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A Retrospective Study on the Regional Benefits and Spillover Effects of High-Speed Broadband Networks: Evidence from German Counties

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Abstract

There is still hardly any empirical evidence on how divergent broadband technologies, and, by extension, bandwidth levels, influence GDP growth, or on the extent of spatial externalities at a regional level. Our study aims to assess the economic benefits of high-speed broadband networks within and across neighbouring counties in Germany. Utilizing a balanced panel dataset of 401 German counties with data from 2010-2015 as well as different panel estimation techniques, we find that the availability of high-speed broadband (which enables transfer rates of 50 Mbit/sec and higher) has a small but significant positive effect on regional GDP growth in the average German county, when compared to normal broadband availability. Furthermore, we find that broadband deployment in German counties induces substantial economic benefits in terms of direct effects and regional externalities. According to our main estimation results, an increase in bandwidth coverage of 50 Mbit/sec and higher by one percentage point induces a rise in regional GDP of 0.05%. This effect is almost doubled if we also take regional externalities into account and is of particular relevance for urban counties. Furthermore, our cost-benefit analysis suggests substantial efficiency gains, as the total economic benefits of subsidy programs to encourage broadband expansion substantially exceeded their associated costs.

1 Introduction

The economic benefits of broadband networks for consumers have been increasingly emphasized by economic research. Proponents of comprehensive broadband availability underscore its character as a general purpose technology (GPT) that induces positive externalities in major economic sectors (Bresnahan and Trajtenberg, 1995). Indeed, numerous studies have provided evidence for the positive impact of “basic” (i.e. copper- or coaxial cable-based) broadband networks on employment, productivity and economic growth (Bertschek et al., 2016). Similarly, the wide-scale roll-out of new fiber-optic based, high-speed broadband networks is believed to spur job creation in information and communications technology (ICT) and other related industries, and, more generally, is ascribed enormous potential for facilitating productivity increases and economic growth.

Accordingly, in 2010 the European Commission (EC) launched the Digital Agenda for Europe (DAE), which “seeks to ensure that, by 2020, (i) all Europeans will have access to much higher internet speeds of above 30 Mbit/s[ec] and (ii) 50% or more of European households will subscribe to internet connections above 100 Mbit/s[ec]” (European Commission 2010, p. 19). While the first target is a goal for the supply side, the second refers to a minimum level of household adoption on the demand side. Achieving these goals promises economic returns, but they also entail substantial deployment costs. While reliable estimations of costs related to broadband deployment based on various network architectures do exist (e.g. BCG, 2016; FTTH Council Europe, 2012), there is hardly any sound empirical evidence on whether positive externalities beyond those associated with basic broadband networks will emerge under the new fiber-based broadband infrastructure.

In order to achieve the DAE’s goals, ambitious targets have been implemented in most EU member states. In Germany, for instance, the DAE informs the government’s goal of providing at least 50 Mbit/sec to all households by 2018 in its "Digital Agenda 2014-2017" strategy, which was adopted in August 2014.[1] Note that high-speed broadband infrastructure enabling ≥ 50 Mbit/sec must be at least in part fiber-cable based in the access network, or, with a view to wireless broadband, must be based on fourth generation (4G) mobile technology (Long Term Evolution, LTE) which was introduced in Europe in 2010.

Our study employs a unique balanced panel data set from 2010 to 2015 for all 401 German counties.[2] Using various panel estimation techniques we investigate the following five research questions: (i) What is the impact of high-speed broadband coverage on economic growth? (ii) Is there a differential impact with regard to various quality levels of broadband coverage, when one distinguishes between "basic" broadband (≥ 6 Mbit/sec and ≥ 16 Mbit/sec) and "high-speed" (≥ 50 Mbit/sec) broadband? (iii) Are there positive or negative[3] externalities among neighbouring counties at a regional level? (iv) Is there a difference in effect in urban vs. rural counties (reflecting the so-called phenomenon of "digital divide")? (v) Are the total benefits sufficient to cover public expenditures for the funding of high-speed broadband infrastructure?

Understandably, the economic outcomes associated with the adoption of a given policy is of crucial concern. This is particularly true of public broadband funding, which in Germany primarily aims to extend coverage to areas of the country where commercial providers do not see sufficient profitability, primarily due to low population density. In order to reach the ubiquitious coverage target, Germany's federal and state governments have provided substantial funding to encourage broadband installation in areas in which providers deem

[1] Detailed information on the "Digital Agenda 2014-2017" is available at: https://ec.europa.eu/digital-agenda/en/news/digitale-agenda-2014-2017 (last accessed on 1 February 2019).

[2] A county ("Kreis"; "kreisfreie Stadt") is the second administrative unit in Germany after a municipality (Gemeinde) and followed by a state (Bundesland).

[3] Negative effects may arise from competitive effects ("beggar-thy-neighbour policies").

investment unprofitable. However, there is hardly any empirical ex post assessment on the actual economic benefits of such programs.[4] Our study aims to assess the economic benefits of high-speed broadband networks within and across neighbouring counties in Germany. We find that broadband deployment in German counties induces substantial economic benefits in terms of direct effects and regional externalities. According to our main estimation results, an increase in bandwidth coverage of 50 Mbit/sec and higher by one percentage point increases regional GDP by about 0.05%. This effect is almost doubled if we also take regional externalities into account and is particularly pronounced in urban counties. Furthermore, we find that the total benefits substantially exceed the costs of public funding programs; we do not find, however, evidence that higher-broadband quality levels lead to increasing returns for the average German county.

The remainder of this article is organized as follows. The second section presents a brief review of the existing empirical literature on the economic impact of broadband networks. The third section provides a simple regression model framework and a characterization of our panel data set. The forth section presents our identification strategy, while section five discusses our main estimation results. Drawing on our estimation results, section six compares the estimated benefits and costs of implementing the “Digital Agenda 2014-2017” in Germany. The final section concludes the paper with a review our main findings. It also summarizes the key insights generated by our research for policy makers.

[4] A recent exception is Briglauer et al. (2019) who assess the impact of public subsidies for basic broadband granted in the German State of Bavaria on local labour market effects.

2 Literature review

Bertschek et al. (2016) review more than 60 studies that investigate the causal effects of broadband coverage and adoption on key economic indicators such as economic growth, employment and productivity. In view of this large amount of prior research on the impact of basic broadband, we limit our review to studies that examine the GDP impacts of broadband access. Although we focus on the impact of broadband coverage on the supply side, we also review adoption-related studies, since both broadband measures are highly informative. Whereas (output-oriented) adoption on the demand side is more informative from a welfare perspective, (input-oriented) coverage studies are more informative from a policy perspective.

Czernich et al. (2011) examine data on 25 OECD countries from 1996 to 2007 and find that basic broadband access[5] contributed between 2.7 to 3.9 percent to GDP per capita. Furthermore, they find that an additional 10 percentage point increase in the rate of broadband adoption led to a 0.9 to 1.5 percentage point increase in annual growth of GDP per capita. The general finding of a positive and statistically significant effect of broadband coverage (or adoption) on GDP growth is shared by the large majority of country-level studies. Koutroumpis (2009), for example, provides an assessment of broadband adoption in OECD countries for 2002-2007 and Gruber et al. (2014) estimate the impact of broadband adoption on GDP in 27 EU countries for 2005 to 2011. For the US, Greenstein and McDevitt (2011) employ disaggregated household level data from 1999-2006 and find positive and statistically significant relationships between basic broadband availability and economic growth.

Only very few empirical studies explicitly include fiber-based broadband availability, a topic that was recently surveyed by Abrardi and Cambini (2019). We therefore review all available

[5] Czernich et al. (2011) use a rather old definition of broadband with bandwidth levels of at least 256 kbit/sec enabling very basic internet access and functionality.

studies even though they relate to different outcome variables. Briglauer and Gugler (2019) employ a comprehensive panel dataset of EU27 member states for the period 2003-2015. The authors find that fiber-based broadband has a small but significantly higher GDP effect than basic broadband. Their estimates suggest that a 1% increase in the adoption of fiber-based broadband leads to a GDP increase 0.002-0.005% higher than basic broadband. Bai (2017) is another recent study that examines the impact of different broadband speed levels using US county level data from 2011-2014. The author assesses the differential impact on employment and finds, similar to Briglauer and Gugler (2019), a positive impact of broadband coverage, but that, compared to basic broadband, fiber-based broadband did not generate substantially greater positive effects on employment. Hasbi (2017) estimates the impact of high-speed broadband on local economic growth utilizing data on more than 36,000 French municipalities for the period 2010-2014. The author finds a positive impact on the number of companies of all non-primary sectors, on company creation and, finally, in terms of unemployment reduction. Fabling and Grimes (2016) estimate the productivity gains from high-speed broadband adoption on employment using firm-level fiber data for New Zealand for the years 2010 and 2012. The authors find no significant effect of fiber-based broadband on employment on average, but only for firms making complementary investment in organizational capital.

To summarize, most of the studies analyze the impact of basic broadband on the macroeconomic level. Yet very few draw on data related to broadband connection type in order to assess the economic impact of high-speed broadband availabililty. Second, micro-based evidence on the impact of fiber-optic availability is largely missing, and existing studies focus on outcome variables other than economic growth. There is no empirical evidence as regards the differential impact of relevant broadband technologies and bandwidth levels on GDP or on the extent of externalities at a regional level. While spatial externalities among countries can be ignored in aggregated country-level studies (Moreno-Serrano et al., 2005), spatial externalities appear to be of much stronger relevance within countries at a disaggregated level. The aim of this paper is to fill these research gaps, particularly in light of the ubiquitious household coverage goal that is foreseen at the EU level and that has been adopted in the "Digital Agenda 2014-2017" strategy of the German government.

