JCMS Journal of Common Market Studies UACES

JCMS 2019 Volume 57. Number 5. pp. 1071–1090 DOI: 10.1111/jcms.12872

Go for Gigabit? First Evidence on Economic Benefits of High-speed Broadband Technologies in Europe*

WOLFGANG BRIGLAUER[1] and KLAUS GUGLER[2]

[1]ZEW Centre for European Economic Research, Mannheim [2]Department of Economics and Research Institute for Regulatory Economics, Vienna University of Economics and Business, Vienna

Abstract

The literature on the effects of investment in broadband infrastructure finds positive macroeconomic effects. However, it is severely constrained because it could hitherto only analyse investment or adoption up to basic broadband, but not up to the newer generations of hybrid fibre and end-to-end fibre-based broadband. Utilizing a comprehensive panel dataset of EU27 member states for the period from 2003 to 2015, we estimate a small but significant effect of end-to-end fibre-based broadband adoption over and above the effects of basic broadband on GDP; specifically, we find that a 1 per cent increase in adoption leads to an incremental increase of 0.002–0.005 per cent in GDP. The incremental effect of hybrid fibre broadband adoption over basic broadband is slightly lower (0.002–0.003%). Our cost-benefit analysis implies that policy intervention – as foreseen by the European Commission – is only justified for coverage and adoption levels of around 50 per cent, whereas for a 100 per cent coverage level net losses are likely.

Keywords: Cost-benefit analysis; EU27 panel data; High-speed broadband adoption; EU broadband; policy targets

Introduction

In the late 1990s broadband markets experienced their first disruptive innovation when internet technology transitioned from narrowband to basic broadband via digital subscriber line (DSL) and cable modems based on copper wire and coaxial cable access infrastructures, respectively. On the grounds of their alleged huge positive externalities, economists analysed the effects of these infrastructure investments on macroeconomic growth, and found a broadly positive effect. Currently, broadband markets are subject to major disruptive innovations in the forms of the transition to modern broadband internet, which is based in part or entirely on a fibre-optic (wireline) infrastructure in the final segments of access networks. Deployment costs, however, increase disproportionately when switching from hybrid to end-to-end fibre technologies. Whereas in the former case fibre is deployed only at distribution points as far as several hundred metres away from the customer's premises, the latter involves deploying fibre access networks directly into the building or apartment of a customer. Given substantial differences in deployment costs, it is important to quantify the economic benefits and costs when deciding on the optimal evolution of broadband deployment and associated policies.

* The authors are very grateful for the insightful and valuable comments of three anonymous referees and to Frank Verboven, Thomas Niebel, Günter Knieps, Volker Stocker and conference participants in Trento at the 29th ITS European Regional Conference for many useful comments and suggestions. Financial support by the State Government of Baden-Württemberg, Germany, through the research programme 'Strengthening Efficiency and Competitiveness in the European Knowledge Economies' (SEEK) is gratefully acknowledged.

The deployment of hybrid and end-to-end fibre-based broadband technologies is currently a hot policy issue. In its current major framework review, the European Commission (EC) published its proposal for a directive establishing the European Electronic Communications Code (EC, 2016a), with one key aim being the provision of sufficient incentives for investment in the infrastructure of fibre-based communications networks. Following the Digital Agenda Europe (DAE) objectives for 2020 (EC, 2010), the EC further specified ambitious and specific long-term objectives for 2025 with a strong emphasis on the promotion of very high-capacity networks that enable gigabit connectivity (EC, 2016b).[1] Although these objectives appear to be neutral regarding the preferred type of technology, the EC implicitly favours end-to-end fibre-based network technologies (see EC, 2016a, recital 13 and Art. 2 (2)).

From a dynamic perspective the core question is to what extent welfare is lost through slower rather than faster migration to end-to-end gigabit networks and whether dirigiste market interventions, such as those favouring certain broadband technologies in public policy targets instead of market-driven technology choices, are justified in view of considerably higher deployment costs. The latter is referred to as the principle of technological neutrality (EC, 2009, recital 18). The answer depends on the extent of incremental economic benefits related to end-to-end fibre-based broadband and on the further evolution of hybrid broadband. As shown in Section I, the empirical literature on economic effects related to specific fibre technologies is extremely scant, and the evolution of future technology standards and demand is subject to a high degree of uncertainty. This implies that rigorous empirical evidence on the causal impact of modern broadband internet is much needed. Accordingly, we provide evidence on the following research question: What are the incremental economic benefits of different fibre technologies vis-à-vis basic broadband and do incremental benefits justify favouring high-cost investment scenarios?

We utilize a recent panel dataset on 27 EU member states from 2003 to 2015, covering almost the entire fibre-deployment period. The present analysis provides econometric evidence based on EU data with unique data for all relevant wireline broadband technologies.[2] We employed a twofold research strategy. First, in order to identify causal effects of individual broadband technologies on economic benefits, which we measured in terms of gross domestic product (GDP), we explicitly accounted for potential endogeneity utilizing panel econometric estimators with instrumental variables. Second, we related the estimated benefits of broadband adoption to available cost estimates from external industry studies in order to provide some rudimentary cost-benefit analysis. We found that the incremental benefits of end-to-end fibre-based broadband are statistically significant and slightly larger than those of hybrid-fibre broadband, however, we found the largest estimated growth effects for basic broadband adoption. Our cost-benefit analysis reveals that partial but not full end-to-end fibre-based broadband coverage entails the largest net benefits.

The article is organized as follows. Section I reviews the recent and most relevant empirical literature. Section II then presents the empirical baseline specification and our

[1]In its gigabit society objectives the EC foresees '[a]ll European households, rural or urban, as having access to internet connectivity offering a downlink of at least 100 Mbps, upgradable to gigabit speed' (European Commission, 2016b, pp. 35–36).
[2]Although mobile broadband will assume an increasingly important role in view of current 4G and upcoming 5G technologies (as acknowledged in the EC's gigabit society objectives), the EC as well as most national regulators have not to date defined common fixed and mobile broadband markets due to the lower average bandwidth and quality levels in the past.

identification strategy. Section III describes our panel data set. Section IV discusses the main results of our empirical estimation and cost-benefit analysis. Finally, Section V summarizes and compiles the most relevant policy implications of our results.

I. Literature Review

The study of the economic impact of broadband availability and adoption has attracted a significant amount of empirical research. Note that availability in terms of broadband coverage is related to investment activities, whereas adoption on the demand side has a direct impact on its economic outcomes. The former are typically more informative from a policy perspective (e.g., the impact of regulation or public funding on investment incentives), whereas the latter are more informative from a welfare perspective or for a cost-benefit analysis. A recent survey by Bertschek *et al*. (2016) reviewed more than 60 studies that investigate the causal effects of broadband availability and adoption and found positive effects on most relevant economic outcomes such as economic growth and employment, as well as productivity and firm performance.

Regarding economic growth, the first seminal contribution with country-level data comes from Röller and Waverman (2001), who investigated the impact of telecommunications infrastructure for narrowband landline on economic growth in 21 OECD countries from 1970 to 1990. Their results show that the increase in the number of mainlines per capita positively impacts on economic growth. Overall, telecommunications infrastructure is estimated to account for approximately one-third of annual GDP growth between 1970 and 1990. Following this study, several other country-level studies investigated the impact of broadband infrastructure on economic growth. Koutroumpis (2009) examined the relationship between broadband adoption and GDP growth, utilizing data for 22 OECD countries from 2002 to 2007. The author found a significant positive impact of broadband adoption on GDP, with a one per cent increase in broadband adoption generating a 0.023 per cent increase in GDP growth. Czernich *et al*. (2011) employ data for 25 OECD countries from 1996 to 2007 and find that a 10 percentage point increase in the rate of broadband adoption led to a 0.9 to 1.5 percentage point increase in the annual growth of GDP per capita. Gruber *et al*. (2014) used data for EU 27 states from 2005 to 2011 to evaluate the benefits and costs of the DAE. Their estimates suggest that broadband adoption rates had a significant and positive effect on GDP in the observed period.

