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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

This study aims to assess the economic benefits of high-speed broadband within and across neighboring counties in Germany. Utilizing a balanced panel dataset of 401 German counties with data from 2010 to 2015 as well as different panel estimation techniques, we find that an increase in average broadband speed has a significantly positive effect on regional GDP in the average German county. Furthermore, we find that broadband deployment in German counties induces not only substantial economic benefits in terms of direct effects within counties but also positive regional externalities across counties. According to our estimation results, an increase in average bandwidth speed by one unit (1 Mbit/s) induces a rise in regional GDP of 0.18%. This effect is almost doubled if we also take regional externalities into account (0.31%). Moreover, we find that regional agglomeraton effects are of particular relevance for rural counties. Our cost-benefit analysis of subsidies based on conservative estimates suggests efficiency gains, as the total economic per capita benefits (€164) of subsidy programs to encourage broadband expansion exceeded their associated per capita costs (€114).

1. Introduction

The economic benefits of “old” broadband networks for consumers have been increasingly emphasized by economic research (Bertschek et al., 2016). 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). Similarly, the wide-scale roll-out of “new” broadband networks which are largely based on fiber-optic transmission technologies in most or all parts of the network is believed to spur job creation in information and communications technology

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(ICT) and other related industries, and, more generally, is ascribed enormous potential for facilitating productivity increases, product innovations 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 (Bock & Wilms, 2016; FTTH Council Europe, 2012). There is, however, hardly any empirical evidence on whether positive externalities beyond those associated with basic broadband networks will emerge under the new 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/s 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 $\geq$ 50 Mbit/s must be at least in part fiber-cable based in the access network, or, with a view to wireless broadband, must be based on (advanced) 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 speed on economic outcome (in terms of regional gross domestic product (GDP))? (ii) Are there increasing returns to scale with respect to higher broadband speed levels? (iii) Are there positive or negative[3] externalities among neighboring counties at a regional level? (iv) Is there a difference in effect in urban vs. rural counties? (v) Are the total benefits sufficient to cover past 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 for public broadband funding, which in Germany primarily aims to extend high-speed broadband to areas of the country where commercial providers do not see sufficient profitability, primarily due to low population density. In order to reach the ubiquitous coverage target, Germany's federal and state governments have provided substantial funding. 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 within and across neighboring counties in Germany. We find that broadband deployment in German counties induces substantial economic benefits in terms of direct effects and regional externalities. An increase in average broadband bandwidth speed by one unit (i.e. 1 Mbit/s) induces a rise in regional GDP of 0.18%. This effect is almost doubled if we also take regional externalities into account (0.31%). We thus find evidence of strong regional agglomeration effects which are of particular relevance for rural counties. The latter is of importance for broadband policies aimed at closing the digital divide between urban and rural areas. Taking diminishing returns of average bandwidth speed into account, our estimates further imply an optimal broadband bandwidth coverage of 37.4 Mbit/s for regional GDP. Finally, our cost-benefit analysis of subsidies suggests efficiency gains, as the total economic per capita benefits (€164) related to German subsidy programs to encourage high-speed broadband expansion and increase average broadband speed exceeded their associated per capita costs (€114).

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 and related speed levels. 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 of our main findings. It also summarizes the key insights generated by our research for policy makers and outlines an agenda for future research.

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 GDP, 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 availability (coverage) and adoption and related bandwidth (speed) levels. Although we focus on the impact of broadband coverage on the supply side, we also review adoption-related studies on high-speed broadband, since both broadband measures are

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[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 October 25th 2020). Meanwhile more ambitious and long-term objectives for 2025 were specified by the EC in its gigabit-connectivity strategy in 2016. The latter inter alia requires that "*[a]ll European households, rural or urban, to have access to Internet connectivity offering a downlink of at least 100 Mbps, upgradable to Gigabit speed*" (European Commission, 2016, pp. 35-36). Broadband plans in most of the developed countries have been also adjusted accordingly since 2016 (OECD, 2018).

[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").

[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 labor market effects.

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% and 3.9% 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 outcome.

Another branch of the literature focuses on the impact of broadband speed on various economic outcomes. Ahlfeldt et al. (2017) measure the effect of basic broadband speed levels on property prices using micro data from England between 1995 and 2010. The authors find a significantly positive effect, but diminishing returns to speed. De Stefano et al. (2018) examine the effects of heterogeneous types of ICT on firm performance using UK micro-level data for the years 1999 to 2005. Using basic broadband enablement as an instrument, the authors find that ICT causally affects firm size but not productivity. Canzian et al. (2019) analyze the impact of basic broadband accessibility on firm performance using regional data from Italy for the years from 2008 to 2014. The authors find that advances in DSL technology speed is associated with increases in firms' revenue and total factor productivity. Koutroumpis (2019) utilizes data on OECD countries between 2002 and 2016. The author finds a consistent effect of broadband adoption on GDP with diminishing returns to scale and that broadband speed is a moderator of these effects. Beyond a certain speed threshold, however, further quality increases are deemed unproductive. Mayer et al. (2020) use OECD country-level data for the years from 2008 to 2012. The authors investigate the impact of broadband speed and its interaction with broadband adoption on GDP per capita and find, contrary to other studies, that adoption is statistically insignificant with speed.

Whereas all above-mentioned studies focus on basic broadband speed levels well below 50 Mbit/s, only very few empirical studies explicitly include high-speed, i.e. fiber-based, broadband availability and related speed levels, a topic that was recently surveyed by Abrardi and Cambini (2019). The authors conclude (p. 14): "There is still a very scant literature that addresses the impact of fiber investment on economic growth and assesses the differentiated effect (if any) of speed on national or local growth." 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 to 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 (2020) 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.