3 Model framework and data

In the following, we first outline our empirical baseline specification in Section 3.1 before describing our data set in Section 3.2.

3.1 An augmented production function

Following the specifications in Koutroumpis (2009) and Czernich et al. (2011), economic output (*Q*) is related to input factors, i.e., capital (*K*) and labour (*L*). The starting point of the analysis is a regional production function that allows for different levels of technology (*A*) in county i ($i = 1, \ldots, N$) in period t ($t = 1, \ldots, T$) and reads as follows:

$$Q_{it} = A_{it} F(K_{it}; L_{it}) \qquad \text{Equation (1)}$$

where A_{it} represents total factor productivity as a function of capital and labour and is considered here as part of the growth that cannot be attributed to changes in observable production inputs but to a number of factors affecting overall efficiency. In Equation (1) it is assumed that the production function has the same functional form in each county and is separable in A_{it}. As another starting point, most empirical estimations assume a Cobb-Douglas type production function (Cardona et al., 2013) where all input factors are weighted by their (constant but otherwise unconstrained)[6] output elasticities. Rewriting Equation (1) thus yields:

$$Q_{it} = A_{it} K_{it}^{\beta_1} L_{it}^{\beta_2} \qquad \text{Equation (2)}$$

[6] In particular, we do not impose any assumptions on returns to scale.

where β_1 and β_2 represent the output elasticities of capital and labour, respectively. Following Czernich et al. (2011) we further assume that the technological state evolves according to an exponential growth pattern:

$$A_{it} = A_0 e^{\lambda_i t} \qquad \text{Equation (3)}$$

where λ_i is the growth parameter of technological progress in county i and t is a yearly trend variable and hence $\lambda_i t$ represents the compound growth rate. The adoption of broadband, and more generally of ICT, creates a range of technological complementarities (e.g. software products), many varied uses (different broadband services and mobile apps), wide-ranging applicability across many sectors (broadband as a crucial input factor in most industries) and much scope for technological improvement (e.g. various xDSL and fiber technology upgrades) and thus exhibits all essential features of a GPT (Bresnahan and Trajtenberg, 1995). The notion of broadband infrastructure as a key GPT in the ICT sector suggests that it will also impact the growth parameter λ by continuously spurring innovation and increased productivity. According to this view, broadband's impact on growth and productivity goes beyond pure capital deepening and input substitution effects due to falling broadband prices and/or increased quality of broadband products. Based on the GPT hypothesis, we assume that broadband availability directly impacts total factor productivity via externality growth effects and can be characterized by the following functional relationship (Czernich et al., 2011):

$$\lambda_i t = \alpha + \beta_3^q B_{it}^q \qquad \text{Equation (4)}$$

where the supraindex q represents broadband quality in terms of a specific bandwidth level and B_{it} is broadband coverage in county i in year t. Taking logs, and substituting for $\lambda_i t$ this results in a modified Equation (2) which reads as follows (where $lnA_0 + \alpha = \beta_0$):

$$logQ_{it} = \beta_0 + \beta_1 logK_{it} + \beta_2 logL_{it} + \beta_3^q B_{it}^q \qquad \text{Equation (5)}$$

To Equation (5) we add a variable, human capital, *EDUC*, to measure separately the impact of human capital stock. Furthermore, in order to examine the existence of externalities among neighbouring counties, we consider a spatial dependence using a weight matrix that defines the proximity of neighbouring counties to a focal county *i*, denoted with $\boldsymbol{W}$ (Anselin and Florax, 1995). The resulting spatial lag spillover variable is a weighted sum of broadband availability in neighbouring counties $j \neq i$ and denoted with $\boldsymbol{W}B_{jt}^{NB,q}$ where *NB* refers to a set of nearest neighbouring counties for a certain bandwidth level q (further described in section 3.2.2). It has been increasingly recognized in the literature (Cabrer-Borrás and Serrano-Domingo, 2007; Seck, 2012) that spillovers from external sources may have an impact on innovation and economic growth. In this context, we analyse broadband deployment in German counties where the effects of broadband can unfold both within and between counties. On the one hand, broadband availability in neighbouring counties might induce positive externalities ("spill-over effects") due to various impacts, e.g. employment effects in neighbouring counties, which might also create economic growth in the first county due to increased income. Another branch of the literature highlights the role of public knowledge spillovers (Audretsch and Feldman, 1996), which might affect the adoption of innovative broadband services by households and firms while also stimulating regional interactions. On the other hand, additional broadband availability might make neighbouring counties comparatively more competitive, leading to migration and an erosion of value added and employment in the focal county ("beggar-thy-neighbour"). Our baseline estimating equation further includes a variable measuring the number of years since broadband introduction in a certain county, *years since*, to capture different points in time in the deployment processes among counties (Gruber and Verboven, 2001; Czernich et al., 2011). It reads as follows:

$$\begin{aligned} logGDP_{it} = \beta_0 + \beta_1 logK_{it} + \beta_2 logL_{it} + \beta_3^q B_{it}^q + \\ \beta_4 logEDUC_{it} + \boldsymbol{\beta_5^q W} B_{jt}^{NB,q} + \beta_6 years\_since_{it} + \epsilon_{it} \end{aligned} \quad \text{Equation (6)}$$

where the additive error term, ε_{it}, is capturing random variations between counties and time.

3.2 Data

Our empirical analysis makes use of several separate data sets which we merge: First, the German Broadband Atlas[7] provides data on broadband coverage with measures for various bandwidth levels of broadband coverage for both wireline and wireless (4G/LTE) access technologies. Second, the GENESIS database from the German statistical office[8] and the INKAR[9] database provide most of our capital and labour controls as well as data on our outcome variable. Overall, our balanced panel data set comprises all 401 German counties for the years 2010 to 2015, resulting in a total of 2,406 observations.

All variable definitions and sources are provided in Table A.1 and summary statistics of all variables are provided in Table A.2 in the Appendix. Below, we describe our dependent variable (Section 3.2.1) and main explanatory variables (Section 3.2.2) in more detail. Section 3.2.3 then describes the variables used to proxy labour and capital stocks.

3.2.1 Dependent variable: Economic growth in German counties

Figure 1 shows the average annual growth in GDP per capita, denoted with *GDP_pc*, normalized to the working age population and at market prices. Overall, we observe rather steep increases from 2010 to 2011 and from 2014 to 2015, the last year of our observation period. Annual growth is more moderate in the interim years. In the average German county, GPD per

7 See https://www.bmvi.de/DE/Themen/Digitales/Breitbandausbau/Breitbandatlas-Karte/start.html (last accessed on 1 February 2019).

8 See https://www.statistikdaten.bayern.de/genesis/online (last accessed on 1 February 2019).

9 See http://www.inkar.de/ (last accessed on 1 February 2019).

capita was about €65,599 in 2015. When comparing urban and rural counties we find similar growth patterns but with rural counties at a persistently lower level.

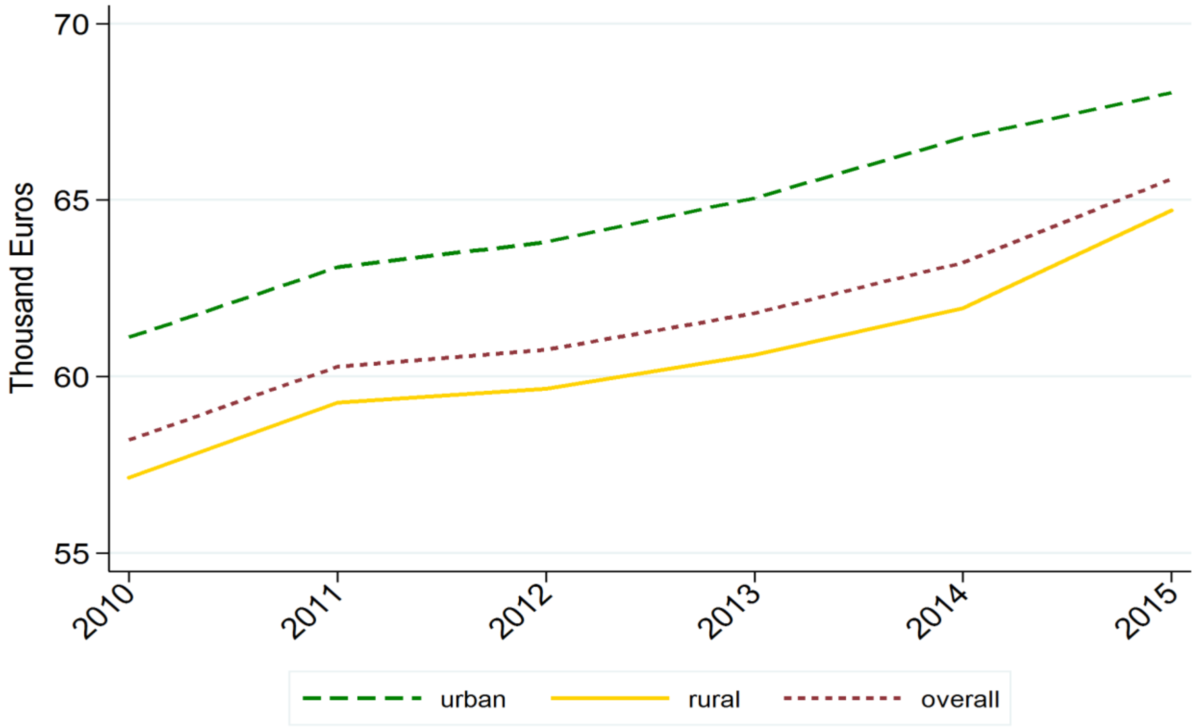

Figure 1: Average GDP per capita (in thousands of euros) in German counties

3.2.2 Explanatory variables: Broadband infrastructure stocks

Broadband availability is measured as the percentage of households in a county that have access to a particular bandwidth level. In particular, we measure broadband availability with several different but overlapping ranges of download speed (≥ 6, ≥ 16 and ≥ 50 Mbit/sec) from 2010 to 2015. The gap between 16 and 50 Mbit/sec is substantially different in terms of technological infrastructure requirements and feasible applications for consumers. Following our research questions, we consider bandwidth levels of ≥ 50 Mbit/sec as high-speed internet, which requires at least partial use of fiber optic cable.[10]

[10] This fulfils the ubiquitious household coverage target as foreseen in the DAE (≥ 30 Mbit/sec) and also the more ambitious coverage target of the German government (≥ 50 Mbit/sec) in its "Digital Agenda 2014-2017" strategy.