Only very few studies explicitly include data on fibre-based broadband (Abrardi and Cambini, 2019). In a study prepared for the EC, WIK-Consult/Ecorys/VVA (2016) shows that broadband speed is positively correlated with total factor productivity across major industrial sectors, which is then channelled into a GDP growth rate of 0.15 percentage points. Sosa (2015) estimated the differential effect of gigabit broadband availability which is measured at the US state level for nine states where at least 50 per cent of households have gigabit coverage. Data are available for the years 2011 and 2012. The authors control for the unemployment rate, state and period fixed effects and found that per capita GDP was about 1.1 per cent higher in states that have more than 50 per cent gigabit coverage. Bai (2017) is another recent study that examined the impact of different broadband speed levels using US county-level data for the years from 2011 to 2014. The study is closest to our approach as it employs data on speed levels, which act as a fairly reliable proxy for different basic broadband, hybrid fibre and end-to-end fibre technologies. The author assessed the differential impact on employment and found a positive impact of broadband availability, but that, compared to basic broadband, fibre-based broadband did not generate substantially greater positive effects on employment. Finally, Hasbi (2017) estimated the impact of ultra-fast broadband on local economic growth, utilizing data on more than 36,000 French municipalities for the years from 2010 to 2014. The author found it had a positive impact on the number of companies, on company creation and in terms of unemployment reduction.

In summary, the general result of a positive and statistically significant effect of basic broadband availability (or adoption) on either GDP or GDP growth is found at the macro-level in all the country-level studies reviewed in the older broadband-related literature. However, there is still only very scant empirical evidence available so far as regards the causal and differential impact of various fibre-based broadband access technologies on economic outcomes such as employment and economic growth. Accordingly, Bertschek *et al.* (2016) conclude that '[r]eliable and broad evidence on economic impacts of high-speed wireline or wireless broadband infrastructure and adoption is still largely missing so far'. The few existing studies are non-EU based or focus on outcomes other than GDP or GDP growth. There is hardly any evidence available so far on the impact of fibre-based broadband on economic growth and in terms of the costs and benefits of different fibre roll-out scenarios that allows us to draw any conclusions on the attractiveness of the policy targets currently being set at the member state and EU level. The aim of our work is to fill this research gap and to inform the ongoing policy debate on the promotion of gigabit networks at the EU level and in other jurisdictions.

II. Empirical Specification

We first outline our empirical specification and then our identification strategy. Following the specifications in Röller and Waverman (2001), Koutroumpis (2009) and Czernich *et al.* (2011), national aggregate economic output (GDP) is related to various input factors, that is, labour (L), all forms of non-broadband capital stock (C) and different stocks of broadband infrastructure (BB). The starting point of analysis is a production function that allows for different levels of technology (A) in country i in period t and reads as follows:

$$GDP_{it} = A_{it}F\left(L_{it}; C_{it}; \sum_j BB_{it}^j\right) \tag{1}$$

where the variables BB^j represent different broadband technologies (basic broadband, hybrid and end-to-end fibre-based broadband). According to Cardona *et al.* (2013), who surveyed the empirical literature on information and communications technologies (ICT), most econometric estimations of the production function are derived from log-linearizing static versions of Equation 1. We therefore take logs of a Cobb–Douglas type production function in Equation 1, and add a vector of macroeconomic covariates $\boldsymbol{X_{it}}$ to capture time-variant heterogeneity within countries, a constant (α), country fixed effects (α_i) and period effects (α_t) as well as an error term η_{it} which yields the following estimating equation:

$$\ln(GDP_{it}) = \alpha + \alpha_L \ln(L_{it}) + \alpha_C \ln(C_{it}) + \sum_j \beta^j \ln\left(BB_{it}^j\right) + \gamma' \mathbf{X}_{it} + \alpha_i + \alpha_t + \varepsilon_{it} \quad (2)$$

where $\varepsilon_{it} = \eta_{it} + ln\ (A_{it})$ and the parameters α_L and α_C represent output elasticities of labour and capital, respectively. From the previous discussion, we expect all $\beta s > 0$. Furthermore, if the EC's assumptions expressed in its gigabit objectives are correct, we should also observe a larger incremental effect of end-to-end fibre than of hybrid fibre-based broadband technologies. As regards period and country fixed effects, it is assumed that they do not interact with any of the input factors. Period effects capture macroeconomic shocks that are common to all countries and are not captured in $\boldsymbol{X_{it}}$.

In the case of basic broadband as analysed in the older empirical literature, the distinction between availability and adoption was less relevant in view of typically rather high take-up rates (i.e., the ratio between connections adopted to all available connections). In contrast, this distinction is of high relevance in fibre-based broadband markets, where take-up rates are persistently low in most European countries (i.e., far below 30 per cent on average, see Figure 1 and Figure 2). Low take-up rates imply that the willingness of consumers to adopt and therefore migrate to the new broadband services is moderate on the demand side, which also gives rise to substantial and costly over-capacities on the supply side. The production function underlying our estimating equation, however, assumes full network utilization (i.e., the take-up rate is equal to one), which is apparently not valid for fibre-based broadband in particular. In view of low fibre-based broadband take-up rates, we thus employ data on output-related broadband adoption ($BB_{it}s$) to estimate the augmented production function in Equation 2.[3]

Identification Strategy

Estimating Equation 2 has to take potential endogeneity into account; in particular, GDP and broadband adoption may be simultaneously determined. Another source of endogeneity is related to omitted variables such as broadband subsidies (Czernich *et al.,* 2011). In view of such sources of endogeneity we employ a two-stage-least squares (2SLS) estimator using two sets of sources of exogenous variation.

First, regulation of broadband infrastructure and competition in broadband markets can be expected to have a strong impact on both investment and adoption. Regulation in general exerts a twofold impact, which is well documented in the theoretical and empirical literature[4]: on the one hand, it has an impact on the investment and innovation incentives of network operators. On the other hand, it is supposed to stimulate (service-based) competition by enabling alternative operators to access monopolistic bottlenecks (broadband infrastructure) at regulated fees.[5] The former effect impacts on adoption via investment activities, whereas the latter impacts on adoption as it pushes retail competition and yields

[3]Note that we refer to broadband adoption in terms of the consumer's participation decision but we do not investigate further the determinants of broadband adoption. Admittedly, adoption and usage not only depend on bandwidth but on a variety of factors. For an extensive conceptual discussion of the complexity of the relationship between the quality of service and the quality of experience the reader is referred to Stocker and Whalley (2018). The authors conclude that broadband access speed is only necessary, but not sufficient, for a good consumer experience.

[4]For literature related to basic broadband the reader is referred to Koutroumpis (2009), Bouckaert *et al.* (2010), and Grajek and Röller (2012); for literature dealing with the newer and fibre-based broadband see Bacache *et al.* (2014) and Briglauer (2015).

[5]Note that traditional access regulations imposed on basic and new broadband infrastructure require the dominant ('incumbent') operators to provide some form of access to their network infrastructure. The term incumbent refers to former – mostly state-owned – telecommunications monopolists of wireline networks.

Figure 1: Availability and adoption of fibre-based broadband in EU 27 (millions of households). FTTH/B, FTTH/B, fibre-to-the-home (FTTH) and fibre-to-the-building (FTTB).

