Mbit/s–1 Gbit/s	OLS IV	High-speed broadband adoption has a positive impact on multifactor productivity (TFP) over a four-year horizon. Positive TFP and labor productivity effects are most clearly observed in firms that also make complementary investments.
Gallardo et al. (2021)	USA 3073 counties (max. no.) 2017	Adoption Wireline ≥1 Gbit/s; ≥50 Mbit/s; ≥25 Mbit/s	SEM CEM	No significant results for 50 Mbit/s and 1 Gbit/s on labor productivity – measured as GDP/labor – for the whole sample. An increase of 1% in the population with access to at least 1-Gbit/s broadband speed even decreases GDP per job in rural areas by 0.09%.
Edquist (2022)	116 countries 2014–2019	Adoption Wireless 146 kbit/s–55 Mbit/s	FE FD	There is no contemporaneous relationship for the total sample, but there is a significant association when a one-year lag of mobile broadband speed is introduced. The interpretation of the results is that a 10% increase in mobile broadband speed in the previous period is associated with a 0.2% increase in labor productivity – measured as GDP/labor. The results only hold for non-OECD and low-income countries.
Cambini et al. (2023)	Italy 3 million firm-year obs. 2013–2019	Availability Wireline FTTC/FTTH 30 Mbit/s–1 Gbit/s	FE IV	There is a positive effect of the most advanced FTTH networks on firm productivity. TFP increases by 2.9% and labor productivity by 3.9%. Services companies benefit the most from advanced broadband technologies, as do firms located in the northwest and south of Italy.

Notes: * Authors do not provide numerical interpretation of marginal effects of dummy variables indicating fiber adoption; marginal effects appear to be high.

Table 5: Firm creation and education

Authors	Dataset	Broadband data	Methods	Main results
		Firm creation (*broadband → capital → GDP; broadband → labor → GDP*)		
Cambini and Sabatino (2022)	Italy 7799 municipalities 14 industrial sectors 2012–2019	Availability Wireline FTTC/FTTH 30 Mbit/s–1 Gbit/s	FE IV	The exit of small firms increases in magnitude by 1.8% each year since the high-speed broadband introduction, particularly for small firms. Firm entry rises only in digital-intensive sectors and in the most developed geographical areas.
Hasbi (2020)	France 5000 municipalities 2010–2015	Availability Wireline FTTx ≥30 Mbit/s	FE Count and negative binomial model	Municipalities with FTTx connections have a 2.7% higher chance of creating new establishments than other municipalities. The author finds heterogeneous effects for different sectors of the economy and education levels. The tertiary and construction sectors show a positive effect. People that are more educated are more likely to adopt and benefit from ICT.
McCoy et al. (2018)*	Ireland 192 urban fields 2002–2011	Availability Wireline xDSL and middle-mile fiber	SEM	Having a metropolitan area network (MAN) operational in an area is associated with 0.103 (or 83%) more new foreign firms. This effect is higher in areas with higher education levels. No effect on domestic firms.
		Education (*broadband → human capital → GDP; human capital → broadband → GDP*)		
Grimes and Townsend (2018)	New Zealand 1818 state schools 2012–2016	Adoption Wireline ≥100 Mbit/s	DiD	Fiber availability in schools increases positive grades (i.e., passing) by around 1 p.p. per year in primary schools, and schools with more pupils from a lower social background (low income of parents) tend to benefit more from access to fiber.
Campbell (2022)	USA North Carolina 5,158,485 students 2011–2019	Availability Wireline FTTx	DiD DCDH	FTTx availability increases student math and reading test scores by, on average, 1.0 and 1.1 % of a standard deviation. These effects are persistent and grow over time.

Notes: * Urban fields are calculated as aggregations of contiguous electoral divisions at or above the 75th percentile of employment density. The so-called "middle mile" connects the operators' access network ("last mile") and their retail customers with the so-called core and backbone networks. Although our focus is on access networks and technologies, middle-mile networks exhibit investment characteristics similar to access networks.