Figure 2 reports the national average German household coverage for different bandwidth levels based on all relevant wireline and wireless access technologies.[11] Figure 2 shows that there are substantial differences between high-speed broadband (≥ 50 Mbit/sec), denoted with *broadband* $^{50\ Mbit/sec}$, and basic broadband (≥ 6, ≥ 16 Mbit/sec), denoted with *broadband* $^{6Mbit/sec}$ and *broadband* $^{16\ \mathrm{Mbit/sec}}$. Different levels between high-speed and basic broadband reflect different deployment costs borne by operators and divergent willingness to pay for broadband services on the part of consumers. Furthermore, Figure 2 shows that there has been an almost ubiquitous coverage with elementary broadband internet access (≥ 2 Mbit/sec) due to so-called "universal service obligations" (European Commission, 2002). The latter have been designed to ensure all households have affordable access to basic internet since the beginning of market liberalisation in EU member states in the end of the 1990s. We exclude these elementary bandwidth levels from our analysis as they show hardly any variation in our observation period, and, due to EU-wide universal service obligatons, also low variation between member states. Focusing on bandwidth levels of ≥ 6 Mbit/sec implies that all our estimates capture incremental effects to elementary broadband bandwidth levels (< 6 Mbit/sec).

[11] Whereas county-level data is only available for 2010-2015, national data is available for 2010-2018 (TÜV Rheinland, 2018).

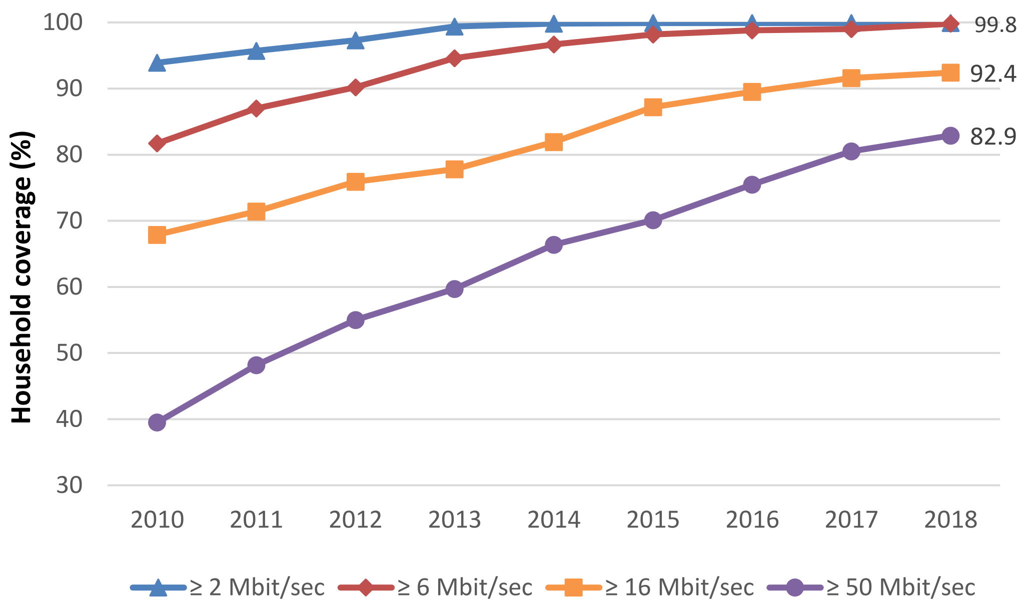

Figure 2: Percentage of German households with broadband coverage split by bandwidth levels

Figure 3 shows that national average German household coverage exhibits substantial and persistent gaps between urban and rural counties which is particularly pronounced for higher bandwidth levels reflecting digital divide due to typically much higher average deployment costs in rural areas.

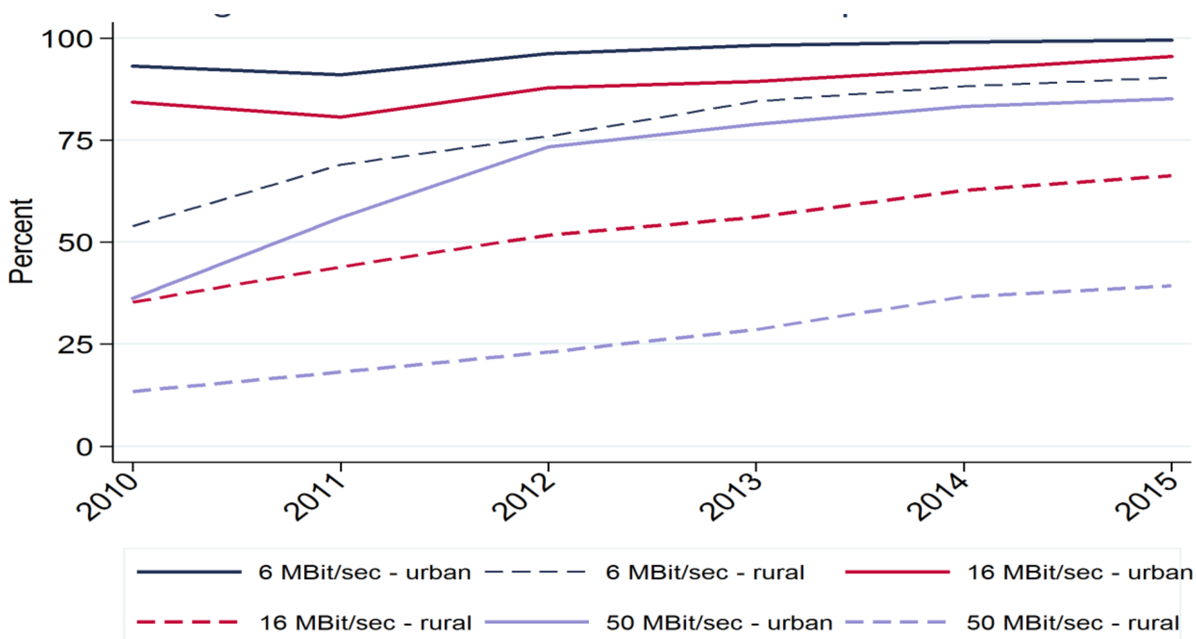

Figure 3: German (%) households with broadband coverage split by urban and rural counties

As indicated in Section 3.1, spatial externalities from neighbouring counties are likely to exist at the regional level within countries. To estimate spatial externalities, we consider the average impact of broadband availability of the five closest neighbours, denoted with $\boldsymbol{W}broadband_{jt}^{NB,q}$, which are weighted by their linear distance to the respective county centers and their population as follows:

$$\boldsymbol{W}broadband_{jt}^{NB,q} = \sum_{j=1}^{5} weight_{jt} \times broadband_{jt}^{q} \qquad \text{Equation (7)}$$

where

$$weight_{jt} = \left(1 - \frac{distance\ to\ focal\ county_i}{\max(distance)}\right) \times \left(\frac{population_{jt}}{\max(population)}\right)$$

where "max(·)" refers to the respective maximum values across Germany. Accordingly, the lower the linear distance to focal county *i* and the higher the population in neighbouring county *j* relative to the maximum of all other neighbouring counties is, the higher is the individual weight of neighbouring county *j* in year *t*, $weight_{jt}$. Furthermore, individual weights are normalized ($\frac{weight_{jt}}{\sum_{i=1}^{5} weight_{jt}}$), so that $0 < weight_{jt} < 1$.[12]

Figure 4 illustrates the construction of the average neighbour variable based on five neighbouring counties. We show by way of example the focal county Aschaffenburg Stadt with its neighbouring counties Aschaffenburg Land, Miltenberg, Odenwaldkreis, Offenbach, and Main-Kinzig-Kreis. Their linear spatial relationships, in bold lines, indicate the linear distance in each instance to the focal county's centre.

[12] A second way of incorporating the spatial dimension is to specify a spatial autoregressive process for the disturbance term; this is done in particular in cross-sectional analyses (Moreno-Serrano et al., 2005).