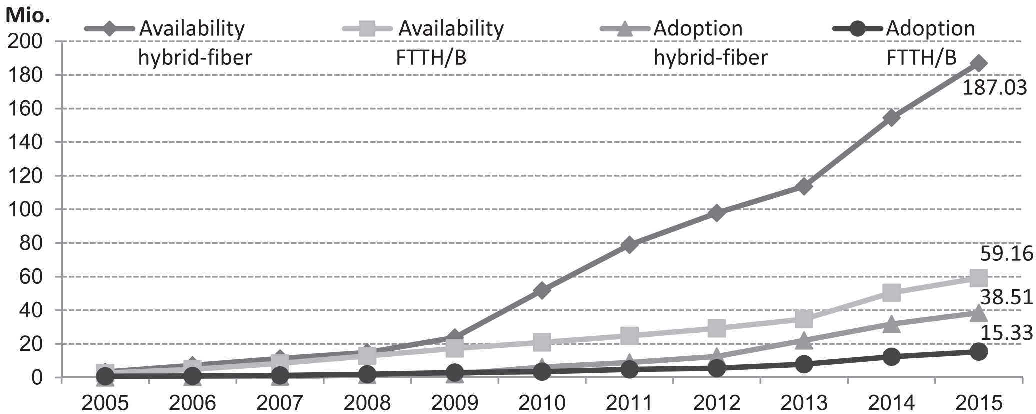
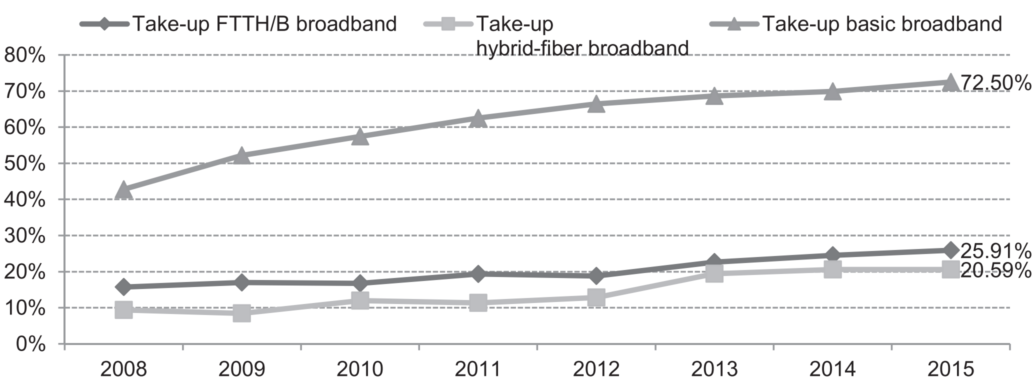


Figure 2: Average EU 27 take-up rates (adopted connections/available connections) in percentages. FTTH/B, fibre-to-the-home (FTTH) and fibre-to-the-building (FTTB).



lower prices. Similarly, competition in broadband markets stemming from independent mobile and all other (non-incumbent) wireline network operators determines retail prices and quality levels and hence adoption in broadband markets.[6]

Second, we make use of the factual circumstance that broadband adoption in all other ($i \neq j$) EU 26 member states exerts considerable pressure on national politicians in any given member state i not to fall too far behind the development in the other member states. Indeed, in its gigabit strategy the EC explicitly acknowledges the great success of the former broadband policy target expressed in its DAE:

[6]Note that while we exclude mobile broadband from our dependent variable for reasons related to market definition as noted in footnote 2, we can employ competition from the mobile sector – next to wireline competition – as a predictor for basic and fibre-based wireline broadband adoption.

'These objectives progressively have become a reference for public policy.… At the national level, setting objectives has become the cornerstone of broadband deployment public policy.… Many member states have indeed aligned their national or regional NGN [next generation networks] plans to the DAE speeds' (EC, 2016b, p. 31).

We thus expect national broadband adoption to be strongly influenced by the average adoption of basic and fibre-based broadband in all other EU member states, which at the same time should not have any direct impact on national GDP. We estimate the baseline specification in Equation 2 utilizing an ordinary least squares fixed effects (OLS FE) estimator as well as a 2SLS FE estimator with an over-identifying set of external restrictions which allows us to examine the validity of our instruments.

III. Data

We employed an unbalanced panel dataset of EU 27 member states[7] for the period from 2003 to 2015. In constructing our data we used three main sources: First, for our dependent variable measuring real gross domestic product (*GDP*)[8] at constant 2011 prices as well as for variables measuring non-broadband real capital stock (*capital_stock*) and labour in terms of total hours worked (*work_hours*) we utilized data from the Penn World Table. Second, our source for the main independent variables of interest was the database of FTTH Council Europe, which includes annual numbers of fibre-based broadband lines adopted for EU member states. In view of the baseline specification in Equation 2 we took logs of GDP, capital and labour inputs and all broadband variables. Third, we used data from the EC's Progress Report on the Single European Electronic Communications Market, in conjunction with its Digital Agenda Scoreboard, which provide data on basic broadband and related access regulations as well as data on competition in broadband markets. Finally, we also employed several other data sets to construct our control and instrumental variables.

All sources and variable definitions are listed and described in detail in Table 1, while descriptive statistics are provided in Table 2. Owing to the fact that some values are missing, there are fewer observations than the maximum number (13*27 = 351) and some 0.74 per cent of all the raw data was calculated using linear interpolation.

Broadband Variables

Our main variables of interest represent different broadband adoption technologies denoted by *BB*, which measure the number of subscribing consumers and businesses who show sufficient willingness to pay for broadband services. These variables differ from broadband availability measured in real terms as physical connections deployed (installed capacity). The variables *BBs* measure broadband connections in terms of adopted connection lines, as the main impact on economic growth is associated with the adoption (and not the mere deployment) of broadband connections accruing from usage of new services and applications or employing existing services faster and more efficiently.[9]

[7]We do not include Croatia, which joined the EU in 2013.
[8]In Section IV we discuss the imperfect nature of GDP as a measure of the economic benefits of broadband. Most likely, the GDP measure underestimates the true benefits of broadband adoption. However, we use it as a measure as it is correlated with the benefits of broadband adoption and it is both an established and politically relevant measure.
[9]Adoption of broadband connections enables access to internet applications free of charge or at a cost. Whereas connections are based on different internet access infrastructures, internet applications require end-to-end active traffic management with varying levels of quality dimension requirements for different types of applications (Knieps and Zenhäusern, 2015; Stocker and Whalley, 2018).