To summarize, most of the available studies analyze the impact of basic broadband on the macroeconomic level. Some basic and high-speed broadband related studies find diminishing returns of broadband bandwidth quality levels. Yet very few draw on data to assess the economic impact of high-speed broadband. Micro-based evidence on the impact of high-speed broadband is largely missing, and existing studies focus on outcome variables other than economic performance in terms of GDP. Furthermore, there is no empirical evidence 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 ubiquitous 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 labor (L). The starting point of the analysis is a regional production function that allows for

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

different levels of technology (A) in county i ($i = 1, \ldots, N$) in period t ($t = 1, \ldots, T$) and reads as follows:

$$Q_{it} = A_{it} F(K_{it}; L_{it}) \tag{1}$$

where A_{it} represents total factor productivity, and it 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 Eq. (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 Eq. (1) thus yields:

$$Q_{it} = A_{it} K_{it}^{\beta_1} L_{it}^{\beta_2} \tag{2}$$

where β_1 and β_2 represent the output elasticities of capital and labor, respectively. Following Czernich et al. (2011, p. 510), we further assume that the technological state evolves according to an exponential growth pattern:

$$A_{it} = A_0 e^{\lambda_i t} \tag{3}$$

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.

Adoption by residential consumers drives real household income through various channels; e.g. consumers benefit from broadband adoption via easy and cheap access to e.g. administration or banking services or from economies of time due to innovative online services such as hotel booking, e-commerce platforms or online education as well as from access to e-health. Different types of teleworking provide spatial and time flexibility and for example allow households in remote areas to participate in the labor force. Adoption within firms gives rise to potential productivity gains via more efficient business processes, e.g. due to remote monitoring, logistics management and online procurement, or acceleration of innovation on new products and new business creation. Based on the GPT hypothesis, we assume that broadband availability directly impacts total factor productivity via externality growth effects as described and can be characterized by the following functional relationship (Czernich et al., 2011, p. 510):

$$\lambda_i t = \alpha + \beta_3 B_{it} \tag{4}$$

where B_{it} is broadband coverage in county i in year t. Taking logs, and substituting for $\lambda_i t$ this results in a modified Eq. (2) which reads as follows (where $lnA_0 + \alpha = \beta_0$):

$$logQ_{it} = \beta_0 + \beta_1 logK_{it} + \beta_2 logL_{it} + \beta_3 B_{it} \tag{5}$$

To Eq. (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 neighboring counties, we consider a spatial dependence using an inverse distance weight matrix that defines the proximity of neighboring 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 neighboring counties $j \neq i$ and denoted with $\boldsymbol{W} B_{jt}^{NB}$ where *NB* refers to a set of nearest neighboring counties (further described in Section 3.2.3). 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 analyze broadband deployment in German counties where the effects of broadband can unfold both within and across counties. On the one hand, broadband availability in neighboring counties might induce positive externalities ("spill-over effects") due to various impacts, e.g. employment effects in neighboring counties, which might also create economic growth in the focal 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 neighboring counties comparatively more competitive, leading to migration and an erosion of value added and employment in the focal county ("beggar-thy-neighbor").

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 stages in broadband availability and adoption in different counties (Gruber and Verboven, 2001; Czernich et al., 2011, p. 511). Note that the variable *years_since* is different from a linear time trend, as broadband in German counties was introduced in different years resulting in a different number of zero values across counties at the beginning of the deployment period. It indeed takes time until broadband coverage on side of operators translates into broadband adoption on side of consumers with the latter actually capturing the main welfare effects;

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

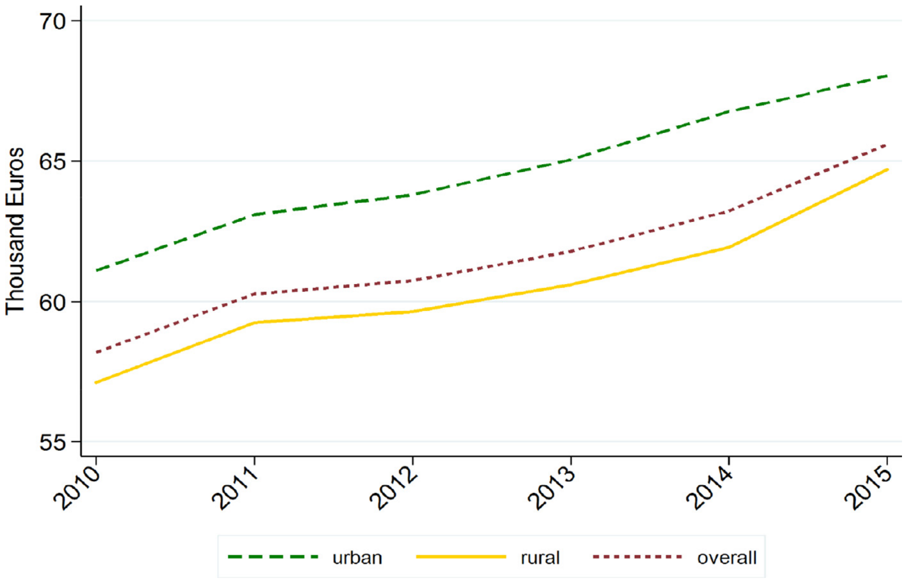

Fig. 1. Average GDP per capita (in thousands of euros) in German counties.

hence the more time has passed since the first introduction of broadband, the higher are broadband service utilization by consumers and hence welfare related GDP effects.