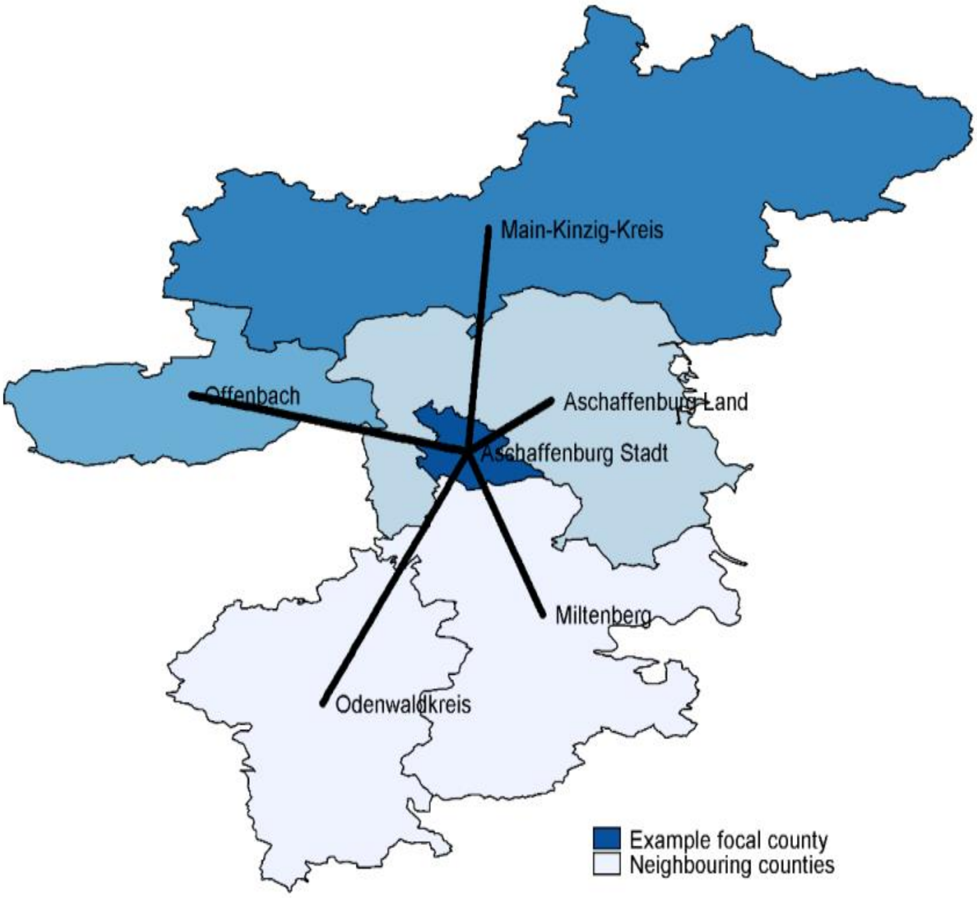

Figure 4: Example construction of focal county with five closest neighbouring counties

3.2.3 Control variables: Capital and labour inputs

The capital accumulation variable, denoted with *capital*, is proxied by subtracting labour income from gross value added and divided by GPD (Czernich et al., 2011). Human capital accumulation is proxied by the percentage of school leavers with a higher education entry qualification (German: "Abitur" and "Fachabitur") in relation to the total number of school leavers, and denoted with *higher education*. The labour accumulation variable, denoted with *labour*, is defined as the number of employees with social insurance as measured at place of residence per 100 residents. Following our baseline specification in equation (6), we take logs of our capital and labour control variables.

4 Estimation and identification strategy

Estimating Equation (6) has to take into account potential endogeneity, given that GDP and broadband infrastructure might be simultaneously determined (the introduction of broadband and its subsequent adoption might depend on the economic development). Another source of endogeneity is related to omitted variables such as broadband subsidies. This form of intervention is strongly promoted at the EU and member state levels in order to realize pre-defined broadband coverage and adoption targets and to avoid a "digital divide" in rural areas. However, the profitability gap is, inter alia, determined by the economic development and the average income of consumers in a specific county.

In order to address potential endogeneity related to broadband infrastructure, we employ different estimation techniques with different identifying assumptions. First, from the related literature (e.g. Bacache et al., 2014; Briglauer 2015; Briglauer et al., 2018; Grajek and Röller, 2012) we can infer the relevant demand and cost shifters in estimating broadband investment models. Consumers' demand for broadband services is determined by income levels as well as average education levels. Higher levels of education improve e-literacy skills, which considerably increases the utility derived from new broadband services. Also, more highly educated people tend to be more prone to adopting new technologies. As education represents human capital it also directly impacts on GDP (Equation (6)), and therefore we explicitly control for education in our baseline specification. Deployment costs crucially depend on population or household density as they exert a massive impact ("economies of density") on average deployment costs. The housing structure in terms of apartments as a share of family homes, *apartments_share*, crucially determines average deployment costs and thus household broadband coverage (FTTH Council Europe, 2016). Although this cost control variable is a strong predictor of broadband investment, it exhibits low variation over time. However, we can apply this cost control within an instrumental variable (IV) regression framework.[13] We contrast the results from the IV model with pooled ordinary least squares (OLS) estimates.

Second, in view of the potentially strong role of fixed effects (α_i), we employ a *fixed effects* estimator. The fixed effects model ensures that individual county-level effects capture any time-invariant unobserved heterogeneity that is possibly correlated with the regressors. Although the α_i's can be viewed as nuisance parameters that do not need to be consistently estimated, fixed effects estimation still requires strict exogeneity. To obtain consistent estimates for the vector of coefficients, $\boldsymbol{\beta}$, this specification requires $E(\varepsilon_{it}|\boldsymbol{x}_{i1},..., \boldsymbol{x}_{iT}, \alpha_i) = E(\varepsilon_{it}|\boldsymbol{x}_{it}, \alpha_i) = 0$ (Cameron and Trivedi, 2005, p. 727), where $\boldsymbol{x}_{it}$ represents the vector of covariates as specified in Equation (6). Strict exogeneity rules out any contemporaneous, past and future correlation of regressors and idisosyncratic errors.

Strict exogeneity represents a strong identifying assumption in general. However, major cost determinants of broadband deployment, such as costs for civil engineering and network construction, are impacted by topographical factors such as ground conditions and regulations, including rights of way and provisions on network cooperation (FTTH Council Europe, 2012, 2016). These factors either show no or only very low variation over time and are largely captured by the α_i's. Furthermore, broadband infrastructure is subject to rather long investment horizons. Whereas tax depreciation schedules are typically 15 years and more, the service lifetime of fiber optical cable is at least 25 years, and, in practice, fiber optic cable in backbone networks has already been in use for over 30 years.[14] Therefore, broadband infrastructure represents a long-run investment decision that relies on the expectation of stable market

[13] Variables measuring population or urbanization are also important determinants of deployment costs but cannot be considered as an exogenous source of variation.

[14] Information available at: https://www.corning.com/media/worldwide/coc/documents/Fiber/RC-%20White%20Papers/WP5082%203-31-2016.pdf.

conditions. Furthermore, as mentioned above, public subsidies have played a major role in expanding broadband coverage to otherwise unprofitable areas. Funding programs aimed at promoting high-speed broadband infrastructure did not get underway until in the last quarter of 2015 in Germany, however, and thus only coincide with the very end of observation period (programs are further described in Section 5.4). Funding programs targeted at basic broadband have existed before, but these programs have also stayed in place for a longer period of time once ratified by local or national governments. The only major funding program at the state level related to basic broadband was implemented in Bavaria.[15] The program "Schnelles Internet für Bayern" started in 2008 and lasted until 2011. In view of the above, broadband coverage, while subject to regional fixed effects, may plausibly be considered exogenous (Akerman et al., 2015).

Third, we estimate Equation (6) by applying first-differencing and the standard Arellano-Bond (Arellano and Bond, 1991) instruments for potentially endogenous broadband variables. Applying Arellano-Bond (AB) type instruments allows us to check that fixed effects estimates are not confounded by time-varying omitted factors. The model in first differences provides an alternative way to control for fixed effects and reads as follows:

$$\begin{gathered} logGDP_{it} - logGDP_{it-1} = \\ \beta_0^{AB} + \beta_1^{AB}(logK_{it} - logK_{it-1}) + \beta_2^{AB}(logL_{it} - logL_{it-1}) + \\ \beta_3^{q,AB}(B_{it} - B_{it-1}) + \beta_4^{AB}(logEDUC_{it} - logEDUC_{it-1}) + \\ \boldsymbol{\beta}_5^{AB,j}(\boldsymbol{W}B_{it}^{NB,q} - \boldsymbol{W}B_{it-1}^{NB,q}) \quad + \\ \beta_6^{AB}(years\_since_{it} - years\_since_{it-1}) + \quad \epsilon_{it}^{AB} - \epsilon_{it-1}^{AB} \end{gathered} \qquad \text{Equation (8)}$$

[15] For detailed information on this state program the reader is referred to Bavarian Ministry of Economic Affairs and Media, Energy and Technology (2012). The state of Bavaria also has the most ambitious funding programs for high-speed broadband infrastructure (see Section 6).

where individual fixed effects (α_i) are differenced out and a constant term, β_0^{AB}, is added. The AB estimator is derived within a generalized method of moments (GMM) framework and identification is based on so-called internal instruments for endogenous independent variables making use of the first differences and lags of endogenous variables. The initial AB estimator (Arellano and Bond, 1991) is called "difference GMM" which has been further developed by Arellano and Bover (1995) and Blundell and Bond (1998). The augmented version of the AB estimator builds on a system of two sets of equations – the original equation in levels and the transformed one in first differences – which allows a substantial improvement in efficiency and is called "system-GMM". AB-GMM panel data estimators have been commonly used in studies quantifying the impact of ICT on economic growth to address the issue of endogeneity in the absence of appropriate external instruments (Bloom et al., 2012; Cardona et al., 2013; Dimelis and Papaioannou, 2011). Using internal GMM type instruments the AB estimator allows for arbitrary correlations between independent variables with past and current realizations of the error term. Moreover, the AB-GMM estimator is particularly useful for panel data where the time dimension is relatively small and the number of cross-sectional units is comparatively large (Roodman, 2006). This is the case with respect to our panel data set ($T = 6$ and $N = 401$).