Table 1: Variable descriptions

Variable	*Description*	*Source**
	Dependent variable	
Real GDP, *GDP*	Real GDP at constant 2011 national prices (in 2011 million US$)	Penn World Table[1]
	Broadband variables	
End-to-end fibre-based broadband, $BB^{FTTH/B}$	Total number of consumers subscribed to FTTH/FTTB services. Subscribers can be households or businesses. FTTH/FTTB is defined as an access network architecture in which the final connection to the subscriber is optical fibre and terminates inside the premises or on an external wall of the subscriber's premises, or no more than 2 m from an external wall of the subscriber's premises.	FTTH Council Europe[2]
Hybrid-fibre broadband, BB^{Hybrid}	Total number of consumers subscribed to FTTC and FTTLA services. Subscribers can be households or businesses. FTTC is when the modern VDSL technologies are run on a hybrid fibre-based network, which extends to street cabinets, and copper lines, which typically run for around several hundred metres from the street cabinet to the customers' premises. VDSL/XGfast is a recent hybrid copper fibre technology that is not included. FTTLA means high-speed access enabled by the DOCSIS 3.0 technology on hybrid fibre coaxial cables.	FTTH Council
Basic broadband BB^{Basic}	Number of total broadband internet subscribers based on access ≥ 256 Kbit/s as the sum of the capacity in both directions	EU DAE Scoreboard[3]
	Capital and labour inputs	
Capital stock, *capital_stock*	Capital stock at constant 2011 national prices (in 2011 US$ million)	Penn World Table
Total work hours, *work_hours*	Total hours worked by persons employed	Penn World Table
	Macroeconomic control variables	
Networked readiness index, *nri*	Macroeconomic environment and propensity of a country to exploit the opportunities offered by ICT	Euromonitor[4]/World Economic Forum[5]
Interest rate, *interest rate*	Long-term interest rate for debt security issued at 10 years maturity at local currency unit	European Central Bank[6]
Economic freedom, *eco_freedom*	Economic freedom index between 0 and 100, based on four broad categories: the rule of law; limited government; regulatory efficiency; and open markets	The Heritage Foundation[7]
	Instrumental variables (competition and regulation)	
Mobile-to-fixed ratio, *mobile_comp*	Share of the total number of mobile-cellular telephone subscriptions to the total number of mobile-cellular telephone subscriptions and total number of active fixed landlines	ITU[8]
Entrant's market share, *broadband_comp*	Entrant's (non-incumbent operator's) retail market share in fixed broadband lines	EU DAE Scoreboard

Table 1: (Continued)

Variable	*Description*	*Source**
Price for full LLU, *llu_price*	Monthly average total cost regulated access price for full local loop unbundling (LLU) in €	EU DAE Scoreboard
	Instrumental variables (geographical)	
End-to-end fibre-based broadband other EU, $BB^{FTTH/B}\_eu26$	Average number of adopted FTTH/FTTB technologies in all other EU 26 countries (other than the country *i*)	FTTH Council Europe
Hybrid-fibre broadband other EU, BB^{Hybrid}_eu26	Average number of adopted FTTC and FTTLA technologies in all other EU 26 countries (other than the country *i*)	FTTH Council Europe
Basic broadband other EU, BB^{Basic}_eu26	Average number of fixed broadband adoptions in all other EU 26 countries (other than country *i*)	FTTH Council Europe

1 Data available online at: http://www.rug.nl/ggdc/productivity/pwt/ 2 FTTH Council Europe data are available to its members at: http://www.ftthcouncil.eu/resources?category_id=6. 3 Data available online at https://ec.europa.eu/digital-single-market/en/digital-scoreboard 4 Data available online at http://www.euromonitor.com/. 5 Data available online at http://reports.weforum.org/global-information-technology-report-2016/networked-readiness-index/. 6 Data available online at https://www.ecb.europa.eu/stats/html/index.en.html. 7 Data available online at http://www.heritage.org/index/explore. 8 Data available online at: http://www.itu.int/ITU-D/ict/statistics/.

Table 2: Summary statistics

	Count	*Mean*	*SD*	*Min*	*Max*
GDP	351	612346.5	863176.9	8402.4	3613889.2
BB^{Basic}	337	3932314.9	6160487.5	2146	30104018
$BB^{FTTH/B}$	346	166997.0	348469.2	0	2587387
BB^{Hybrid}	346	526169.0	1196282.5	0	9366700
capital_stock	351	2718601.9	3820867.1	27606.0	13875688
work_hours	351	13639.3	16252.8	310.8	58895.4
nri	349	4.626	0.647	2.700	6
interest rate	351	4.235	2.264	−0.0200	22.50
eco_freedom	351	68.81	6.057	50	82.60
mobile_comp	351	0.736	0.0913	0	0.931
broadband_comp	337	0.507	0.158	0	1
llu_price	335	11.43	4.623	5.110	42
BB^{Hybrid}_eu26	346	2151314.3	2283850.7	1	7193497.4
$BB^{FTTH/B}\_eu26$	346	773391.5	668928.2	1	2275478.4
BB^{Basic}_eu26	346	3935307.1	1590957.3	1182851.5	6140723.2

Different broadband technologies are distinguished on the basis of fibre reach: end-to-end fibre-based broadband is denoted as $BB^{FTTH/B}$ and is defined as the sum of fibre-to-the-home (FTTH) and fibre-to-the-building (FTTB) access networks. Hybrid fibre-based broadband, denoted by BB^{Hybrid}, comprises hybrid fibre networks based on VDSL (very-high-bit-rate digital subscriber line) technologies employed by former monopolist (incumbent) operators. This case is referred to as fibre to the cabinet (FTTC). The other hybrid case is based on coaxial-cable and DOCSIS 3.0, the technologies of cable TV operators. This case is referred to as fibre-to-the-last-amplifier (FTTLA). Both hybrid broadband networks rely on old copper wire and coaxial cable lines in the remaining part of the access network connecting the customer premises with the last distribution point. From that point on all data transmission is fibre-based. In contrast, basic broadband technologies, BB^{Basic}, mainly rely on existing (legacy) copper or coaxial cable and DSL or cable modem technologies in the entire network. Note, however, that our measure for basic broadband adoption, that is, connections with download speed ≥ 256 Kbps, also includes hybrid and end-to-end fibre-based broadband connections, although most basic broadband connections consist of much lower bandwidth levels.

Figure 1 shows average EU deployment patterns on the availability and adoption of fibre-based broadband for the years 2005–2015. In view of the total number of households in the EU 27 (about 218,072,600 in 2015), this results in an average household coverage with fibre-based broadband (246,193,367 households in 2015)[10] of about 113 per cent. This number is above 100 per cent due to a parallel coverage with fibre-based broadband infrastructure, in particular in urban areas, where homes and businesses are often supplied by incumbent, cable and other wireline operators (EC, 2017).

In order to capture this asymmetry in maximum adoption and coverage levels, an alternative measure is the take-up rate. As one can infer from Figure 1, there has been a considerable gap between available and adopted fibre-based broadband connections, implying persistently low take-up rates for both technologies (Figure 2).[11] This phenomenon is even more pronounced with respect to hybrid-fibre broadband. As one can also infer from Figure 2, basic broadband take-up rates (72.50%) are much larger than for hybrid (20.59%) and end-to-end fibre-based (25.91%) broadband.[12]

Control Variables

In line with the related empirical literature we further employed the following macroeconomic controls in estimating the aggregate production function in Equation 2 in order to control for time-variant heterogeneity at the country level. They are the long-term interest rate (*interest rate*), indices measuring the degree of economic freedom (*eco_freedom*) and a country's networked readiness (*nri*) in terms of its environment and propensity to exploit the opportunities offered by ICT. We expect a higher degree of economic freedom and network readiness to translate into higher GDP. The long-term interest rate for debt security issued at 10 years of maturity captures financing costs and thus is expected to be negatively related to GDP.