Table 6: Property prices (*broadband → capital → GDP; broadband → TFP → GDP*)

Authors	Dataset	Broadband data	Methods	Main results
Deller and Whitacre (2019)	USA 887 rural counties (five-year average survey data) 2016	Availability Wireline ≥25 Mbit/s; ≥50 Mbit/s; ≥100 Mbit/s ≥1000 Mbit/s	Spatial 3SLS	A 10% increase in the availability of at least 25 Mbit/s results in the median house value increasing by $232, for at least 100 Mbit/s effect becomes nonsignificant. Estimates suggest that there are declining returns to speed availability.
Molnar et al. (2019)	USA >500,000 real estate transactions in 50 states 2011–2013	Availability Wireline ≤25 Mbit/s; ≤50 Mbit/s; ≤100 Mbit/s	FE HPM IV	Single-family homes with access to a 25-Mbit/s broadband connection have a transaction price that is about $5.977 more than similar homes in neighborhoods with 1-Mbit/s connection. Homes with access to a 50-Mbit/s connection have a price that is about $1.450 more than homes with 25 Mbit/s, and homes with access to a 100-Mbit/s connection have a price that is about $1.352 more than homes with 50 Mbit/s.
Conley and Whitacre (2020)	USA, Oklahoma 2,700 housing transactions in 2 rural counties 2011–2017	Availability Wireline <4 Mbit/s–>50 Mbit/s	SEM HPM	The authors find no significant effects for different bandwidth speed levels in selected Oklahoma counties when controlling for county and year-fixed effects.
Fackler et al. (2022)	Germany 11,000 municipalities 2010–2019	Availability Wireline 16 Mbit/s–50 Mbit/s	SRDD HPM	Positive effects of broadband speed on rents and real estate prices. For 16 Mbit/s, the average estimated effect on sale prices of 6.7% relates to an increase of the property price by 13,260 euros. The effects are stronger for houses than for apartments. There is decreasing marginal willingness to pay for speed, at least once a desired broadband speed level is reached; i.e., upgrades to 30 Mbit/s and 50 Mbit/s are valued less than 16 Mbit/s.
Klein (2022)	Germany 7,323 apartments within rural county 2014–2018	Availability Wireline FTTH	DiD quasi-natural experiment	An increase in the private utility of real estate values due to FTTH availability is significant and incorporates a rental increase of approximately 3%.
Guiffard (2023)	France Postcode obs. quarterly 2018–2021	Availability Wireline FTTH	SRDD	FTTH eligibility is a significant determinant of property prices, with an average increase of 1.7% (2.4% for houses).

Table 7: Economic resilience (broadband → GDP)

Authors	Dataset	Broadband data	Methods	Main results
Katz et al. (2020)*	178 countries 2000–2017	Availability Wireline	OLS IV	Countries with better broadband availability could mitigate the economic losses during SARS pandemic. If adoption increases from 10 to 15 %, more than half of GDP loss could be mitigated.
Barrero et al. (2021a)*	US counties 38,250 survey respondents 2020–2021	Availability Wireline	FE	Universal access to high-speed internet could have increased earnings-weighted productivity by 0.3 % after the pandemic. During the Covid-19 pandemic, insufficient availability of internet services caused a 0.7 % decrease in the productivity of workers.
Katz and Jung (2021)*	104-129 countries 2010–2020	Adoption Wireline and wireless	SEM	During Covid-19 pandemic, countries with at least 90% fixed broadband adoption experienced 21% less GDP contraction than countries with low adoption rates (equal to 30% or less).
Zhang (2021)*	31 Chinese regions 2019 - 2020	Adoption Wireline	OLS	An increase of broadband adoption of 1% led to an increase in economic growth of 0.08 % in March 2019 and April 2020. In March 2020, the effect was 0.19 % and in April 2020 0.13 %. Thus, the positive effect of broadband on GDP growth is larger in times of a pandemic.
Katz and Jung (2022)**	50 US states 2016–2020	Adoption Wireline ≥25 Mbit/s	SEM	Counties with better availability of broadband infrastructures could mitigate the economic losses during SARS pandemic more easily.
Isley and Low (2022) **	US counties with pop. < 20.000 April and May 2020	Availability and adoption Wireline >25 Mbit/s	2SLS	During the pandemic, an increase in the rate of wired broadband adoption increased the employment rate by 0.87 p.p.
Abrardi and Sabatino (2023)	Italy Municipality level 2019–2020	Availability Wireline FTTH/FTTC ≥30 Mbit/s, ≤1000 Mbit/s	FE IV	Availability of high-speed broadband mitigates the negative effect of the pandemic on local employment. One additional year of availability increases local employment by 1.3 p.p.
Abidi et al. (2023)*	13 Asian countries 2018–2020	Adoption Wireline	DiD	Sales of digitally enabled firms shrank by 4 p.p. less than those of digitally-constrained firms during the Covid-19 pandemic.