5 Main estimation results

Section 5.1 first reports the results of our baseline model (Equation (6)) for instrumental variable (IV) and ordinary least squares (OLS) estimation. Section 5.2 then reports fixed effects estimation results where we include county-level fixed effects to our baseline model. Section 5.3 provides further robustness analysis.

5.1 Ordinary least squares and instrumental variables estimation results

Results on the OLS estimates are summarized in Table 1. Columns (1) to (6) report estimation results based on robust standard errors for different bandwidth levels. Whereas the specifications in columns (1) to (3) include the respective spatial lag variable, $broadband^{NB,q}$, it is excluded in columns (4) to (6). The coefficient estimates of our broadband variables vary between 0.0016 and 0.0024 depending on bandwidth levels. In view of our log-level model specification in equation (6), the size of the respective coefficients can be interpreted as follows: A one percentage point increase in broadband infrastructure at, for example, bandwidth level ≥ 50 Mbit/s, denoted $broadband^{50Mbit/sec}$, leads to an increase in regional GDP per capita of approximately $100 \times \beta_3\%$, i.e. 0.16% (column (3)). In addition to the direct effects of broadband within a certain county, we can also observe a positive and significant effect from the average neighbouring county, $broadband^{NB,q}$, in columns (1) to (3), ranging from 0.09% to 0.16%. All control variables, except for higher education, are significant and positive as expected.

Comparing OLS (Table 1) with IV (Table 2) estimation results, one can observe a similar structure of coefficient estimates for all broadband related variables. IV coefficient estimates appear to be, however, higher – varying from 0.18% to 0.49% – for broadband variables measuring the direct impact of broadband in a certain county on regional GDP. In contrast, the effect of broadband deployment in the average neighbouring county is similar for significant estimates ranging from 0.08% to 0.16%. The combined effect of broadband deployment, i.e. $broadband^{50Mbit/sec} + broadband^{NB,q}$, captures direct as well as indirect effects in a focal county, and is significant and postive in all OLS and IV specifications.

To deal with endogeneity, we employ the share of apartments in family homes, *apartments_share*, as a source of exogenous variation in the IV estimation. Durbin-Wu-Hausman (DWH) tests do not reject the null hypothesis of broadband infrastructure being an exogenous variable except for columns (1) and (3). First stage *F*-statistics of excluded instruments suggest that our instrument is a strong predictor of our broadband infrastructure variables. The Cragg-Donald Wald (CDW) and Kleibergen-Paap-Wald (KPW) weak instrument tests clearly reject the null hypothesis that the respective estimating equation is weakly identified for all regressions at the 5% significance level. *F*-tests of overall model significance are reported as well.

The variable measuring the number of years since broadband has been deployed, *years_since,* exhibits a positive and significant effect on GDP in most OLS and IV specifications. That was to be expected, as the actual welfare effects of broadband are primarily related to the adoption of broadband services by consumers, which typically lags behind broadband infrastructure deployment on the supply side. Therefore, the more years have passed since broadband infrastructure deployment, the higher the adoption rates and, by extension, related effects on regional GDP.

Table 1: Ordinary least squares estimation results

Dependent variable: ***log(GDP_pc)***	(1) 6 Mbit/sec	(2) 16 Mbit/sec	(3) 50 Mbit/sec	(4) 6 Mbit/sec	(5) 16 Mbit/sec	(6) 50 Mbit/sec
broadband $^{6Mbit/sec}$	0.0018***			0.0020***		
	(0.0003)			(0.0002)		
broadband $^{16Mbit/sec}$		0.0021***			0.0024***	
		(0.0003)			(0.0003)	
broadband $^{50Mbit/sec}$			0.0016***			0.0023***
			(0.0002)			(0.0002)
broadband ^{NB,q}	0.0009*	0.0016***	0.0009***			
	(0.0005)	(0.0003)	(0.0003)			
test of hypothesis $\beta^q + \beta^{NB,q} = 0$	0.0027***	0.0038***	0.0026***			
	(0.0004)	(0.0004)	(0.0003)			
log(capital/GPD)	1.0452***	1.0443***	1.0417***	1.0241***	1.0576***	1.0178***
	(0.0817)	(0.0795)	(0.0819)	(0.0854)	(0.0805)	(0.0838)
log(labour)	0.0735***	0.0635***	0.0597***	0.0655***	0.0530***	0.0510***
	(0.0076)	(0.0074)	(0.0076)	(0.0087)	(0.0085)	(0.0088)
log(higher education)	0.0417**	0.0305**	0.0334**	0.0078	0.0063	0.0015
	(0.0165)	(0.0124)	(0.0139)	(0.0127)	(0.0111)	(0.0108)
years_since	0.0172***	0.0101***	0.0106***	0.0195***	0.0158***	0.0112**
	(0.0021)	(0.0020)	(0.0024)	(0.0016)	(0.0017)	(0.0056)
constant	10.8452***	10.9802***	11.1850***	10.8212***	11.1108***	11.2173***
	(0.1198)	(0.1120)	(0.1175)	(0.1069)	(0.1098)	(0.1166)
R^2 (overall)	0.5458	0.6336	0.5847	0.5429	0.6118	0.5561
# Observations	2,406	2,406	2,406	2,406	2,406	2,406

Notes: Ordinary least squares estimation for 401 German counties for the period 2010-2015. Broadband coverage is measured as percentage of households covered with broadband bandwidth levels of at least 6 Mbit⁄sec, 16 Mbit⁄sec, 50 Mbit⁄sec. For the variables *broadband* ^{q} and *broadband* ^{NB,q} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta^q + \beta^{NB,q} = 0$) where supraindex *q* stands for the respective bandwidth level in columns (1)-(3). Standard errors in parentheses are clustered at the county level and robust to both arbitrary heteroskedasticity and intra-group correlation. Significance at * 10%, ** 5% and *** 1% levels.

Table 2: Instrumental variable estimation results

Dependent variable: ***log(GDP_pc)***	(1) 6 Mbit/sec	(2) 16 Mbit/sec	(3) 50 Mbit/sec	(4) 6 Mbit/sec	(5) 16 Mbit/sec	(6) 50 Mbit/sec
broadband $^{6Mbit/sec}$	0.0048***			0.0049**		
	(0.0008)			(0.0022)		
broadband $^{16Mbit/sec}$		0.0025***			0.0021***	
		(0.0003)			(0.0007)	
broadband $^{50Mbit/sec}$			0.0023***			0.0018***
			(0.0002)			(0.0007)
broadband ^{NB}	-0.0001	0.0016***	0.0008***			
	(0.0004)	(0.0002)	(0.0001)			
test of hypothesis $\beta^q + \beta^{NB,q} = 0$	0.0047***	0.0041***	0.0031***			
	(0.0006)	(0.0003)	(0.0002)			
log(capital/GPD)	1.0609***	1.0074***	1.0128***	1.0595***	1.0522***	0.9885***
	(0.0432)	(0.0390)	(0.0419)	(0.0913)	(0.0842)	(0.0995)
log(labour)	-0.0019	0.0033	-0.0019	-0.0021	0.0080	0.0064
	(0.0061)	(0.0052)	(0.0052)	(0.0127)	(0.0114)	(0.0117)
log(higher education)	0.0581***	0.0519***	0.0411***	0.0579***	0.0542***	0.0583***
	(0.0041)	(0.0035)	(0.0040)	(0.0098)	(0.0088)	(0.0126)
years_since	0.0017	0.0074***	0.0062***	0.0007	0.0176***	0.0179
	(0.0042)	(0.0025)	(0.0021)	(0.0136)	(0.0060)	(0.0109)
constant	10.8869***	11.0081***	11.2907***	10.9227***	11.1201***	11.2209***
	(0.0559)	(0.0526)	(0.0604)	(0.1103)	(0.1101)	(0.1163)
DWH (*p*-value)	0.0000	0.1551	0.0006	0.1722	0.7295	0.4531
CDW	195.1182	619.5690	715.4002	49.0595	79.2243	45.8676
KPW	149.4168	315.3718	333.1077	112.9995	543.2869	234.3197
F-test (excl. instr.)	193.3773	538.3472	601.3088	80.0787	161.3864	74.6026
F-test (overall)	300.5097	490.2861	391.9091	91.7976	129.9790	88.2569
# Observations	2,406	2,406	2,406	2,406	2,406	2,406

Notes: IV estimation for 401 German counties for the period 2010-2015. Broadband coverage is measured as percentage of households covered with broadband bandwidth levels of at least 6 Mbit⁄sec, 16 Mbit⁄sec, 50 Mbit⁄sec. For the variables *broadband* ^{q} and *broadband* ^{NB,q} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta^q + \beta^{NB} = 0$) where supraindex q stands for the respective bandwidth level in columns (1)-(3). Broadband variables are instrumented with the variable *apartments_share*. Robust standard errors in parentheses are clustered at county level. Significance at * 10%, ** 5% and *** 1% levels.

5.2 Fixed effects estimation results

Table 3 shows the main results using fixed-effects ("FE") regressions to estimate the baseline specification in equation (6). Columns (1) to (6) report estimation results based on robust standard errors for different bandwidth levels. The *F*-test (all α_i = 0) clearly rejects the null hypothesis that all fixed effects are zero, which means that the composite error terms ($\alpha_i+\varepsilon_{it}$) are correlated. As county-level FEs are significant, pooled OLS or IV would produce inconsistent estimates if the FEs are correlated with the independent variables. A heteroskedastic- and cluster-robust Hausman test strongly rejects the random effects (pooled OLS) models identifying assumption (i.e. $E(\alpha_i|\mathbf{x}_i) = E(\alpha_i) = 0$) and corresponding estimates would thus be inconsistent. FE specifications are also preferable in view of our data set, which consists of all German counties. These represent a particular set of rather homogenous cross-sectional units and cannot be considered as a random sample drawn from the population of all counties in Europe, much less at a global level. For these reasons, and for reasons given in Section 4, we consider FE coefficient estimates as the most appropriate estimator.