Instrumental Variables

As explained in Section II, we employed two distinct sources of exogenous variation to identify causal effects of broadband on GDP. First, broadband access regulation is

[10]Source for household data: Euromonitor.
[11]All data reported in Figures 1 and 2 are taken from FTTH Council Europe.
[12]There is, however, considerable heterogeneity across the EU member states. In particular, eastern European countries are characterized by a lack of well-developed broadband legacy networks (Briglauer and Cambini, 2019). This imposes a lower replacement effect on the supply side as well as lower switching costs for consumers when adopting new broadband services. The lack of a well-established previous broadband infrastructure in eastern European transitional economies in parts also explains the substantially higher end-to-end fibre-based take-up rates as reported in Figure 2, as consumers were confronted with much lower switching costs in those countries. In contrast, consumers in most of western and northern European countries are content with the quality of basic broadband services delivered via a well-established old broadband infrastructure, which imposes substantial switching costs on the side of consumers.

measured by the monthly so-called unbundling access price, denoted as *llu_price*, which has been by far the most important broadband access solution under the EU regulatory framework since the liberalization of the telecommunications markets first began. A larger access price implies more lenient regulation of the incumbent and less scope for service-based competition. Infrastructure-based competition in broadband markets is measured by relevant forms of competition stemming from mobile (*mobile_comp*) and all other (non-incumbent) wireline broadband networks (*broadband_comp*). Mobile and wireline broadband services provided over independent networks (and via unbundling regulations) exert substantial competitive pressure on the former incumbent monopolist operator. We expect regulation and competition in broadband markets to affect investment significantly as well as the price and quality of broadband services and thus broadband adoption, but not GDP.

Second, average broadband adoption in all other ($i \neq j$) EU26 member states is denoted as BB^{Hybrid}_eu26, $BB^{FTTH/B}\_eu26$, and BB^{Basic}_eu26. It is defined as the ratio of household broadband adoption with hybrid, end-to-end fibre-based and basic broadband in EU26 countries (i.e., other than country *i*) to the total number of other countries. Due to broadband target-related benchmarking effects, we expected below-average countries to catch up.

IV. Empirical Results

We first report estimation results for our aggregate production function (Equation 2) in this section. Based on these results, we provide a rudimentary cost-benefit analysis of the economic net benefits of relevant broadband access technologies.

Aggregate Production Function

Table 3 shows the main regression results for 2SLS fixed-effects (FE) specifications, whereas OLS-FE results are reported in the Appendix in Table A.1. Overall, OLS and 2SLS regression results point to a similar structure of coefficient estimates. *F*-tests of the null hypothesis that all FE are zero (reported at the bottom of Table A.1) clearly suggest that pooled OLS estimates would yield inconsistent estimates.

Table 3 reports 2SLS estimates that take into consideration potential endogeneity underlying our broadband adoption variables. To deal with endogeneity we employed the regulation, competition and geography-based instruments described in Section 4.3 as sources of exogenous variation. According to Hansen tests, our instruments are jointly valid in all specifications. First stage Angrist–Pischke *F*-statistics of excluded instruments suggest that our instruments are also strong (close to or above the value of 10) for our broadband adoption variables. The Kleibergen–Paap test of under-identification clearly rejects the null hypothesis that the respective estimating equation is under-identified for all regressions at the 5 per cent significance level, implying that the excluded instruments are correlated with the endogenous regressors and thus relevant. Durbin–Wu–Hausman tests do not reject the null hypothesis of broadband adoption being an exogenous variable in all regressions. Hence, the latter tests suggest that the included broadband variables can be considered exogenous and OLS estimates reported in Table A.1 should be consistent and overall more efficient in this case. Nevertheless, 2SLS coefficient estimates point to

Table 3: **Two-stage-least squares estimation results for production function model (Equation 2)**

Dep. var.: ln (GDP) *Incl. broadband var. (superscripts):*	*(1)* *Basic*	*(2)* *Basic, FTTH/B*	*(3)* *Basic, hybrid*	*(4)* *FTTH/B*	*(5)* *Hybrid*
Broadband adoption					
$ln\ (BB^{Basic})$	0.026 (1.22)	0.024 (1.16)	0.024 (1.11)		
$ln\ (BB^{FTTH/B})$		0.004* (1.80)		0.005** (2.31)	
$ln\ (BB^{Hybrid})$			0.002 (1.27)		0.003* (1.71)
Non-broadband inputs					
ln (work_hours)	0.324*** (3.23)	0.344*** (3.34)	0.322*** (3.17)	0.331*** (3.00)	0.305*** (2.86)
ln (capital_stock)	0.536*** (3.44)	0.521*** (3.31)	0.529*** (3.34)	0.601*** (4.95)	0.610*** (5.31)
Macroeconomic controls:					
eco_freedom	0.005*** (2.97)	0.004** (2.39)	0.004*** (2.79)	0.004** (2.41)	0.004*** (2.93)
nri	0.048 (1.56)	0.049 (1.57)	0.048 (1.56)	0.041 (1.15)	0.041 (1.12)
interest rate	−0.011*** (−6.63)	−0.011*** (−7.49)	−0.011*** (−7.16)	−0.009*** (−7.86)	−0.009*** (−7.57)
Country dummies	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes
RMSE	0.032	0.032	0.032	0.032	0.032
Hansen test (*P* value)	0.162	0.237	0.203	0.186	0.141
DWH test (*P* value)	0.304	0.224	0.597	0.164	0.673
KP (*P* value)	0.020	0.020	0.014	0.001	0.001
AP F test (excl. instr.)					
$ln\ (bb^{Basic})$	11.89	9.81	10.32		
$ln\ (bb^{Hybrid})$			54.87		6.44
$ln\ (bb^{FTTH/B})$		6.89		40.81	
Observations (*N*)	329	329	329	329	329

Notes: Year effects are jointly significant and therefore included in all regressions as well as EU member state fixed effects. We instrumented the broadband adoption variables $ln\ (BB^{Basic})$, $ln\ (BB^{FTTH/B})$ and $ln\ (BB^{Hybrid})$ using the following list of excluded instruments: *mobile_comp*, *broadband_comp* and *llu_price* in regressions (1) to (5), $ln\ (BB^{Basic}\_eu26)$ in regressions (1) to (3), $ln\ (BB^{Hybrid}\_eu26)$ in regressions 3 and (5) and $ln\ (BB^{FTTH/B}\_eu26)$ in regressions (2) and (4). Coefficient estimates in all regressions are based on standard errors which allow for arbitrary forms of heteroscedasticity and autocorrelation. *t*-statistics in parentheses. * $P < 0.10$, ** $P < 0.05$, *** $P < 0.01$, AP, Angrist-Pischke; DWH, Durbin-Wu-Hausman; GDP, gross domestic product; inst., instruments; KP, Kleibergen -Paap; RMSE, Root Mean Square Error.

a greater influence of broadband adoption on GDP, particularly for basic and end-to-end fibre-based broadband.

The coefficient estimates for basic broadband (*ln* (BB^{Basic})) are 0.026 in the 2SLS estimation (regression 1 in Table 3) and 0.015 in the OLS specification (regression 1 in Table A.1). OLS coefficient estimates are smaller but more efficiently estimated. OLS estimates for hybrid and end-to-end fibre-based broadband (*ln* (BB^{Hybrid}); *ln* $(BB^{FTTH/B})$) are of quite similar magnitude in all regressions ranging from 0.002 to 0.003. Controlling for basic broadband adoption we find weak and marginally significant incremental effects for hybrid and end-to-end fibre-based broadband (*ln* (BB^{Hybrid}); *ln* $(BB^{FTTH/B})$), in 2SLS regressions (2) and (3) in Table 3 with coefficient estimates of 0.004 and 0.002, respectively. When dropping the basic broadband variable, we find slightly higher and significant effects as expected for hybrid (0.003) and end-to-end fibre-based (0.005) broadband in regressions (4) and (5), respectively. This effect is also visible in OLS estimation results (Table A.1). Whereas the coefficient estimate for basic broadband is at the lower range of estimates identified in the related empirical literature (see Czernich *et al.* [2011] and Koutroumpis, [2009] for basic broadband adoption in OECD countries), the incremental effect of fibre-based broadband adoption appears to be weak but marginally significant (no comparable values from the previous literature available). The 2SLS and OLS estimates suggest that a 1 per cent increase in adoption leads to an incremental increase of about 0.002–0.005 per cent in GDP with respect to end-to-end fibre-based broadband and to a 0.002–0.003 per cent increase with respect to hybrid-fibre broadband. Estimated coefficient estimates of broadband adoption therefore suggest that the incremental benefits related to fibre-based broadband are positive and significant, while they are slightly smaller for hybrid broadband.