Notes: * Authors do not specify the broadband speed levels of their data. ** Authors use broadband data with >25 Mbit/s, but their data mainly contain (much) higher speed levels in view of the underlying time period of analysis.

3.2 Literature review: main results

This section provides a concise summary of the key findings from Tables 2-7, encompassing various outcome variables analyzed across the reviewed studies.

3.2.1 GDP and economic growth (Table 2)

Edquist et al. (2018) is the first study to focus on the impact of new mobile broadband (3G and 4G) on GDP. The authors find evidence of a substantial and significant effect, which declines over time and is more pronounced for non-OECD countries. Bahia et al. (2019) use a slightly larger country-level panel dataset and find a similar effect for mobile broadband. Furthermore, the authors find that the effect is more pronounced for countries with higher education levels. For European countries, Briglauer and Gugler (2019) report a positive relationship, which is supported for the USA by Katz and Callorda (2020). Both studies show that fiber-based broadband availability increases GDP. Using county-level data, Briglauer et al. (2021) find significant positive spillovers between neighboring German counties, in addition to positive effects within counties. Spillovers are more pronounced in rural areas. Briglauer et al. (2023a) is the first study to examine the simultaneous effects of broadband availability and adoption for both wireline and wireless broadband technologies. The authors find that the availability effect on GDP is of minor importance, while both wireline and mobile broadband adoption have a significant impact on GDP. De Clercq et al. (2023) examine the regional distribution of potential gains from the availability of high-speed broadband for NUTS-3 regions in the EU. The authors find a positive effect of broadband coverage of at least 30 Mbit/s for both rural and urban areas, with larger effects for the latter group. An important finding of the study is that the growth effects diminish with increasing broadband speed. There are no additional growth effects from upgrading broadband speeds to 100 Mbit/s. Evidence of diminishing effects has also been found for different samples in Briglauer and Gugler (2019) and Briglauer et al. (2021).

All reviewed studies find positive and significant effects on GDP, but the evidence also suggests diminishing effects for technological infrastructure upgrades and higher bandwidths. Three studies (Bahia et al., 2019; Briglauer, 2023a; Edquist et al., 2018) include data on mobile broadband (3G and 4G) and find very similar elasticity estimates (about 0.08), all suggesting a comparatively strong impact on GDP. Interestingly, Katz and Jung (2021), using a broader definition of broadband adoption for panel data covering 129 countries for fixed and mobile broadband, also find that the economic growth impact of mobile broadband between 2010 and 2020 is higher in the aggregate, although the impact declines with the level of economic development when comparing different world regions.

3.2.2 Labor market effects (Table 3)

The majority of studies find positive labor market effects. Most of these studies use data from individual high-income countries such as Austria, Switzerland, Sweden, the USA, New Zealand, or Italy. Isley and Low (2022) is the only paper where the authors use both adoption and availability data and find – similar to Briglauer et al. (2023a) – that the adoption-related effect is more than twice as large as the availability effect. Two studies in this group also find evidence of regional heterogeneity (Firgo et al., 2018; Lobo et al., 2020), suggesting that rural areas benefit more than urban areas. Katz and Callorda (2020), using a broad country-level panel, find that increases in fiber-based broadband speeds increase total employment in all sectors, with an increase in the service sector being much larger than in the economy as a whole. Balsmeier and Woerter (2019) examined data for Switzerland and found only a positive impact of fiber-based broadband availability on high-skilled employment. However, they did not find statistically significant or positive results for the whole sample (i.e., without splitting the sample into high-, medium-, and low-skilled workers). An earlier study by Bai (2017) did not find such a positive effect (after corrections identified by Whitacre et al., 2018). Similarly, with respect to unemployment, Hasbi and Bohlin (2022), using data from Swedish municipalities, found no effect of download speed on unemployment. Nordin et al. (2019) found evidence of regional heterogeneity, with positive employment effects in rural areas and negative effects in urban areas. Fabling and Grimes (2021) found a negative effect of fiber-based broadband on employment, and this effect is stronger for firms with low computer intensity.