FE coefficient estimates for all broadband related variables appear to be much lower in magnitude than OLS and IV coefficients expressing the relevance of fixed effects underlying the broadband deployment process; however, they remain significant. In line with IV estimates, broadband coefficient estimates in the FE specifications are lower for higher levels of bandwidth, $broadband^q$, ranging from 0.0009 to 0.0005 in columns (4) to (6). The corresponding broadband coefficients for the different bandwidth levels are estimated in a rather narrow range, suggesting that an increase in broadband coverage by 1 percentage point leads to an increase in regional GDP by about 0.05-0.09%. Comparing the different bandwidth levels and in view of the respective definitions with overlapping bandwidth levels (≥), we can infer the effect of interval bandwidth levels by comparing different regression specifications.

Coefficient effects of direct broadband estimates are lower when we also control for the effect from the average neighbouring county, *broadband* ^{NB,q}, which is significant at the 1% level in all specifications reported in columns (1) to (3). In line with OLS and IV estimation results we find strong evidence for spill-over effects in term of positive externalities from the average broadband deployment in neighbouring counties toward a focal county. The average German county thus benefits from regional spill-overs in terms of economic value added. Taking direct and indirect benefits of broadband deployment together, *broadband* ^{q} + *broadband* ^{NB,q}, we do not find evidence, however, for high-speed bandwidth (≥ 50 Mbit/sec) leading to increasing returns. Increasing the minimum bandwidth level by 10 Mbit/sec, i.e. comparing bandwidth level ≥ 6 Mbit/sec and bandwidth level ≥ 16 Mbit/sec, yields an increase in the broadband coefficient estimate by 0.0002. A further increase in minimum bandwidth by 34 Mbit/sec, i.e. when moving from ≥ 16 Mbit/sec to ≥ 50 Mbit/sec, even produces a decline in the combined coeffienct estimate (0.0008 - 0.0017). Comparing only direct effects of different bandwidth levels (columns (4)-(6)) we even find decreasing returns throughout.

Controls for capital and labour input variables, *log(capital)* and *log(labour)*, as well as the state of the broadband deployment process, *years since*, are also significant at the 1% level with expected signs in all specifications. The respective coefficient estimates vary in rather narrow ranges in different specifications for broadband variables. Overall, our fixed effects specification explains at least 83% of the relevant within variation in the regression specifications reported in columns (1) to (6).

Table 3: Fixed effects estimation results

Dependent variable: *log(GDP_pc)*	(1) 6 Mbit/sec	(2) 16 Mbit/sec	(3) 50 Mbit/sec	(4) 6 Mbit/sec	(5) 16 Mbit/sec	(6) 50 Mbit/sec
broadband $^{6Mbit/sec}$	0.0005***			0.0009***		
	(0.0001)			(0.0001)		
broadband $^{16Mbit/sec}$		0.0003***			0.0007***	
		(0.0001)			(0.0001)	
broadband $^{50Mbit/sec}$			0.0000			0.0005***
			(0.0000)			(0.0001)
broadband ^{NB,q}	0.0010***	0.0015***	0.0008***			
	(0.0001)	(0.0001)	(0.0001)			
test of hypothesis $\beta^q + \beta^{NB,q} = 0$	0.0015***	0.0017***	0. 0008***			
	(0. 0001)	(0. 0001)	(0. 0001)			
log(capital/GPD)	0.8930***	0.8768***	0.9007***	0.8898***	0.8763***	0.8970***
	(0.0254)	(0.0268)	(0.0273)	(0.0263)	(0.0282)	(0.0262)
log(labour)	0.2277***	0.3021***	0.3124***	0.2407***	0.3909***	0.4062***
	(0.0329)	(0.0362)	(0.0394)	(0.0378)	(0.0442)	(0.0406)
log(higher education)	0.0056**	0.0089***	0.0015	0.0047*	0.0045	0.0012
	(0.0025)	(0.0028)	(0.0031)	(0.0026)	(0.0030)	(0.0031)
years_since	0.0147***	0.0118***	0.0155***	0.0172***	0.0144***	0.0167***
	(0.0008)	(0.0009)	(0.0009)	(0.0008)	(0.0010)	(0.0009)
constant	9.1105***	8.2921***	8.2980***	9.0115***	7.4041***	7.2982***
	(0.3494)	(0.3840)	(0.4196)	(0.4005)	(0.4708)	(0.4349)
F-test (all $\alpha_i = 0$) (p-value)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hausman test ($E(\alpha_i \| \boldsymbol{x}_i) = 0$) ($p$-value)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
R^2 (within)	0.8906	0.8596	0.8489	0.8777	0.8316	0.8351
# Observations	2,406	2,406	2,406	2,406	2,406	2,406

Notes: Fixed effects estimation for 401 German counties for the period 2010-2015. Broadband coverage is measured as percentage of households covered with broadband bandwidth levels of at least 6 Mbit⁄sec, 16 Mbit⁄sec, 50 Mbit⁄sec. For the variables *broadband* ^{q} and *broadband* ^{NB,q} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta^q + \beta^{NB,q} = 0$) where supraindex q stands for the respective bandwidth level in columns (1)-(6). All regressions include county fixed effects. Standard errors in parentheses are clustered at county level and robust to both arbitrary heteroskedasticity and intra-group correlation. Significance at * 10%, ** 5% and *** 1% levels.

5.3 Robustness analysis

This section presents further analyis to validate the robustness of our main results. Robustness checks are based on a different estimator (GMM), construction of the weighting matrix (distance weights only) and a different number of neighbouring counties (15 instead of 5). Furthermore, we examine the impact of broadband coverage separately for urban and rural counties.

Our GMM estimation results are based on internal instruments and reported in Table 4. The basic structure of coefficient estimates remains similar to our FE estimation results, although the direct effects of broadband deployment are substantially higher for GMM coefficient estimates. At the same time, the indirect effects of broadband deployment are substantially lower than our corresponding FE estimates. All coefficient estimates for our control variables exhibit expected positive signs and are significant in most cases except for the variable *higher education*.

Table 5 reports separate FE estimation results for urban (columns (1)-(3)) and rural (columns (4)-(6)) German counties. The latter consist of all rural districts („Landkreis“ or „Kreis“ in German administrative language) whereas urban counties consist of all cities („Kreisfreie Stadt“ or „Stadtkreis“ in German administrative language). Comparing urban and rural counties it first appears that direct effects play a much stronger role for basic broadband in rural areas, whereas only high bandwidth levels (> 50 Mbit/sec) exhibit a significant direct effect in urban counties. The relevance of high bandwidth in urban counties is due to much higher coverage levels (Figure 3) and consequently higher adoption of innovative and bandwidth demanding broadband services in urban counties. Similarly, spillover effects from neighbouring counties are particularly strong for high bandwidth levels in urban counties which points to the existence of strong agglomeration effects among (sub-)urban counties in close proximity to one another.

Table 6 reports FE estimation results for an alternative weighting matrix for average neighbours. Whereas the weighting matrix outlined in Section 3.2.2 was based on the linear distances between focal county centre and neighbouring county centres as well as on population in neighbouring counties, the weighting matrix underlying the coefficient estimates in Table 5 is based on the linear distance metric only. The FE estimation results remain quite similar to the respective FE coefficient estimates reported in Tables 2 and 3. Columns (4) to (6) report FE estimation results on the basis of an alternative weight matrix using the linear distance metric only and the 15 closest neighbours (instead of 5). Here, the coefficient estimates for the variable $broadband^{NB}$ are substantially lower than the respective estimates on the basis of the 5 closest neighbours (reported in columns (1) to (3) and columns (1) to (3) in Table 3). In particular, the FE estimates are positive and significant but substantially lower for all bandwidth levels compared to the estimates in Table 3, e.g. for bandwidth level ≥ 50 Mbit/s: 0.0001 < 0.0008. This confirms our initial hypothesis that potential regional spill-over effects are stronger the higher geographical proximity is, as welfare effects are limited by various factors, such as the maximum travel time commuters are willing to accept.