Our final baseline specification reads as follows:

$$\begin{aligned}&logGDP_{it} = \beta_0 + \beta_1 logK_{it} + \beta_2 logL_{it} + \beta_3 B_{it} + \beta_4 logEDUC_{it} + \\ &+ \beta_5 \boldsymbol{W} K^{NB}_{jt} + \beta_6 \boldsymbol{W} L^{NB}_{jt} + \beta_7 \boldsymbol{W} EDUC^{NB}_{jt} + \beta_8 \boldsymbol{W} B^{NB}_{jt} + \\ &\beta_9 year\_since_{it} + \alpha_i + \epsilon_{it}\end{aligned} \tag{6}$$

where the additive error term, ε_{it}, is capturing random variations between counties and time. Including fixed effects (α_i) ensures that individual county-level effects capture any time-invariant unobserved heterogeneity (for the important role of fixed effects in explaining broadband expansion see Section 4). According to the spatial econometrics literature (Elhorst, 2014), we specify a global instead of a local spillover model which includes spatial lags of all main explanatory variables reflecting that all regional observations might be related to each other but near regions are more related than distant ones.

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 data on our capital and labor controls as well as 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 2406 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 (Sections 3.2.2 and 3.2.3) in more detail. Section 3.2.4 then describes the variables used to proxy labor and capital stocks.

3.2.1. Dependent variable: GDP per capita in German counties

According to our empirical specification and in line with Czernich et al. (2011) our dependent variable measures the log of GDP per capita, denoted with $log(GDP\_pc)$.[10] Fig. 1 shows average annual GDP per capita which is measured 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. Average annual GDP growth is more moderate in the interim years. In the average German county, GPD per 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.

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[7] See https://www.bmvi.de/DE/Themen/Digitales/Breitbandausbau/Breitbandatlas-Karte/start.html (last accessed on October 25th 2020).

[8] See https://www-genesis.destatis.de/genesis/online (last accessed on October 25th 2020).

[9] See http://www.inkar.de/ (last accessed on October 25th 2020).

[10] Note that we normalized GDP to the working age population.

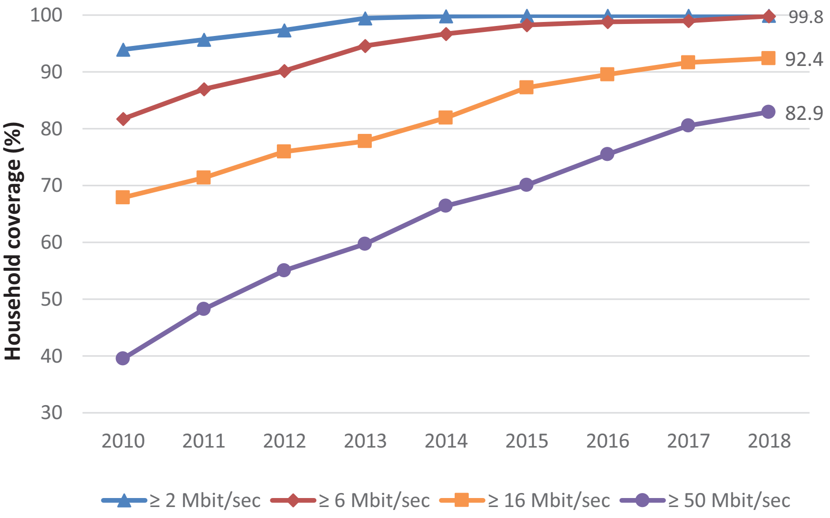

Fig. 2. Percentage of German households with broadband coverage split by bandwidth levels.

3.2.2. Explanatory variables: average broadband speed

Fig. 2 reports the national average German household coverage for different bandwidth levels based on all relevant wireline and wireless access technologies. Broadband coverage or availability is a pre-condition for broadband adoption on the demand side and an important input factor according to our production function approach. Fig. 2 shows that there are substantial differences between high-speed broadband ($\geq$ 50 Mbit/s) and basic broadband ($\leq$ 16 Mbit/s). 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. Note that the gap between 16 and 50 Mbit/s is also substantially different in terms of technological infrastructure requirements and feasible applications for consumers. Furthermore, Fig. 2 shows that there has been an almost ubiquitous coverage with elementary broadband internet access ($\geq$ 2 Mbit/s) 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 liberalization in EU member states in the end of the 1990s.

Our main explanatory variable is average broadband speed, *broadband_speed*. It is measured as the percentage of households covered with bandwidth,[11] where bandwidth is averaged over different download speed ranges (≥ 1, ≥ 2,≥ 6, ≥ 16 and ≥ 50 Mbit/s) weighted with the respective household coverage shares ($HH_{50Mbit/s}$, $HH_{16Mbit/s}$, …).[12] Eq. (7) below shows the construction of average broadband speed.

$$\begin{aligned} broadband\_speed = \{ & \left(HH_{50MBit/s} \times\ 50\right) + \left(\left(HH_{16MBit/s} - HH_{50MBit/s}\right) \times \tfrac{50+16}{2}\right) \\ & + \left(\left(HH_{6MBit/s} - HH_{16MBit/s}\right) \times \tfrac{16+6}{2}\right)\ + \left(\left(HH_{2MBit/s} - HH_{6MBit/s}\right) \times \tfrac{6+2}{2}\right) \\ & + \left(\left(HH_{1MBit/s} - HH_{2MBit/s}\right) \times \tfrac{2+1}{2}\right) + \left(\left(100 - HH_{1MBit/s}\right) \times \tfrac{1+0}{2}\right)\}\ \times\ 0.01 \end{aligned} \tag{7}$$

By constructing our average broadband speed variable as shown in Eq. (7), we employ all information available on household bandwidth coverage in each county. Moreover, by taking the differences between the respective speed levels, we explicitly take care of overlaps, so that no household is counted twice.[13]