In contrast to studies examining the impact on GDP, studies examining the impact of broadband on labor market outcomes are mixed. Heterogeneous effects are related to regional disparities (rural vs. urban areas) and education levels (high-skilled vs. low-skilled) and, in some cases, suggest insignificant effects or even negative labor market effects. While rural areas tend to have positive labor market effects, the effects for urban areas are mixed or negative. Similarly, high-skilled workers tend to benefit, while low-skilled workers face negative labor market effects.

3.2.3 Productivity (Table 4)

Gal et al. (2019) found an increase in TFP at the firm level due to the additional availability of high-speed broadband internet, and this effect is more pronounced in the manufacturing sector. Cambini et al. (2023) found increased labor and total factor productivity. However, there are important differences across sectors and regions. Only firms in the service sector showed significant productivity gains from new broadband. Moreover, firms in the northwest and south of Italy benefited the most.

Dalgic and Fazlioglu (2020) find both a contemporaneous and a lagged effect of broadband speed on firm productivity. Edquist (2022) is the only study to use data on mobile broadband (3G and 4G) and find a positive effect, but only with a one-year lag after the introduction of mobile broadband. Fabling and Grimes (2021) find evidence of dynamic productivity effects unfolding over a longer period. The effects on TFP and labor productivity are most pronounced for firms that also make complementary investments.

Barrero et al. (2021a, 2021b) point out that traditional productivity measures underestimate the effect of broadband internet on productivity. Optimized working environments and arrangements to facilitate the effectiveness of work from home are likely to significantly increase workers' productivity due to a higher degree of flexibility in work time. For example, Viete and Erdsiek (2020) show that a 20 p.p. increase in the use of mobile ICT solutions leads to an additional 1.05% increase in productivity (for firms with an average share of trust-based working time). This effect increases with a higher share of trust-based working time. In companies in which 85% of employees work under trust-based working hours, the additional productivity increase rises to 4.64%. According to Barrero et al. (2021b), workers, on average, say that they are 4.6% more productive when working from home rather than working in the office all the time due to shorter meetings. Altogether, only 20% of this productivity gain is measured by conventional productivity measures, as savings from less commuting time are not considered. Barrero et al. (2021a) also shed light on the fact that high-income workers on average live in areas with more stable and reliable internet connections and can more easily afford higher bills accompanied with higher bandwidth: Whereas for people who have not finished high school reported internet access quality is good in 85.3 % of worktime, for people with a graduate degree this value is 6.3 p.p. higher. Similar results are obtained when comparing the accessibility of low-income vs. high-income earners.

Thus, except for Gallardo et al. (2021), who find insignificant effects, all other available studies show some positive impacts of high-speed broadband internet on TFP or labor productivity. However, the productivity effects may not be fully contemporaneous but unfold in subsequent periods after the introduction of high-speed broadband technologies and show heterogeneity across economic sectors. Finally, not all realised productivity gains are captured by conventional productivity measures and are therefore not visible in the available empirical literature.

3.2.4 Education and human capital (Table 5)

Grimes and Townsend (2018) investigated the impact of high-speed internet on education and found a positive effect on primary school performance. These findings highlight that the availability and adoption of high-speed digital infrastructure are crucial from an educational perspective. In this regard, it is important to make progress in closing the digital divide not only between urban and rural areas but also between those who can afford high-speed internet connections and those families and individuals who cannot. Similarly, Campbell (2022) found that the availability of high-speed broadband had a positive effect on students' test scores in mathematics and reading in the USA. Moreover, these positive effects were sustained and even increased over time, suggesting the positive potential of high-speed internet connections, which can provide real-time access to information and encourage the application of new learning methods in the classroom and beyond.

Empirical evidence on the ICT–human capital–GDP link using new broadband data is very limited. The two studies reviewed confirm results from the older literature by showing a positive impact on education in terms of student achievement.

3.2.5 Firm and business creation (Table 5)

Evidence in this category is also very limited, with only three studies available. Moreover, the results obtained in these studies do not point to any similar results, so no preliminary conclusions can be drawn here regarding this outcome variable.