Table 4: AB system-GMM estimation results

Dependent variable: ***log(GDP_pc)***	(1) 6 Mbit/sec	(2) 16 Mbit/sec	(3) 50 Mbit/sec	(4) 6 Mbit/sec	(5) 16 Mbit/sec	(6) 50 Mbit/sec
broadband $^{6Mbit/sec}$	0.0014**			0.0025***		
	(0.0007)			(0.0004)		
broadband $^{16Mbit/sec}$		0.0036***			0.0035***	
		(0.0008)			(0.0008)	
broadband $^{50Mbit/sec}$			0.0010***			0.0010***
			(0.0002)			(0.0002)
broadband $^{NB,\,q}$	0.0008	0.0007*	0.0006***			
	(0.0005)	(0.0004)	(0.0002)			
test of hypothesis $\beta^q + \beta^{NB,q} = 0$	0.0022***	0.0043***	0.0016***			
	(0.0003)	(0.0006)	(0.0002)			
log(capital/GDP_pc)	0.9822***	1.5608***	1.0056***	1.2450***	1.5127***	0.7722***
	(0.0864)	(0.2053)	(0.0470)	(0.0766)	(0.2177)	(0.2805)
log(labour)	0.0686***	0.0348***	0.0561***	0.0599***	0.0374***	0.0644***
	(0.0086)	(0.0116)	(0.0093)	(0.0088)	(0.0121)	(0.0134)
log(higher education)	0.0077	0.0157	0.0116	0.0126	0.0133	0.0078
	(0.0091)	(0.0113)	(0.0075)	(0.0087)	(0.0109)	(0.0146)
years_since	0.0193***	0.0056	0.0179***	0.0178***	0.0089**	0.0196***
	(0.0011)	(0.0034)	(0.0009)	(0.0014)	(0.0042)	(0.0013)
constant	10.8420***	11.6077***	11.1067***	11.1209***	11.5911***	10.8524***
	(0.1171)	(0.2533)	(0.1115)	(0.1137)	(0.2534)	(0.3126)
Hansen (*p*-value)	0.054	0.548	0.157	0.737	0.365	0.387
AR(1) (*p*-value)	0.041	0.034	0.216	0.004	0.036	0.672
AR(2) (*p*-value)	0.476	0.792	0.248	0.358	0.622	0.256
# Instruments	9	8	16	7	7	12
# Observations	2,406	2,406	2,406	2,406	2,406	2,406

Notes: Columns (1) to (6) report the results of system-GMM estimation (Arellano and Bover, 1995; Blundell and Bond, 1998) for 401 German counties for the period 2010-2015. Broadband coverage is measured as percentage of households covered with broadband bandwidth levels of at least 6 Mbit ⁄sec, 16 Mbit ⁄sec, 50 Mbit ⁄sec. For the variables *broadband*^{q} and *broadband*^{NB,q} point estimates and standard errors are provided for the test $\beta^q + \beta^{NB,q} = 0$. Broadband coverage variables in first differences are instrumented with their own lagged levels and first differences with a maximum lag number of four. The two-step system-GMM estimator is based on the finite sample correction (Windmeijer, 2005). For the Arellano-Bond autocorrelation tests (AR(1) and AR(2)) and the Hansen test of overidentifying restrictions corresponding *p*-values are reported. Standard errors in parentheses are clustered at county level and robust to both arbitrary heteroskedasticity and intra-group correlation. Significance at * 10%, ** 5% and *** 1% levels.

Table 5: Fixed effects estimation results for urban and rural counties

Dependent variable: *log(GDP_pc)*	(1) 6 Mbit/sec	(2) 16 Mbit/sec	(3) 50 Mbit/sec	(4) 6 Mbit/sec	(5) 16 Mbit/sec	(6) 50 Mbit/sec
	Urban	Urban	Urban	Rural	Rural	Rural
broadband $^{6Mbit/sec}$	-0.0000			0.0007***		
	(0.0002)			(0.0001)		
broadband $^{16Mbit/sec}$		0.0000			0.0003***	
		(0.0001)			(0.0001)	
broadband $^{50Mbit/sec}$			0.0002***			-0.0004***
			(0.0000)			(0.0001)
broadband ^{NB,q}	0.0006***	0.0007***	0.0198***	0.0009***	0.0015***	0.0143***
	(0.0002)	(0.0002)	(0.0015)	(0.0001)	(0.0002)	(0.0011)
broadband ^{q} + *broadband* ^{NB,q}	0.0006***	0.0007***	0.0005***	0.0016***	0.0019***	0.0007***
	(0.0002)	(0.0003)	(0.0002)	(0.0000)	(0.0001)	(0.0000)
log(capital/GPD)	0.8280***	0.8242***	0.8408***	0.9409***	0.9176***	0.9374***
	(0.0413)	(0.0429)	(0.0399)	(0.0293)	(0.0319)	(0.0346)
log(labour)	0.0770	0.0731	0.1601**	0.2735***	0.3809***	0.3946***
	(0.0796)	(0.0862)	(0.0790)	(0.0350)	(0.0435)	(0.0465)
log(higher education)	0.0023	0.0033	0.0004	0.0047*	0.0084***	0.0020
	(0.0061)	(0.0064)	(0.0084)	(0.0027)	(0.0030)	(0.0033)
years_since	0.0209***	0.0208***	0.0198***	0.0121***	0.0087***	0.0143***
	(0.0015)	(0.0018)	(0.0015)	(0.0008)	(0.0010)	(0.0011)
constant	10.8074***	10.8460***	9.9450***	8.6524***	7.4771***	7.4387***
	(0.8647)	(0.9416)	(0.8471)	(0.3725)	(0.4601)	(0.4932)
F-test (all $\alpha_i = 0$) (p-value)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hausman test ($E(\alpha_i \vert \boldsymbol{x}_i) = 0$) ($p$-value)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
R^2 (within)	0.8959	0.8869	0.8646	0.8979	0.8607	0.8537
# Observations	642	642	642	1,764	1,764	1,764

Notes: Columns (1) to (6) report the results of FE estimation results for 642 urban (columns (1)-(3)) and 1,746 rural (columns (4)-(6)) German counties for the period 2010-2015. Broadband coverage is measured as percentage of households covered with broadband bandwidth levels of at least 6 Mbit ⁄sec, 16 Mbit ⁄sec, 50 Mbit ⁄sec. For the variables *broadband* ^{q} and *broadband* ^{NB,q} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta^q + \beta^{NB,q} = 0$) where supraindex q stands for the respective bandwidth level in columns (1)-(6). Columns (1) to (6) include county fixed effects. Standard errors in parentheses are clustered at county level and robust to both arbitrary heteroskedasticity and intra-group correlation. Significance at * 10%, ** 5% and *** 1% levels.

Table 6: FE estimation results with different weighting matrix (linear distance) and different number of neighbouring counties ((5) and (15))

Dependent variable: ***log(GDP_pc)*** FE (#neighbouring counties)	(1) 6 Mbit/sec FE (5)	(2) 16 Mbit/sec FE (5)	(3) 50 Mbit/sec FE (5)	(4) 6 Mbit/sec FE (15)	(5) 16 Mbit/sec FE (15)	(6) 50 Mbit/sec FE (15)
broadband $^{6Mbit/sec}$	0.0005***			0.0004***		
	(0.0001)			(0.0001)		
broadband $^{16Mbit/sec}$		0.0002***			0.0001**	
		(0.0001)			(0.0001)	
broadband $^{50Mbit/sec}$			0.0001			0.0000
			(0.0000)			(0.0000)
broadband ^{NB,q}	0. 0015***	0.0017***	0.00075***	0.0005***	0.0003***	0.0001***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
test of hypothesis $\beta^q + \beta^{NB,q} = 0$	0.0010***	0.0015***	0.0007***	0.0001***	0.0002***	0.0001***
	(0.0001)	(0.0001)	(0.0001)	(0.0000)	(0.0000)	(0.0000)
log(capital/GPD)	0.8958***	0.8790***	0.9040***	0.9021***	0.8878***	0.9135***
	(0.0253)	(0.0263)	(0.0268)	(0.0257)	(0.0278)	(0.0260)
log(labour)	0.2252***	0.2933***	0.3118***	0.2100***	0.2288***	0.2777***
	(0.0325)	(0.0355)	(0.0393)	(0.0316)	(0.0347)	(0.0380)
log(higher education)	0.0055**	0.0095***	0.0022	0.0055**	0.0101***	0.0013
	(0.0024)	(0.0027)	(0.0031)	(0.0024)	(0.0025)	(0.0029)
years_since	0.0144***	0.0115***	0.0154***	0.0134***	0.0101***	0.0138***
	(0.0008)	(0.0009)	(0.0009)	(0.0008)	(0.0009)	(0.0009)
constant	9.1408***	8.3918***	8.3097***	9.2960***	9.0703***	8.6821***
	(0.3461)	(0.3772)	(0.4199)	(0.3352)	(0.3661)	(0.4063)
F-test (all $\alpha_i = 0$) (*p*-value)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hausman (FE vs. RE) (*p*-value)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
R^2 within	0.8909	0.8607	0.8482	0.8957	0.8736	0.8548
# Observations	2,406	2,406	2,406	2,406	2,406	2,406

Notes: Columns (1) to (6) report the results of FE estimation results for 401 German counties for the period 2010-2015 with an alternative weighting matrix (columns (1)-(3)) and with an alternative number of neigbouring counties (columns (4)-(6)). Broadband coverage is measured as percentage of households covered with broadband bandwidth levels of at least 6 Mbit ⁄sec, 16 Mbit ⁄sec, 50 Mbit ⁄sec. For the variables *broadband*^{q} and *broadband*^{NB,q} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta^q + \beta^{NB,q} = 0$) where supraindex q stands for the respective bandwidth level in columns (1)-(6). Columns (1) to (6) include county fixed effects. Standard errors in parentheses are clustered at county level and robust to both arbitrary heteroskedasticity and intra-group correlation. Significance at * 10%, ** 5% and *** 1% levels.