Following our research questions, we consider bandwidth levels of $\geq$ 50 Mbit/s as high-speed broadband, which requires at least partial use of fiber optic transmission technologies. This also fulfills the ubiquitous household coverage target as foreseen in the DAE ($\geq$ 30 Mbit/s) and also the more ambitious coverage target of the German government ($\geq$ 50 Mbit/s) in its "Digital Agenda 2014–2017" strategy. Fig. 3 shows the distribution of bandwidth among households and the resulting average broadband speed for an example county (Merzig-Wadern) in the years 2010, the first year of our observation period (left) and 2015, the last year of the observation period (right). As can be seen, a right shift of the curve, i.e. higher shares of coverage with $\geq$ 50 Mbit/s bandwidth levels, leads to a substantially higher average speed level at the end of our period of observation. In fact, most of the network investment activities during our period of analysis resulted in higher shares of

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[11] Note that although our broadband data measure household coverage, underlying broadband bandwidth levels are also subscribed by most SMEs who show similar broadband demand patterns in particular with respect to our period of analysis where high bandwidth demanding business applications did not exist; a notable exception was "Skype business" featuring video conferences for business meetings.

[12] Note that whereas our data measure nominal (theoretical) speed levels, actual speed levels are typically lower as some broadband technologies are subject to a significant dissipation effect with distance (such as hybrid copper-fiber networks) or represent a shared access medium in the last segment of the network (such as cable TV networks).

[13] As parts of our robustness analysis and as suggested by a referee, we also constructed an alternative measure of average broadband speed where only the respective lower bounds are considered in terms of a "worst-case" measurement (definition and results are reported in the Appendix in Table A.3).

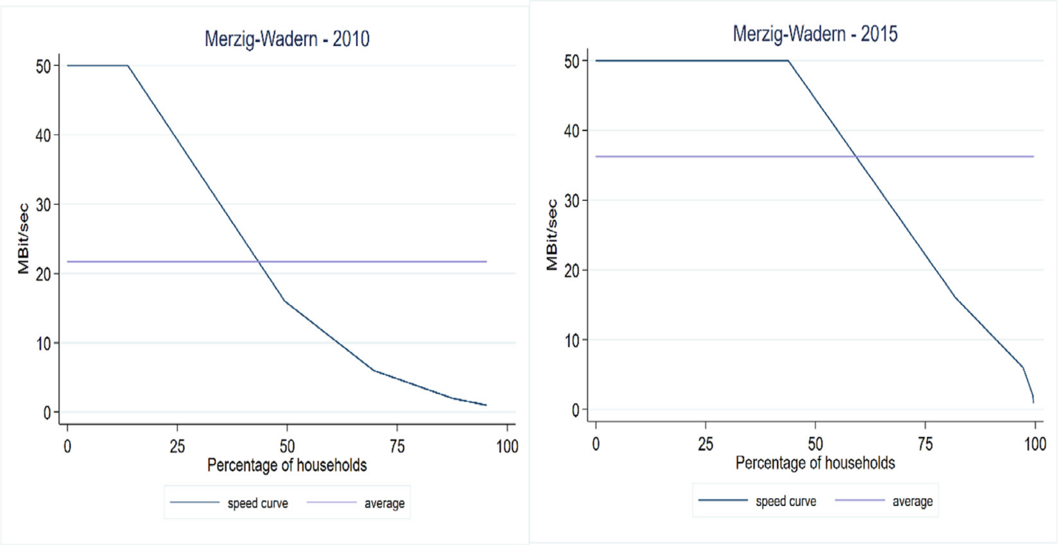

Fig. 3. Speed curve for an example county (Merzig-Wadern).

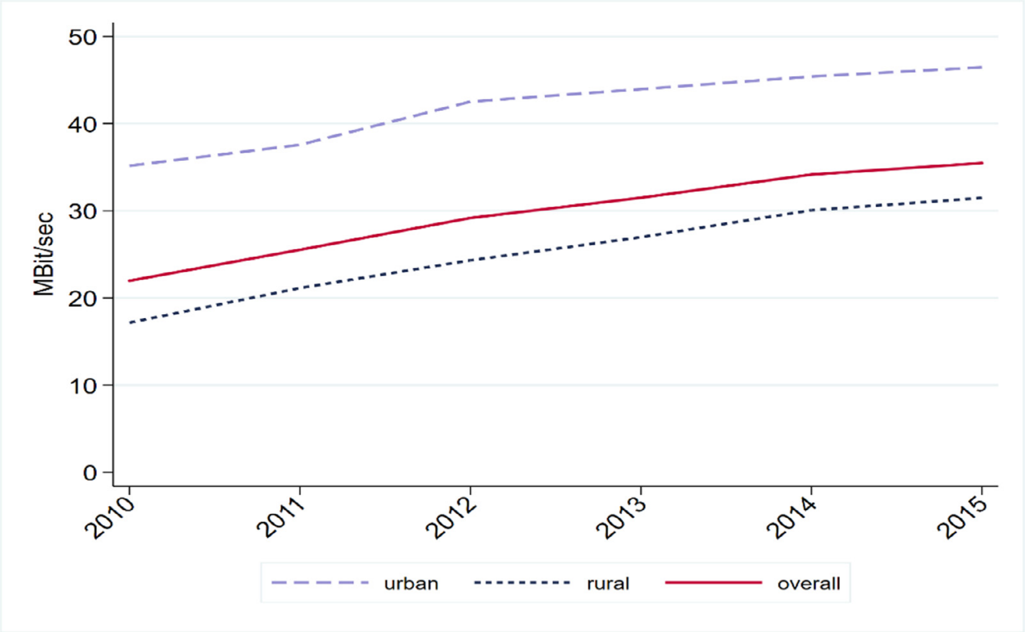

Fig. 4. German average broadband coverage (Mbit/s) split by urban and rural counties.

coverage with $\geq$ 50 Mbit/s. In the case of this example, this leads to an increase of 14.53 Mbit/s (21.71 Mbit/s compared to 36.24 Mbit/s) in average speed.