Coefficient estimates for the other (non-broadband) input factors labour and capital (*ln (work_hours)*; *ln (capital_stock)*), are significant and exhibit a rather strong impact on GDP, as expected. Our macroeconomic control variables (*eco_freedom; nri*; *interest rate*) are significant in most specifications and – if significant – in line with prior expectations and corresponding OLS estimates in Table A.1.[13]

Cost-benefit Analysis

Using our main estimation results, we aimed to construct a basic cost-benefit analysis. In the first step we calculated average benefits on the basis of a set of assumptions: In our best-case scenario estimated EU average benefits (column 1 in Table 4) are based on the upper bounds of the 2SLS and OLS coefficient estimates ($\overline{\beta}$) in Table 3 and Table A.1, respectively. Furthermore, we assumed the highest value of hybrid and end-to-end fibre take-up rates observed at the end of our period of analysis (i.e., TUR^{2015} ~20% for hybrid-fibre and TUR^{2015} ~25% for FTTH/B, according to Figure 2). In order to also establish a break-even scenario, we calculate the required take-up rates (TUR^{r}) at the lower and upper bounds of OLS and 2SLS coefficient estimates ($\overline{\beta};\underline{\beta}$), which equalize the total deployment costs as reported in external cost studies (column 2 in Table 4). Our assessment of average benefits is further based on the grand mean of GDP (GDP_{gm})

[13]Estimates are robust towards the omission of individual control variables; results are available upon request from the authors.

Table 4: Benefits and costs of broadband adoption and coverage (EU 27 averages)

Estimated benefits (EUR, billions)	*Estimated costs (EUR, billions)*	*Source*
(i) Hybrid-fibre broadband DAE coverage target: 30 Mbit/s with 100% coverage with FTTH/B/C/FTTLA in 2020		
Total benefits: 29.062 ($\overline{\beta}^{Hybrid}$: 0.003; TUR^{2015}: 20%) TUR^{r}: $\underline{\beta}^{Hybrid}$: ~57% ($\overline{\beta}^{Hybrid}$: ~38%)	Total coverage cost: 55 Period: 2011–2020 %ΔGap[1] to target (100%) in 2011: 104.08%	EIB (2011)
Total benefits: 29.062 ($\overline{\beta}^{Hybrid}$: 0.003; TUR^{2015}: 20%) TUR^{r}: $\underline{\beta}^{Hybrid}$: ~64% ($\overline{\beta}^{Hybrid}$: ~43%)	Total coverage cost: 31–62 Period: 2011–2020 %ΔGap to target (100%) in 2011: 104.08%	Analysys Mason (2013)
(ii) End-to-end fibre-based broadband DAE adoption target: 100 Mbit/s with 50% adoption with FTTH/B in 2020		
Total benefits: **221.501**[2] ($\overline{\beta}^{FTTH/B}$: 0.005; TUR^{2015}: 25%) TUR^{r}:$\underline{\beta}^{FTTH/B}$:~39% ($\overline{\beta}^{FTTH/B}$: ~24%)	Total coverage cost: 209 Period: 2011–2020 %ΔGap to target (50%) in 2011: 380.77%	EIB (2011)
Total benefits: 201.525 ($\overline{\beta}^{FTTH/B}$: 0.005; TUR^{2015}: 25%) TUR^{r}:$\underline{\beta}^{FTTH/B}$: ~41% ($\overline{\beta}^{FTTH/B}$: ~23%)	Total coverage cost: 202 Period: 2012–2020 %ΔGap to target (50%) in 2012: 354.55%	FTTH Council Europe (2012)
Total benefits: 201.525 ($\overline{\beta}^{FTTH/B}$: 0.005; TUR^{2015}: 25%) TUR^{r}:$\underline{\beta}^{FTTH/B}$:~54% ($\overline{\beta}^{FTTH/B}$: ~40%)	Total coverage cost: 154–327 Period: 2011–2020 %ΔGap to target (50%) in 2012: 354.55%	Analysys Mason (2013)
Total benefits: **281.83** (Gruber et al. estimates based on adoption and availability)	Total coverage cost: 213.6	Gruber *et al.* (2014)
(iii) End-to-end fibre-based broadband gigabit society coverage target:100 Mbit/s with 100% coverage with FTTH/B in 2025		
Total benefits: 252.9 ($\overline{\beta}^{FTTH/B}$: 0.005; TUR^{2015}: 25%) TUR^{r}:$\underline{\beta}^{FTTH/B}$:~60% ($\overline{\beta}^{FTTH/B}$: ~36%)	Total coverage cost: 360 Period: 2014–2025 %ΔGap to target (100%) in 2014: 434.76%	BCG (2016)

Notes: 1 Data on gaps (in %) are based on the EC's Digital Agenda Scoreboard reports (available at: https://ec.europa.eu/digital-single-market/en/download-scoreboard-reports). 2 Bold numbers indicate that estimated benefits exceed estimated costs. BCG, Boston Consulting Group; DAE, Digital Agenda for Europe; EIB, European Investment Bank.

which is equal to 612,346.5 million US$ at constant 2011 national prices (Tables 1 and 2) and corresponds to an amount of about €465,376.72 million on the basis of average 2011 exchange rates. Finally, we assume that adoption grows at a linear rate with coverage over the projected deployment period foreseen in the external cost studies until the targeted coverage level is reached.[14] Given these assumptions, estimates of average benefits per

[14]We acknowledge that our assumptions are in parts simplistic; in particular, adoption and coverage in technology migration typically follow non-linear diffusion patterns (see Jiang and Jain, 2012).

year and per country in (billion EUR) are calculated as follows:

$$\text{Average benefits} := \%\Delta Gap^{*}\, TUR^{2015*}\, \overline{\beta}^{*}\, GDPgm \tag{3}$$

where $\%\ \Delta Gap$ is the gap between broadband coverage at the beginning of the deployment period and the target year in percentage terms.

Next, we contrasted our estimates of average benefits (reported in column 1) with the most comprehensive industry cost studies on various broadband deployment scenarios available (column 2). Column 2 also reports the gap in percentage terms, $\%\Delta Gap$, to the respective target underlying each cost study. Column 3 reports the source of the external cost studies. Although the selected cost studies make different assumptions, which in parts deviate considerably from each other, they have similar dates of origin (2011–) in each of the three target subheadings in Table 4 and therefore use comparable forecasting periods. Gruber *et al*. (2014) – reviewed in Section 2 – is the only study that also provides a cost-benefit analysis with respect to the DAE targets. We include the authors' estimates for their deployment scenario – which relates infrastructure costs to FTTH technology – in target (ii).

From our cost-benefit analysis, the following results emerge.

First, at 2015 take-up rates ($TUR^{2015} = 20\%$) benefits related to hybrid-fibre broadband services do not appear to cover estimated costs to close the coverage gaps as of 2011 in target (i). This follows from our estimates based on the upper bound of coefficient estimates and two external cost studies referring to a deployment period from 2011 to 2020. At the beginning of this period, the gap to the desired DAE coverage target (i) requiring 100 per cent with at least 30 Mbit/s was about 104.08 per cent. According to Equation 3, an increase in coverage by this amount would yield an increase in adoption of about 20.82 per cent, assuming a 20 per cent take-up rate. Multiplying this increase in hybrid-fibre broadband adoption with our upper bound coefficient estimate $\left(\overline{\beta}^{Hybrid} = 0.003\right)$ and the grand mean of GDP (€465,376.72 million) yields an estimated EU average benefit of about 29.06 billion EUR, which is apparently below the respective cost estimates of both cost studies conducted by the European Investment Bank (2011) and Analysys Mason (2013). Estimated break-even TUR^{R}s appear to be quite high for the lower (about 57% and 64%) and upper (about 38% and 43%) bounds of coefficient estimates, in view of 2015 take-up rates (about 20%).