3.2.6 Property prices (Table 6)

According to Fackler et al. (2022), there are positive capitalization effects for new broadband (i.e., speeds of 30 and 50 Mbit/s) in Germany. These returns increase over time, but it is important to note that the returns to broadband speed are declining. Comparing the effects for houses and flats, the effect is stronger for lower broadband speeds. Using data for the USA, Deller and Whitacre (2019) and Molnar et al. (2019) also find evidence of diminishing returns for higher broadband speeds. Despite this evidence, Guiffard (2023) and Klein (2022), looking at the impact of high-end FTTH infrastructure availability on property values in France and Germany, respectively, find both significant and substantial effects.

Except for Conley and Whitacre (2020), who found insignificant results, all other studies examining the impact of new broadband on house prices and real estate found significant and positive effects. While studies considering comparatively lower broadband speeds of up to 50 Mbit/s or up to 100 Mbit/s found evidence of diminishing effects at higher speeds, studies using FTTH data still found substantial and significant effects. According to Klein (2022), these results may be due to the different time periods used, and part of the strong FTTH-related effect found may be because the demand for innovative and bandwidth-intensive services develops and increases over time.

3.2.7 Economic resilience (Table 7)

Some studies of economic resilience specifically examine the impact of broadband availability and adoption on workers during pandemics. Katz et al (2020) examine the impact of the SARS pandemic in 2003 and show that a 10% increase in broadband adoption can lead to additional GDP growth of 0.25%. In a simulation, the authors also show that the economic damage suffered by a country with only 10% fixed broadband adoption during the pandemic could be offset by 13% if broadband adoption increased by 1 p.p. If broadband adoption increased to 15%, more than 50% of the negative impact on GDP could be offset. Katz and Jung (2021) highlight the resilience effect of broadband internet during the Covid-19 pandemic. According to this study, countries with higher broadband adoption were better able to absorb the negative economic impact of the Covid-19 pandemic policy measures. The higher the broadband adoption was, the easier it was for households, businesses and governments to continue functioning during the shutdown. Countries with fixed broadband coverage of at least 90% of the population could mitigate a fifth more of the economic downturn than countries with coverage between 30% and 90%. Similar positive effects were found in countries where at least 75% of the population had access to mobile broadband. In countries where fixed broadband adoption was below 30%, the negative economic impact of the Covid-19 pandemic was not mitigated, possibly because not enough people were able to switch to working from home. In this respect, the economic benefits of mobile broadband availability must also be considered: The positive economic impact is particularly high in countries with lower levels of economic development.

Looking at the US, Barrero et al. (2021a) find that during the Covid-19 pandemic, the lack of sufficient availability of broadband infrastructure reduced the productivity of US workers by 0.7%. Therefore, permanent and ubiquitous availability of high-speed broadband internet to workers could increase annual US GDP by $160 billion through positive effects on labor productivity. However, the size of this positive effect varies widely across the labor force: Workers with a four-year college degree experience twice the productivity gains of workers with a high school diploma, and three times the productivity gains of workers who have not completed high school. Overall, telework has the potential to boost the productivity of companies and the economy as a whole, not just in times of crisis but on a sustained basis. However, it is important to bear in mind that this increase in labor productivity also depends on the type of activity, the amount of time worked from home and the individual skills of employees. In addition, Barrero et al. (2021a) show that a 10% increase in broadband internet availability during the pandemic was associated with a 1.4 p.p. increase in well-being, as it ensured social interaction with relatives and friends. Broadband internet quality was also found to have a significant impact on home working productivity. When comparing working from home to working in the office, people whose broadband connection was 100% working reported an 8% increase in productivity, while people whose internet connection was less than 70% working reported a 1% decrease in productivity. Also, for the US, Isley and Low (2022) report that an increase in fixed broadband adoption during the pandemic led to an increase in the employment rate of 0.87 p.p. Zhang (2021) confirms the positive effects of broadband during the pandemic and presents evidence for China. It should be noted, however, that Zhang (2021) only compares data from 2020 with data from 2019 to reach these conclusions. Nevertheless, their results are consistent with the findings of other studies, such as Abrardi and Sabatino (2023), who show that an additional year of high-speed broadband internet availability not only increases local employment, but that this effect is stronger in areas more severely affected by the Covid-19 pandemic. Regarding the development of firms' sales during the pandemic, Abidi et al. (2023) show that firms that had invested in new broadband internet before the pandemic were more successful in continuing their daily business than firms with insufficient ICT investment. The latter were far more affected by government restrictions on their day-to-day operations, while the former proved more resilient and productive in finding new ways of doing business.