Fig. 4 shows that German household average broadband speed exhibits substantial and persistent gaps between urban and rural counties reflecting a "digital divide".

3.2.3. Explanatory variables: average broadband in neighboring counties

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

$$broadband\_speed_{jt}^{NB} = \sum_{j=1}^{5} weight_{jt} \times broadband\_speed_{jt} \tag{8}$$

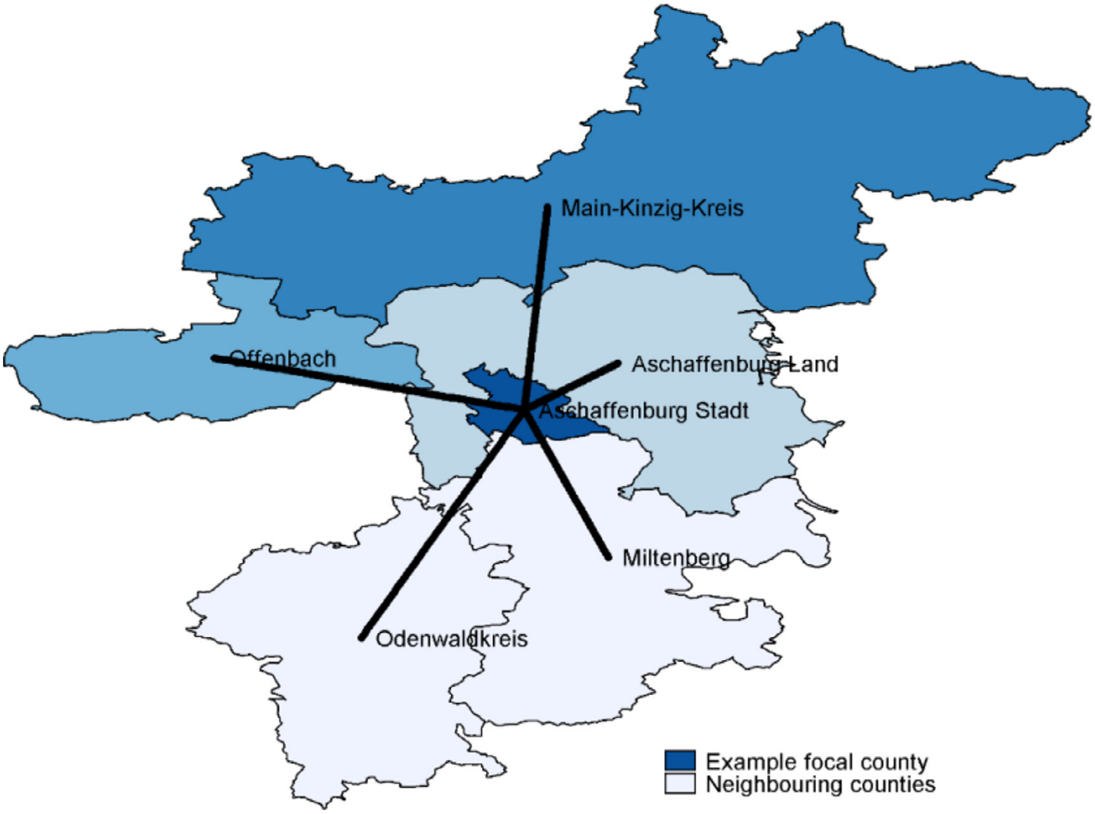

Fig. 5. Example construction of focal county with five closest neighboring counties.

where

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

where “max(•)” refers to the maximum distance across Germany. Accordingly, the lower the linear distance to focal county i is, the higher is the individual weight of neighboring county j in year t, $weight_{jt}$. Furthermore, individual weights are normalized ($\frac{weight_{jt}}{\sum_{i=1}^{5} weight_{jt}}$), so that $0 < weight_{jt} < 1$. As the weights in the weighting matrix sum to one, we take care that all neighboring counties are considered only proportionally so that there is no double (or multi-fold) counting. The coefficient β^{NB} measures the average of those incoming spillovers on the focal county and the sum $\beta + \beta^{NB}$ measures the sum of the average direct and indirect effects.[14]

Fig. 5 illustrates the construction of the average neighbor variable based on five neighboring counties. We show by way of example the focal county, Aschaffenburg Stadt, with its neighboring 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 center.

3.2.4. Control variables: capital and labor inputs

The capital accumulation variable, denoted with *capital*, is proxied by subtracting labor 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 labor accumulation variable, denoted with *labor*, is defined as the number of employees with social insurance as measured at place of residence per 100 residents. Following our baseline specification in Eq. (6), we take logs of our capital and labor control variables.

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[14] Another 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). Instead of specifying more generic spatial autocorrelation models, we apply panel data to control for fixed effects using various estimators as suggested e.g. in Gibbons and Overman (2012).

4. Estimation and identification strategy

Estimating Eq. (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. Thus, the profitability gap and therefore subsidies are, 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 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 GDP (Eq. (6)).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. For this reason, we cannot apply this variable as an instrument in a fixed effects estimator, but we can apply this cost control within an instrumental variable (IV) regression framework. This also holds for other potential instruments which have been used in other studies, such as instrumental variables related to the underlying legacy characteristics of broadband networks (number of ducts and street cabinets, length of local loops, etc.), which however, show hardly or no variation within time. Conversely, time varying variables measuring population or urbanization are further important determinants of deployment costs but cannot be considered as an exogenous source of variation.