5.4 Costs and benefits of the “Digital Agenda 2014-2017” strategy

In order to achieve its ubiquituous coverage goal (i.e. availability of 50 Mbit/sec to all households by 2018), and in view of strongly increasing average costs in low density areas and lower than expected deployment progress, the German government has started to provide substantial public funds to achieve the coverage target set forth by “Digital Agenda” in 2015. In October 2015 the Federal Ministry of Transport and Digital Infrastructure (BMVi, 2017) provided public funds of about €2.7 bn for consulting services, network planning and the actual construction of high-speed broadband infrastructure. The funding program was extended by another €1.3 bn in July 2016. As a general rule, funds were designed to cover 50% of the profitability gap, with the remaining gap covered by complementary funds at the EU or state level. Funded companies, however, had to cover at least 10% of total costs of the deployment project (Gerpott, 2017). State level funds were quite substantial in some German states and added up to more than €2 bn, although some €1.5 bn of all state level funds have been provided by the Bavarian government. In total, about €6 bn of public funds were provided by German authorities at the national and state levels between 2015 and 2018. It should be noted, however, that due to administrative barriers in the awarding process, not all funds have been fully utilized and infrastructure deployment is subject to substantial adjustment costs and delay. Even given substantial public funding, average coverage in German counties based on all available wireline and wireless broadband access technologies enabling at least 50 Mbit/sec reached only 82.9% at the end of 2018 (Figure 2) and thus fell significantly short of the ubiquitous household coverage goal of the “Digital Agenda” (TÜVRheinland, 2018).

Although the funding programs were insufficient to bring about ubiquitious coverage by the end of 2018, they may have been economically efficient, insofar as their positive externalities outweigh their associated cost. Regional spill-over effects represent an important positive externality that can result infrastructure investment. Indeed, our estimates show that broadband infrastructure quality levels have a positive and significant impact on the generation of regional spill-over effects. In order to make a conservative estimate of total benefits, we draw on the FE coefficient estimates related to the variables *broadband*^{,q} and *broadband* ^{NB,q} as reported in Table 3. In order to assess costs and benefits related to the ubiquitious coverage goal of the "Digital Agenda 2014-2017", we rely on the coefficient estimates for ≥ 50 Mbit/sec bandwidth levels ($\beta_3^{50\text{ Mbit/sec}} + \beta_3^{\text{NB,50 Mbit/sec}} = 0.0008$). The average yearly percentage change in *GDP_pc* therefore is:

$$\%\Delta\, GDP\_pc = \%\Delta broadband \times 0.0008^{*} \times 100 \qquad \text{Equation (9)}$$

where %Δ broadband refers to the effective unit change in percentage points of broadband infrastructure coverage with a bandwidth of at least 50Mbit/sec in the funding period 2015-2018. According to Figure 2, the 50 Mbit/sec coverage level was about 70% in 2015 and about 83% in 2018, hence %Δ was about 13 percentage points. For simplicity we assume linear coverage growth over the period 2015-2018. Evaluated at the grand mean of our outcome variable (Table A.2: $\overline{GDP\_pc}$ = €61646.36) the additional broadband deployment of 13 percentage point thus yielded an increase in average GDP per capita in the 2015-2018 period of about €641.12. This number by far exceeds the per capita amount spent on public funding of about €113.95 (= €6 bn divided by the average working age population in Germany, which was about 52.7 million in 2015-2018).

Consequently, our cost-benefit analysis suggests substantial efficiency gains (in line with the findings of Gruber et al. (2014), who evaluated the DAE goals at the EU level). Although we must acknowledge the rudimentary nature of our cost-benefit analysis, it appears that there is a clear case for public intervention to fund broadband deployment in German counties. The high relevance of regional spillovers indicates the importance of coordinated funding policies in order to accrue positive externalities in neighbouring counties.

7 Summary and policy conclusions

Our study empirically investigates the impact of broadband network deployment in German counties on regional GDP. Utilizing a balanced panel dataset of 401 German counties for the period 2010-2015 and different panel estimation techniques, we measured the effect of different basic and high-speed broadband bandwidth levels. We investigated the extent of these effects both within counties and across neighbouring counties. Whereas spatial externalities among countries can be ignored in aggregated country-level studies, spatial externalities appear to be of much stronger relevance within countries at a disaggregated level. Indeed, we found strong evidence for positive spillover effects in the nearest neighbouring counties. Whereas an increase in bandwidth coverage by one percentage point increased regional GDP by about 0.05-0.09%, according to our main fixed effects estimation results, this effect was almost doubled when we took regional externalities into account. We also found, however, that this spillover effect declined as the geographic distance of neighbouring counties increased. With a view to the GDP effects of distinct bandwidth levels, we find that coefficient estimates for high-speed broadband were substantially lower than for basic broadband. Accordingly, we did not find evidence for increasing returns with higher bandwidth capacity. However, when comparing urban and rural counties, we find a strong impact of high bandwidth levels for urban counties, whereas in rural counties lower and medium bandwidth levels appear to be of stronger importance. Our main findings – which are of high relevance to the formulation of future policy interventions – appear to be robust with respect to panel estimators and the definition of neighbouring counties.

When comparing the benefits of broadband expansion, which are derived from our broadband coefficient estimates, with costs of public funding at national and state levels in Germany in 2015-2018, we find that total economic benefits of broadband deployment within and across neighbouring counties substantially exceeded the cost of public subsidies for high-speed broadband deployment. Thus, while this policy intervention was insufficient to achieve the ubiquitous coverage targets set for 2018, it appears to have been efficient from the perspective of a cost-benefit analysis.

Our analysis likely underestimates the true welfare gains related to broadband deployment for the following reasons: first, the future impacts of fiber-based broadband adoption based on more innovative applications and services might be substantially higher than our estimates, which are based on a narrow time range (2010-2015). In particular, the development and adoption of innovative services based on high-speed broadband might be subject to significant time lags, as indicated by the variable for the deployment stage (*years_since*). Coefficient estimates of this variable are furthermore much higher for urban counties than for rural counties for all bandwidth levels which suggests that broadband adoption is faster in urban areas due to agglomeration effects. Second, while previous literature (e.g. Akerman et al., 2015) generally indicates that the relationship between broadband availability and broadband adoption is positive, broadband availability only serves as a pre-condition for broadband adoption. In this regard, Whitacre et al. (2014) suggest based on data from US counties that the influence of broadband availability and actual broadband adoption can differ considerably. Thirdly, we acknowledge the imperfect nature of GDP as a measure of the economic benefits of broadband, as not all value created by broadband networks is captured in standard measures of GDP. The distinction between process and product innovations is important here. Innovations make products and services cheaper to produce, yet are only reflected in the producer surplus (which counts toward GDP) and not in consumer surplus (Briglauer and Gugler, 2019).

Future research should be directed at disentangling the various causal channels related to broadband deployment and adoption, while also examining the knock-on effects to product and process innovation at regional and national levels. In particular, the understanding of broadband infrastructure as a GPT and the fact that most internet applications are provided to consumers free of charge, suggest substantial welfare effects that justify supply and demand side policies.

Appendix

Tables: A.1, A.2

Table A.1: Description of variables and sources

Variable	Description	Source
	Dependent variable	
GDP_pc	Regional Gross Domestic Product at market prices in € divided by the working population (18-65 years)	GENESIS
	Main explanatory variables	
$broadband^{6Mbit/sec}$	Share of households covered with at least 6 Mbit/sec wireline or wireless broadband connections	Breitbandatlas/ TÜV Rheinland
$broadband^{16Mbit/sec}$	Share of households covered with at least 16 Mbit/sec wireline or wireless broadband connections	Breitbandatlas/ TÜV Rheinland
$broadband^{50Mbit/sec}$	Share of households covered with at least 50 Mbit/sec wireline or wireless broadband connections	Breitbandatlas/ TÜV Rheinland
$broadband^{NB,q}$	Average broadband coverage of the five closest neighbouring counties for specific bandwidth levels (q = 6 Mbit/sec, 16 Mbit/sec, 50 Mbit/sec). Indiviudal neighbouring counties are weighted by their population and linear distance (beeline) to centre of focal county	Breitbandatlas/ TÜV Rheinland
years_since	Number of years that have passed since the respective broadband quality level exceeded the first quartile	
	Control variables	
capital	Capital accumulation defined as gross value added minus labour income divided by GDP	INKAR
labour	Number of employees with social insurance, county level at place of residence per 100 residents	GENESIS
higher education	Percentage share of school leavers with a higher education entry qualification in the total number of school leavers (German 'Abitur', 'Fachabitur')	INKAR
	Instrumental variable	
apartments_share	Share of flats in family buildings in the total number of flats	INKAR

Table A.2: Summary statistics

	count	mean	sd	min	max
GDP	2406	4.86836e+09	7.76824e+09	578105088	88095793152
GDP_pc	2406	61646.4	11366.7	41100	141433.8
log(GDP_pc)	2406	11.01453	0.16611	10.62376	11.85959
capital	2406	26953.9	6911.6	13496	81366.8
capital/GDP_pc	2406	0.434	0.0381	0.310	0.629
log(capital/GDP_pc)	2406	-0.839	0.0870	-1.173	-0.464
labour	2406	72678.3	97919.7	11879	1311413
log(labour)	2406	10.88	0.700	9.383	14.09
higher education	2406	31.96	9.515	1	70.30
log(higher education)	2406	3.409	0.383	0	4.253
broadband $^{6Mbit/sec}$	2406	82.11	17.73	0	100
broadband $^{16Mbit/sec}$	2406	62.20	25.04	0	100
broadband $^{50Mbit/sec}$	2406	37.82	31.60	0	99.90
broadband $^{NB, 6Mbit/sec}$	2406	83.99	13.07	31.13	99.94
broadband $^{NB, 16Mbit/sec}$	2406	66.02	17.78	13.03	98.86
broadband $^{NB, 50Mbit/sec}$	2406	42.50	23.75	0.0255	92.95
population	2406	201774.4	231407.0	33944	3520031
years_since (6Mbit/sec)	2406	2.256	1.892	0	6
years_since (16Mbit/sec)	2406	2.346	1.963	0	6
years_since (50Mbit/sec)	2406	2.251	1.895	0	6
apartments_share	2406	54.51	19.54	10.40	88.50

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