3.2.8 Environmental benefits

Although the ICT–energy–CO_2 emission nexus has gained increasing prominence in the policy debate, we did not include this stream of empirical literature in our review for two reasons. First, a comprehensive review of this topic has been provided in a recent publication (Briglauer et al., 2023b); second, as Briglauer et al. (2023b) show, the overall impact is less clear due to several countervailing effects. Their main conclusions are that, first, higher ICT intensity produces mixed results regarding electricity and energy consumption but tends to reduce CO_2 emissions. Second, the latter is particularly true for developed countries. Therefore, ICT elements can have positive environmental effects on society, especially in developed countries, where the adoption of enabling ICT technologies and services is already high.

4 Conclusions and policy recommendations

We provided a comprehensive review of the impact of high-speed wireline and wireless broadband internet based on evidence from 42 empirical contributions covering various countries and regions. In contrast to previous studies, we can draw on better data availability, the ongoing expansion in network availability, and the corresponding adoption of new broadband services. Most previous studies have defined broadband very broadly as internet connections with download speeds of more than 256 Kbit/s, and many studies have not considered different speed ranges or broadband access technologies, focusing for the most part on broadband speeds of less than 30 Mbit/s. However, as different broadband quality levels can have different economic effects, and some individuals, firms, or industries may benefit more from higher broadband speeds than others, an important research question is whether high-speed broadband internet shows similar or stronger results than basic broadband internet. We discuss this in Section 4.1, based upon which we can then draw implications for the ongoing policy discussion on high speed broadband in Section 4.2. Finally, in Section 4.3 we identify the main remaining research gaps and present an agenda for future research.

4.1 Comparison of results from old and new literature

Bertschek et al. (2015) and Gómez-Barroso and Marbán-Flores (2020) have provided important reviews of the causal effects of basic broadband availability and adoption on economic variables such as GDP growth, employment, and productivity. In line with both previous reviews, we find that new broadband internet has a positive and significant effect on GDP at the aggregate level for all studies using country-year panel data. When this result is contrasted with the findings of the older broadband literature, a nonlinear relationship emerges. While the older literature suggests that there seems to be a minimum threshold of broadband quality for economic benefits, the newer literature points to diminishing returns beyond a certain level of broadband quality. However, evidence for diminishing returns may also be due to the fact that demand for innovative and new bandwidth-intensive services develops and increases over time. Findings on employment effects also tend to be consistent with the older literature, with most studies finding positive links between (basic and new) broadband and labor market outcomes. However, both strands of literature also point to heterogeneous effects with respect to differences in urbanization and the skill level of the workforce. While the latter suggests that the effect of broadband is significant mainly for high-skilled workers, the comparatively stronger effect of broadband in remote areas suggests that these regions catch up with more economically developed urban areas once sufficient broadband infrastructure is available. Similar to the literature on basic broadband internet, we find strong evidence of the positive effects of new broadband internet on productivity. However, the effects may vary according to the sector studied and may emerge only over time and in combination with strategic and organizational investments. This also corroborates well with the broader empirical literature on ICT and productivity (Cardona et al., 2013; Jung and Gómez-Bengoechea, 2022) which shows that ICT is evident in the productivity statistics. The productivity effect grows positively over time and ICT investment necessitates complementary organizational investments, skills, and industry structures. Limited evidence supports the positive impact of new broadband on education and human capital, aligning with older literature.

In contrast to the previous surveys, we include other relevant outcome variables. We find additional GDP-relevant effects associated with increases in rents and house prices, which is in line with the basic broadband-related literature (Ahlfeldt et al., 2017). Whereas the above-mentioned effects implicitly all rely on "economic normal times", the lockdown periods during the Covid-19 pandemic showed that digital infrastructures and services are of great importance for the resilience of economies in "times of economic crisis". This significant macroeconomic "resilience effect", in the form of a substantial mitigation of the decline in overall economic performance (GDP) and employment due to a macroeconomic shock and a subsequent faster economic recovery, represents another highly positive externality of digital infrastructures and services. While there was hardly any evidence before the crisis, there exist a few contributions based on new broadband internet data that provide some supportive evidence for this resilience effect. From the few empirical contributions, we infer high welfare effects associated with the increase in socioeconomic resilience generated by both the availability and the use of various digital services. In addition, some studies using different types of digital service data – which were not part of our review – examine the role of crisis-relevant applications such as teleworking. In times of economic crisis, this also includes work from home, contributing not only to higher labor productivity compared to low-quality broadband internet connections but also saving commuting time and thereby increasing leisure and thus consumer surplus (Barrero et al., 2021a, 2021b). Therefore, the total benefits of broadband are largely underestimated if, for example, only GDP-related effects are considered.