Second, in view of the potentially strong role of fixed effects (α_i), we employ a *fixed effects* estimator (without the instrumental variable). 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 $E(\varepsilon_{it}|\boldsymbol{x}_{i1,\ldots,}\ \boldsymbol{x}_{iT,}\ \alpha_i) = E(\varepsilon_{it}|\boldsymbol{x}_{it,}\ \alpha_i) = 0$ (Cameron and Trivedi, 2005, p. 727), where $\boldsymbol{x}_{it}$ represents the vector of covariates as specified in Eq. (6). Strict exogeneity rules out any contemporaneous, past and future correlation of regressors and idiosyncratic 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 strongly impacted by topographical factors such as ground conditions and stable 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. Therefore, broadband infrastructure represents a long-run investment decision that relies on the expectation of stable market 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 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 5.2). 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, pp. 1796–1797) conclude as follows: „We find that 84% of the variation in broadband availability can be attributed to time-invariant municipality characteristics and common time effects, while 1% of the variation in broadband availability can be attributed to a large set of time-varying variables.“

Third, we estimate Eq. (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 (α_i) which are differenced out. 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

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[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 5.2).

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 outcome 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 the combination of fixed effects, the lack of good external instruments and 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 (Eq. (6)) applying instrumental variable (IV) and fixed effects (FE) estimation techniques. Further robustness analysis including the Arellano–Bond (AB) estimator, a different measure of average broadband speed and a different specification of the weighting matrix is provided in the Appendix (Tables A.3–A.5). Based on our main estimation results, Section 5.2 then presents a rudimentary cost-benefits analysis.

5.1. Fixed effects and instrumental variables estimation results

Estimation results of our baseline equation are reported in Table 1 below. Fixed effects (“FE”) regression results in columns (1), (3), (4) and (6) are based on robust standard errors. The *F*-test (all $\alpha_i = 0$) 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, IV estimates 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 models identifying assumption (i.e. $E(\alpha_i|\boldsymbol{x}_i) = E(\alpha_i) = 0$) 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. Overall, our fixed effects specification explains at least 83% of the relevant within variation.

In columns (2) and (5) 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 being an exogenous variable. 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.

Results on the FE and IV estimates with a different number of nearest neighbors (0, i.e. no spatial spillover effects, and 5) are summarized in Table 1. We have limited the number of neighbors and hence the average distance to 5 as the maximum travel time commuters are willing to accept is limited. Whereas the specifications in Table 1 in columns (1) to (3) do not include the respective spatial lag variables (supraindex *NB*), they are included in columns (4) to (6). The coefficient estimates of our broadband variable, *broadband_speed*, vary between 0.0004 and 0.0056 in the specifications in columns (1) to (6). In view of our log-level model specification in Eq. (6), the size of the respective coefficients can be interpreted as follows: an increase in average broadband availability by one percentage point leads to an increase in regional GDP per capita of approximately $100 \times \beta_3$%, i.e. 0.18% (column (1)). In addition to the direct effects of broadband within a certain county, we can also infer a strongly positive and significant effect from the average neighboring county, $broadband\_speed^{NB}$ in columns (4) to (6), with coefficients ranging from 0.0027 to 0.0052. The effect on regional GDP is almost doubled if we also take regional externalities into account (0.31% in column (4)). The resulting combined effect of broadband deployment is significant and positive in all FE and IV specifications.

FE coefficient estimates of our variable measuring the direct impact of broadband appear to be much lower in magnitude than IV coefficients expressing the relevance of fixed effects underlying the broadband deployment process; however, they remain highly significant. Fixed effects coefficient estimates of direct broadband effects (*broadband_speed*) are lower when we also control for the effect from the average neighboring county, $broadband\_speed^{NB}$, which is significant at the 1% level in all specifications reported in columns (4) to (6). In line with IV estimation results, we find strong evidence for spill-over effects in terms of positive externalities from the average broadband deployment in neighboring counties towards a focal county. The average German county thus benefits from regional spill-overs in terms of economic value added.

In terms of the interpretation of marginal effects, our log-level model specification implies that an increase in average broadband speed by 1 unit (i.e. 1 Mbit/s) yields an increase in GDP_pc by a constant percentage value. As this might not be realistic for all levels of broadband speed, we also include a specification with a squared term to allow for a non-linear relationship. Indeed, adding squared terms of average broadband speed, $broadband\_speed^2$ and $broadband\_speed^{2,NB}$, in columns (3) and (6), respectively, indicates diminishing returns beyond a certain threshold value. Fig. 6 visualizes the non-linear (inverted U-shape) relationship with a maximum marginal effect for an average speed value of about 37.4 Mbit/s (inserting exact broadband coefficient estimates in column (3) yields the respective first order condition:

Table 1
Fixed effects (FE) and instrumental variable (IV) estimation results.