Second, 50 per cent adoption targets for end-to-end fibre-based broadband (DAE target ii) comes hand in hand with estimated economic benefits that clearly (estimates in bold) or almost outweigh the estimated deployment costs as reported in four different cost studies, including the only external cost-benefit analysis by Gruber *et al*. (2014). Also, required take-up rates are much lower for end-to-end fibre-based broadband. In contrast, average benefits are apparently fairly low compared with the much higher deployment costs associated with the 100 per cent coverage goal of the gigabit society objectives (target iii).

To summarize, it appears that only the end-to-end fibre-based DAE adoption target (ii) requiring a moderate coverage of (at least) 50 per cent can be justified economically in view of the total deployment costs. In the case of universal (100%) coverage with hybrid-fibre (target i) and end-to-end fibre-based broadband (target iii) the estimated benefits are lower than all cost estimates in our best-case scenario and would require rather high take-up rates; again, at least for the time being such high take-up rates appear to be unrealistic, especially for hybrid-fibre broadband adoption. As a result, a combination of basic and end-to-end fibre-based or a combination of all three types of broadband access technologies would appear to bring the largest economic net benefits.

From our cost-benefit analysis, the following shortcomings emerge:

Whereas our cost-benefit analysis was based on a best-case scenario for fibre deployment and may thus overestimate the true effects of fibre coverage and adoption, we acknowledge that future impacts of fibre-based broadband adoption based on more innovative applications and services may be substantially higher than our estimates based on an average of our overall period of analysis (2003–2015). Moreover, we have to acknowledge the imperfect nature of GDP as a measure of the economic benefits of broadband, as not all value created by broadband deployment is captured in standard measures of GDP. The distinction between process and product innovations is important here. Process innovations make current products cheaper to produce, in so far as spillovers in other sectors of the economy are captured for producer surplus (profits are a part of GDP) but not for consumer surplus. This underestimates the benefits of broadband. If more broadband leads to more product innovations in other sectors of the economy, but with a time lag, we would also be underestimating the overall benefits of broadband, since we capture only contemporaneous benefits.

Overall, we acknowledge that our analysis underestimates the true benefits of fibre-based broadband adoption. Examining the costs and benefits of fibre-based broadband deployment more closely and subjecting this set of assumptions to sensitivity analysis is a possible direction for future research.

V. Summary and Policy Implications

The literature on the effects of broadband infrastructure investments on broader macroeconomic growth found broadly positive effects. The explanations for these positive effects range from the direct effects of deployment to indirect effects due to positive externalities on the macroeconomic level that are related to the adoption of new broadband services. This body of literature has been severely constrained so far because it mainly analysed basic broadband deployment but not newer generations of hybrid and end-to-end fibre-based broadband. This is extremely important, however, since expectations regarding the benefits of these new generations of modern broadband technologies are rather high, as recently expressed by the EC (EC, 2016a, 2016b). This article fills this gap and provides EU-level evidence on the incremental economic benefits of fibre-based broadband services and guidance on related polices. In particular, public broadband targets as stipulated by the EC's gigabit strategy run the risk of distorting market outcomes by picking winners, that is, explicitly favouring certain broadband access technologies. Deviating from the principle of technological neutrality can be justified only in light of sound empirical evidence on the differing welfare effects of different broadband access technologies.

Utilizing a comprehensive panel dataset of EU 27 member states for the period from 2003 to 2015 and controlling for possible endogeneity of broadband adoption, we estimate a small but significant effect of fibre-based broadband over and above the effects of basic broadband on the GDP of the included countries. Our cost-benefit analysis implies that policy intervention would be justified only for moderate coverage levels of around 50 per cent of fibre-based broadband, whereas for 100 per cent coverage levels foreseen in the EC's gigabit society and DAE targets we find net losses to society. Thus, it appears that – for the time being – a combination of basic broadband, hybrid and end-to-end fibre-based broadband brings the largest economic net benefits to society.

One explanation for this could be that there is a great amount of heterogeneity in consumer and business needs as well as deployment costs, and a combination of available technologies caters best to this heterogeneity. This reinforces the long-established principle of technological neutrality according to which none of the feasible network scenarios should be favoured a priori, and winning technologies should instead be identified by the markets. Also, we could not find clear evidence that the adoption of end-to-end fibre-based broadband provides substantially higher benefits than hybrid-fibre broadband. Therefore, rather than choosing a specific technology in stipulated public broadband policy targets, markets provide more efficient investment decisions in a world where there is considerable uncertainty over the future demand for high bandwidth and rapid technological progress. As regards the latter, it is safe to assume that existing and future second-life copper (VDSL/XG.fast) and coaxial (DOCSIS 3.1) technologies will have a crucial role to play in an efficient migration process to next-generation networks, in particular due to their comparative cost advantages. Among other factors, efficient migration will depend on country-specific characteristics such as the availability and quality of ducts or the number of street cabinets. In the near future, another fundamental technological shift can be expected with the advent of 5G networks. As 5G is, at its core, a fibre-based technology that enables ubiquitous mobility as well as high performance and ultra-reliable data transmission, complementarities in the roll-out and use of fibre between fixed and mobile access technologies will become increasingly important. Technological uncertainty arises in terms of the optimal market integration of wireline fibre and wireless 5G access infrastructures as regards the provision of wireless broadband access and connecting base stations with optical fibre lines to core networks. Eventually, hybrid-fibre access networks using XG.fast transmission technology could become a cost-efficient fibre backhaul for 5G networks (Briglauer *et al.,* 2018). These infrastructure deployments are inherently complex as they are complementary but conducted at different times, with 5G deployment lagging, presumably, many years behind. It is currently unclear which access architecture is best suited in terms of fixed-mobile integration in local access networks and in view of substantial asymmetric information towards deployment costs.

From a welfare perspective our estimation results, in combination with technological market uncertainties, call into question 100 per cent ubiquitous and technology non-neutral coverage targets. We acknowledge, however, that in the near future disruptive product innovations (killer apps) based on wireline or wireless access infrastructures may still be developed that make fibre-based networks more valuable to society than can be found in the historical data.