Finally, regarding the ICT–energy–CO_2 emission nexus, which has become increasingly relevant in the empirical literature in the last decade, ICT elements can have positive environmental effects on society, especially in developed countries where the use of ICT is high and which at the same time show low levels of ICT production. Although this externality is at a lower level, it is also policy relevant, as it shows that it is not necessary to decouple ICT from economic growth in order to achieve positive environmental effects. However, further ICT availability and adoption is warranted in order to enhance the usage of emission-reducing enabling technologies.

4.2 Policy recommendations

Our survey finds empirically proven substantial positive externalities of (new) broadband infrastructures and services. Thus, policy targets for the availability of new broadband internet and accompanying public funding measures to reach these goals seem to be well supported. While there is not enough empirical evidence to investigate the efficiency of public funding measures in general, there is some evidence that this is the case in some areas (Bourreau et al., 2020). For example, Briglauer and Grajek (2023) show that past funding models in OECD states have proven not only effective but also efficient. Their cost–benefit analysis clearly suggests that related per capita public funding expenditures generated significantly higher per capita benefits, as measured by the additional GDP growth. Their conclusion is reinforced in view of the other non-GDP-related welfare effects identified in this review, which is disregarded in their analysis. Moreover, by facilitating the availability of new broadband internet in remote areas, the share of employees who benefit from remote work solutions in rural areas can be increased. This contributes to a higher level of competitiveness in peripheral areas, as their competitive disadvantages become less relevant. Public funding therefore also helps combat the digital divide between urban and rural regions and reduce the societal costs associated with further depopulation (Briglauer et al., 2019). De Clercq et al. (2023) further argue that the new broadband internet is a potential game changer for future rural development policies.

The availability costs of the various existing broadband technologies can vary considerably, and there may be considerable uncertainty about future technological advances. Combined with uncertainties about the future development of demand for new broadband connections and related services, it would be beneficial if public funding models were designed technology-neutral (Briglauer et al., 2020), including hybrid fiber-copper technologies that may provide comparatively lower (but yet high, i.e., above 100 Mbit/s) broadband speeds, but are more cost-effective in network roll-out. This recommendation is well in line with our findings of diminishing returns to increasing broadband speeds or technological fiber upgrades and with the comparatively high economic growth effects of mobile broadband.

Furthermore, economic policymakers should pay attention not only to availability but also to the actual demand-side adoption of new broadband connections and the use of digital services (Bourreau et al., 2017). In this context, it is important to consider what incentives can be provided to increase migration from old to new broadband internet and to reduce existing barriers to migration. The implication is that, while current infrastructure support indirectly promotes adoption in subsequent periods, specific demand-side support instruments should also be used at the same time. This argument relates to both the output-related welfare effects and the existing demand gaps that are (too) slowly being filled. The European Commission should be commended that the recently adopted broadband state aid guidelines (European Commission, 2022) explicitly include demand-side measures, such as vouchers, as a remedy that may qualify for state aid to mitigate the market failure of low adoption rates and allow Member States to support mobile networks (including fixed-wireless access solutions) and hybrid fiber-based networks under certain conditions.

With regard to the network availability and consumer adoption targets as formulated in the (supra-) national broadband plans, a conflict of objectives might result between rapid coverage of rural regions with medium bandwidths, including all relevant broadband access technologies, on the one hand, and promotion of maximum bandwidths with significantly higher roll-out costs and roll-out times on the other. Our review of the literature suggests that policymakers should encourage rapid and ubiquitous coverage and close existing adoption gaps.