	(1) FE no neighbors	(2) IV no neighbors	(3) FE no neighbors	(4) FE 5 neighbors	(5) IV 5 neighbors	(6) FE 5 neighbors
broadband_speed	0.0018***	0.0047***	0.0055***	0.0004***	0.0056***	0.0031***
	(0.0002)	(0.0016)	(0.0006)	(0.0002)	(0.0014)	(0.0005)
broadband_speed ^{NB}				0.0027***	0.0037***	0.0052***
				(0.0003)	(0.0009)	(0.0007)
$\beta + \beta^{NB} = 0$				0.0031***	0.0093***	0.0082***
				(0.0003)	(0.0011)	(0.0007)
broadband_speed ^{2}			−0.0001***			−0.0001***
			(0.0000)			(0.0000)
broadband_speed ^{2,NB}						−0.0001***
						(0.0000)
log(capital/GPD)	0.8799***	1.0553***	0.8805***	0.8846***	1.0346***	0.8802***
	(0.0277)	(0.0857)	(0.0285)	(0.0276)	(0.0919)	(0.0275)
log(higher education)	0.0054*	0.0057	0.0050*	0.0011	0.0124	−0.0004
	(0.0030)	(0.0113)	(0.0028)	(0.0049)	(0.0134)	(0.0047)
log(labor)	0.3946***	0.0507***	0.2812***	0.1671***	0.0531***	0.1369***
	(0.0409)	(0.0094)	(0.0441)	(0.0411)	(0.0099)	(0.0441)
years_since	0.0131***	0.0173***	0.0169***	0.0089***	0.0040	0.0131***
	(0.0010)	(0.0061)	(0.0010)	(0.0010)	(0.0042)	(0.0011)
log(capital/GPD) ^{NB}				0.0477	0.0760	0.0398
				(0.0373)	(0.1113)	(0.0373)
log(higher education) ^{NB}				0.0107*	−0.0523**	0.0136**
				(0.0057)	(0.0207)	(0.0054)
log(labor) ^{NB}				0.2754***	−0.0177	0.2555***
				(0.0621)	(0.0143)	(0.0590)
constant	7.3588***	11.150***	8.5495***	6.8240***	11.407***	7.2988***
	(0.4358)	(0.1203)	(0.4665)	(0.5636)	(0.1827)	(0.5599)
R^2 (within)	0.8358	0.6086	0.8524	0.8661	0.6295	0.8784
DWH (*p*-value)		0.18			0.10	
CDW		322.90			99.68	
KPW		531.66			285.98	
F-test (excl. instr.)		183.22			285.98	
F-test (overall)		128.84			102.93	
F-test (all $\alpha_i = 0$) (*p*-value)	0.0000		0.0000	0.0000		0.0000
Hausman test (*p*-value)	0.0000		0.0000	0.0000		0.0000
# Observations	2406	2406	2406	2406	2406	2406
# Clusters	401	401	401	401	401	401

Notes: Fixed effects and IV estimation estimation for 401 German counties for the period 2010-2015. For the variables *broadband_speed* and *broadband_speed*^{NB} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta + \beta^{NB} = 0$) where supraindex *NB* stands for neighboring counties. All FE regressions include county fixed effects. Broadband variables are instrumented with the variable *apartments_share* in IV regressions. 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.

0.0055287+2 × (−0.0000739) × *broadband_speed=0*). This appears to be quite reasonable as there were hardly any widespread household or SME related broadband services requiring substantially higher bandwidth levels during our period of analysis.

The variable measuring the number of years since broadband has been deployed, *years_since*, exhibits a positive and significant effect on GDP in FE and IV specifications (except for column (5)). 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.

All control variables, except for higher education, are significant and positive as expected. Controls for capital and labor input variables, *log(capital)* and *log(labor),* are 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. Adding the

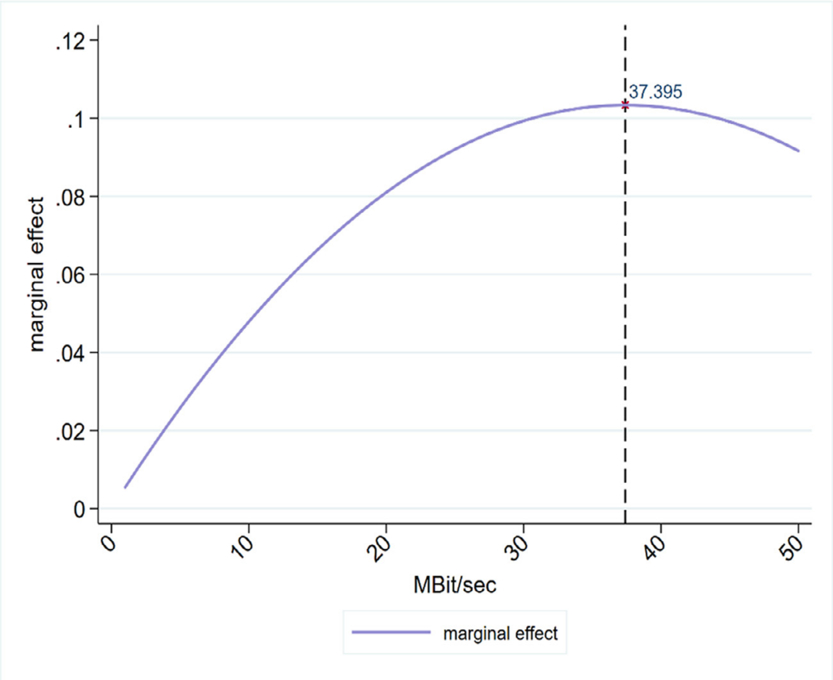

Fig. 6. Marginal effects of higher average broadband household coverage.
(Broadband related coefficients are taken from specification in column (3) in Table 1.)

coefficients of our capital and labor variables, we find values for the sum of both coefficients slightly higher than one suggesting slightly increasing returns to scale. Comparing this result with estimates of the relevant literature, we find that there is considerable variation. Whereas the sum of estimated capital and labor coefficients is quite in the same range in Koutroumpis (2009) it is considerably lower in Czernich et al. (2011).

Table 2 and Table 3 report separate FE estimation results for urban and rural German counties, respectively. 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 in rural areas. Similarly, spillover effects from neighboring counties are stronger in rural counties than in urban counties. Intuitively, distance as well as neighboring counties also matter much more on the countryside than in urban agglomerations where people and firms are nearby anyway. Lower coefficient estimates for urban counties can also be explained in view of diminishing returns beyond the optimal level of bandwidth (i.e., 37.4 Mbit/s). Whereas the average broadband speed mean in urban counties is 41.84 Mbit/s, it is only 25.19 Mbit/s in rural counties and hence still below the optimal broadband speed.