Correspondence: Wolfgang Briglauer, ZEW Centre for European Economic Research, P.O. Box 10 34 43, D-68034 Mannheim, Germany.
email: wolfgang.briglauer@zew.de

A: Appendix

Table A.1: OLS estimation results for production function model (Equation 2)

Dep. var.: ln (GDP) *Incl. broadband var.:*	*(1)* *Basic*	*(2)* *Basic, FTTH/B*	*(3)* *Basic, hybrid*	*(4)* *FTTH/B*	*(5)* *Hybrid*
Broadband adoption					
$ln\ (BB^{Basic})$	0.015* (2.29)	0.014* (2.25)	0.014* (2.31)		
$ln\ (BB^{FTTH/B})$		0.002 (1.65)		0.003* (1.85)	
$ln\ (BB^{Hybrid})$			0.002* (2.25)		0.003** (2.43)
Non-broadband inputs					
ln (work_hours)	0.313*** (4.23)	0.322*** (5.01)	0.308*** (4.36)	0.288*** (4.35)	0.272*** (3.62)
ln (capital_stock)	0.574*** (12.09)	0.566*** (4.02)	0.564*** (3.98)	0.408*** (2.57)	0.410*** (2.61)
Macroeconomic controls					
eco_freedom	0.005*** (5.19)	0.004*** (4.16)	0.004*** (3.85)	0.005*** (4.44)	0.005*** (4.30)
nri	0.051** (3.04)	0.052** (2.65)	0.052** (2.77)	0.051*** (3.42)	0.051*** (3.69)
Interest rate	−0.010*** (−4.72)	−0.010*** (−4.71)	−0.010*** (−4.62)	−0.009*** (−5.14)	−0.009*** (−5.07)
Country dummies	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes
Constant	0.984 (1.11)	1.040 (1.15)	1.189 (1.30)	3.579*** (3.28)	3.684*** (3.49)
F	2182.520	7179.979	10394.302	4787.554	976.616
F (all FE = 0)	216.24	218.78	220.54	182.25	220.54
R^2 (within)	0.814	0.816	0.817	0.810	0.810
Observations (*N*)	337	332	332	344	344

Notes: Year effects are jointly significant and therefore included in all regressions as well as EU member state fixed effects. Coefficient estimates in regr. (1)–(5) are based on standard errors which allow for arbitrary forms of heteroscedasticity, cross-sectional correlation between panels and maximum number of three lags in the autocorrelation structure. *t* statistics in parentheses. OLS, ordinary least squares; Dep. var, Dependent variable; * $P < 0.10$, ** $P < 0.05$, *** $P < 0.01$.

References

Abrardi, L. and Cambini, C. (2019) 'Ultra-fast broadband investment and adoption: A survey'. *Telecommunications Policy*, forthcoming.

Analysys Mason (2013). 'The Socio-economic Impact of Bandwidth'. Study jointly carried out with tech4i2 for the European Commission.

Bacache, M., Bourreau, M. and Gaudin, G. (2014) 'Dynamic Entry and Investment in New Infrastructures: Empirical Evidence from the Fixed Broadband Industry'. *Review of Industrial Organization*, Vol. 44, No. 2, pp. 179–209.

Bai, Y. (2017) 'The Faster, the Better? The Impact of Internet Speed on Employment'. *Information Economics and Policy*, Vol. 40, pp. 21–5.

BCG – Boston Consulting Group (2016). 'Building the Gigabit Society: An Inclusive Path Toward Its Realization'. Study carried out for ETNO.

Bertschek, I., Briglauer, W., Hüschelrath, K., Kauf, B. and Niebel, T. (2016) 'The Economic Impacts of Telecommunications Networks and Broadband Internet: A Survey'. *Review of Network Economics*, Vol. 14, pp. 201–27.

Bouckaert, J., Van Dijk, T. and Verboven, F. (2010) 'Access Regulation, Competition, and Broadband Penetration: An International Study'. *Telecommunications Policy*, Vol. 34, No. 11, pp. 661–71.

Briglauer, W. (2015) 'How EU Sector-specific Regulations and Competition Affect Migration from Old to New Communications Infrastructure: Recent Evidence from EU27 Member States'. *Journal of Regulatory Economics*, Vol. 48, No. 2, pp. 194–217.

Briglauer, W. and Cambini, C. (2019), Does regulation of basic broadband networks affect the adoption of new fiber-based broadband services? *Industrial and Corporate Change*, Vol. 28, No. 2, pp. 219–40.

Briglauer, W. Stocker, V., and Whalley, J. (2018). 'Public Policy Targets in EU Broadband Markets: The Role of Technological Neutrality'. Mimeo. 29th European Regional ITS Conference, Trento 2018. 184936, International Telecommunications Society.

Cardona, M., Kretschmer, T. and Strobel, T. (2013) 'ICT and Productivity: Conclusions from the Empirical Literature'. *Information Economics and Policy*, Vol. 25, No. 3, pp. 109–25.

Czernich, N., Falck, O., Kretschmer, T. and Woessmann, L. (2011) 'Broadband Infrastructure and Economic Growth'. *Economic Journal*, Vol. 121, No. 552, pp. 505–32.

European Commission (EC) (2009). 'Directive 2002/21/EC on a Common Regulatory Framework for Electronic Communications Networks and Services (Framework Directive) as amended by Directive 2009/140/EC and Regulation 544/2009'. Brussels.

EC (2010). 'A Digital Agenda for Europe'. Brussels. Available online at https://www.kowi.de/Portaldata/2/Resources/fp/2010-com-digital-agenda.pdf.

EC (2016a). 'Proposal for a Directive of the European Parliament and of the Council Establishing the European Electronic Communications Code (Recast)'. COM/2016/0590 final 2016/0288 (COD). Brussels.

EC (2016b). 'Connectivity for a Competitive Digital Single Market – Towards a European Gigabit Society'. COM(2016)587 final. Brussels.

EC (2017). 'Broadband Coverage in Europe 2016'. Brussels. Available online at https://ec.europa.eu/digital-single-market/en/news/study-broadband-coverage-europe-2016.

European Investment Bank (2011) 'The Economic Impact of Fixed and Mobile High-speed networks'. *EIB papers*, Vol. 16, No. 2, pp. 30–60.

FTTH Council Europe (2012). 'Creating a Brighter Future: The Cost of Meeting Europe's Network Needs'. Ventura Partners. Available online at http://www.ftthcouncil.eu/documents/Reports/2012/Cost_Model_Report_Full_Version.pdf.

Grajek, M. and Röller, L.H. (2012) 'Regulation and Investment in Network Industries: Evidence from European Telecoms'. *Journal of Law and Economics*, Vol. 55, No. 1, pp. 189–216.

Gruber, H., Hätönen, J. and Koutroumpis, P. (2014) 'Broadband Access in the EU: An Assessment of Future Economic Benefits'. *Telecommunications Policy*, Vol. 38, No. 11, pp. 1046–58.

Hasbi, M. (2017). 'Impact of Very High-Speed Broadband on Local Economic Growth: Empirical Evidence'. Working paper. Paris: Télécom ParisTech.

Jiang, Z. and Jain, D.C. (2012) 'A Generalised Norton-Bass Model for Multigeneration Diffusion'. *Management Science*, Vol. 58, No. 10, pp. 1887–97.

Knieps, G. and Zenhäusern, P. (2015) 'Broadband Network Evolution and Path Dependency'. *Competition and Regulation in Network Industries*, Vol. 16, No. 4, pp. 335–53.

Koutroumpis, P. (2009) 'The Economic Impact of Broadband on Growth: A Simultaneous Approach'. *Telecommunications Policy*, Vol. 33, No. 9, pp. 471–85.

Röller, L.H. and Waverman, L. (2001) 'Telecommunications Infrastructure and Economic Development: A Simultaneous Approach'. *American Economic Review*, Vol. 91, No. 4, pp. 909–23.

Sosa, D. (2015). Early Evidence Suggests Gigabit Broadband Drives GDP. Analysis Group. Available online at http://www.analysisgroup.com/uploadedfiles/content/insights/publishing/gigabit_broadband_sosa.pdf.

Stocker, V. and Whalley, J. (2018) 'Speed Isn't Everything: A Multi-criteria Analysis of the Broadband Consumer Experience in the UK'. *Telecommunications Policy*, Vol. 42, No. 1, pp. 1–14.

WIK/Ecorys/VVA (2016). 'Support for the Preparation of the Impact Assessment Accompanying the Review of the Regulatory Framework for e-communications (SMART 2015/005)'. Study prepared for the European Commission DG Communications Networks, Content & Technology, Brussels.