As the welfare effects of broadband are output-related, sector-specific policies should promote adoption. For example, various empirical studies have shown that investment in new broadband connections and hence adoption are generally lower in countries with more restrictive regulatory environments (Briglauer et al., 2018; Grajek & Roeller, 2012). Therefore, to increase adoption and positive enabling effects, regulators should increase investment incentives. In addition to inhibiting factors, the positive complementary role of workers' qualifications and individuals' e-literacy should be highlighted, as ICT is a skill-intensive technology (Akerman et al., 2015; Balsmeier & Woerter, 2019). Lessons from the crisis show that this is particularly true for important (cross-sectoral) applications with high economic benefits, such as teleworking, digital home-schooling, and virtual care, all of which require a certain level of e-literacy. The OECD (2018) highlights the role that governments can play in raising the awareness and e-literacy of their citizens and in encouraging nonusers to adopt new broadband-based services. Meanwhile, the European Commission (2021) has defined the path to the digital decade with specific targets for the year 2030, including basic digital skills for at least 80% of the population, and more than 90% of SMEs reach at least a basic level of digital intensity and 100% online availability of key public services such as e-health.

Regarding ambiguous labor market effects, policymakers must promote appropriate solutions for the potential losers of digitization, especially in the area of low-skilled workers. A complementary education policy should promote general ICT skills. "e-literacy" is a necessary precondition for ensuring that the services that are essential in times of crisis – but also in normal times – can also be effectively used by large parts of the population. To strengthen resilience in future and comparable crises, companies must also push ahead with appropriate measures, in particular with regard to adjustments in work organization, such as teleworking, and in the provision of technical infrastructures, as well as in the corresponding ICT skills of employees. Investments in organizational adaptation and ICT skills will therefore significantly contribute to further strengthening the resilience of digital infrastructures and services in future times of crisis.

4.3 Future research

At the network level, more evidence is needed on the socioeconomic impact of mobile broadband networks, which is still limited to very few contributions using 3G+/4G data. Further research should examine the extent to which the comparatively high GDP effects reported in the studies prove valid in other samples. Moreover, empirical studies are needed on the actual economic (and environmental) significance of 5G networks and the extent to which significantly higher quality levels are also accompanied by corresponding increases in productivity or consumer gains.

At the service level, a more comprehensive understanding of the benefits of ICT could be achieved in the future by examining the economic relevance of individual applications. For instance, Brynjolfsson et al. (2019) suggest that the greatest potential benefits from, e.g., cloud computing, machine learning, AI, and IoT might still be yet to come and may be realized through complementary innovations. Also applications that are likely to have a particularly high resilience effect in times of crises should be empirically investigated. Note that this could include additional areas of social output, such as the impact of new broadband internet on health (Dutta et al., 2019). Given the central role of adoption-dependent welfare effects, the effectiveness of different demand-side support instruments will also be examined in the future to better exploit macroeconomic effects.

The literature on basic and new broadband internet emphasizes the importance of education and human capital, respectively. However, the respective impact channels are still unclear, as broadband internet has a direct influence on human capital on the one hand, which has also been empirically proven in the more recent literature, but human capital has also been identified as an intermediating welfare effect of broadband internet in the older literature on the other hand.

Finally, empirical evidence on the role of broadband internet in generating consumer surplus is still limited to older studies on narrowband (e.g., Greenstein & McDevitt, 2011) as well as basic broadband (e.g., Dutz et al., 2012; Nevo et al., 2016) internet, which already point to high consumer rents. Due to the substantial technological developments in the last two decades, the consumer rents realized on the basis of high-capacity broadband connections are likely to have been significantly higher than those related to basic broadband internet. The transition to the new broadband internet enabled more complex and bandwidth-intensive services. This, in turn, leads to higher willingness to pay, as these factors increase the value of service use for consumers by providing access to a whole new range of entertainment and information applications. Katz and Callorda (2020) is the first study to explicitly use new broadband data to examine the welfare effects of a full switch to future high-capacity FTTLA cable networks. The authors identify that this could also generate a massive gain in consumer surplus of $71.5 billion over the period 2021 to 2027. However, we know very little about the relevance of broadband quality levels and whether the effects on consumer surplus also show diminishing returns with respect to technological infrastructure upgrades and bandwidth levels. Liu et al. (2018) is one of the first studies to examine consumers' willingness to pay for different dimensions of broadband quality, including bandwidth, data caps and latency. The authors find relatively little added value beyond 100 Mbit/s. Using more recent data, future research should determine whether these results hold for particularly popular classes of service.

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