The Appendix presents further analysis to validate the robustness of our main results. Robustness checks are based on a different construction of the average speed variable with lower bandwidth bounds instead of bandwidth intervals (worst case bandwidth levels), an alternative weighting matrix with a different number of neighboring counties (15 instead of 5) and a different estimator (GMM instead of FE and IV) in Tables A.3 to A.5, respectively. The basic structure of coefficient estimates remains similar to our FE and IV estimation results in Table 1, although the direct effects of broadband deployment are higher for GMM coefficient estimates. At the same time, the coefficient estimates for indirect effects and for the squared term of broadband are rather similar to our corresponding FE estimates.

5.2. Costs and benefits of the “Digital Agenda 2014–2017” strategy

In order to achieve its ubiquitous coverage goal (i.e. availability of 50 Mbit/s bandwidth 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

Table 2
Fixed effects estimation results for urban counties.

	(1) FE urban	(2) FE urban	(3) FE urban	(4) FE urban
broadband_speed	0.0005**	−0.0000	0.0002	−0.0000
	(0.0003)	(0.0012)	(0.0002)	(0.0010)
broadband_speed ^{NB}			0.0015***	0.0034***
			(0.0004)	(0.0010)
$\beta + \beta^{NB} = 0$			0.0017***	0.0034**
			(0.0004)	(0.0014)
broadband_speed ^{2}		0.0000		0.0000
		(0.0000)		(0.0000)
broadband_speed ^{2,NB}				−0.0000*
				(0.0000)
log(capital/GPD)	0.8309***	0.8300***	0.8274***	0.8186***
	(0.0433)	(0.0424)	(0.0471)	(0.0457)
log(higher education)	−0.0002	0.0000	−0.0059	−0.0097
	(0.0066)	(0.0066)	(0.0126)	(0.0128)
log(labor)	0.0953	0.0926	0.0936	0.1068
	(0.0906)	(0.0913)	(0.0797)	(0.0793)
years_since	0.0225***	0.0224***	0.0215***	0.0223***
	(0.0016)	(0.0016)	(0.0027)	(0.0027)
log(capital/GPD) ^{NB}			0.0335	0.0066
			(0.0778)	(0.0821)
log(higher education) ^{NB}			0.0080	0.0127
			(0.0112)	(0.0113)
log(labor) ^{NB}			−0.1011	−0.1100
			(0.0982)	(0.0983)
constant	10.6406***	10.6765***	11.7479***	11.6531***
	(0.9852)	(0.9963)	(1.5756)	(1.5530)
R^2 (within)	0.8829	0.8832	0.8889	0.8916
F-test (all $\alpha_i = 0$) (*p*-value)	0.0000	0.0000	0.0000	0.0000
Hausman test (*p*-value)	0.0000	0.0000	0.0000	0.0000
# Observations	642	642	642	642
# Clusters	107	107	107	107

Notes: Columns (1) to (4) report the results of FE estimation results for 642 urban German counties for the period 2010–2015. Broadband coverage is measured as percentage of households covered with average broadband bandwidth speeds as calculated in Eq. (7). For the variables *broadband_speed* and *broadband_speed*^{NB} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta + \beta^{NB} = 0$) where supraindex *NB* stands for neighboring counties. Columns (1) to (4) 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

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/s reached only 82.9% at the end of 2018 (Fig. 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 ubiquitous 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 from 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. However, it would be unrealistic to assume that all of the observed broadband coverage growth was due to public spending. We therefore borrow from a recent and most related study by Briglauer et al. (2019) who have looked at the impact of broadband subsidies on broadband availability. The authors found that municipalities in the German state of Bavaria that

Table 3
Fixed effects estimation results for rural counties.

	(1) FE rural	(2) FE rural	(3) FE rural	(4) FE rural
broadband_speed	0.0023*** (0.0003)	0.0090*** (0.0006)	0.0003 (0.0002)	0.0055*** (0.0007)
broadband_speed ^{NB}			0.0029*** (0.0003)	0.0038*** (0.0009)
$\beta + \beta^{NB} = 0$			0.0033*** (0.0003)	0.0092*** (0.0008)
broadband_speed ^{2}		−0.0002*** (0.0000)		−0.0001*** (0.0000)
broadband_speed ^{2,NB}				−0.0000** (0.0000)
log(capital/GPD)	0.9178*** (0.0341)	0.9141*** (0.0323)	0.9111*** (0.0339)	0.9059*** (0.0317)
log(higher education)	0.0051 (0.0031)	0.0073*** (0.0028)	0.0019 (0.0052)	0.0031 (0.0049)
log(labor)	0.4703*** (0.0482)	0.3334*** (0.0430)	0.2062*** (0.0573)	0.1862*** (0.0546)
years_since	0.0088*** (0.0011)	0.0153*** (0.0011)	0.0063*** (0.0010)	0.0122*** (0.0012)
log(capital/GPD) ^{NB}			0.0869** (0.0434)	0.0956** (0.0403)
log(higher education) ^{NB}			0.0089 (0.0066)	0.0089 (0.0061)
log(labor) ^{NB}			0.3276*** (0.0770)	0.2673*** (0.0710)
constant	6.5835*** (0.5115)	7.9794*** (0.4555)	5.8793*** (0.5978)	6.6943*** (0.5760)
R^2 (within)	0.8355	0.8741	0.8681	0.8888
F-test (all $\alpha_i = 0$) (p-value)	0.0000	0.0000	0.0000	0.0000
Hausman test (p-value)	0.0000	0.0000	0.0000	0.0000
# Clusters	1764	1764	1764	1764
# Observations	294	294	294	294

Notes: Columns (1) to (4) report the results of FE estimation results for 1764 rural German counties for the period 2010–2015. Broadband coverage is measured as percentage of households covered with average broadband bandwidth speeds as calculated in Eq. (7). For the variables *broadband_speed* and *broadband_speed*^{NB} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta + \beta^{NB} = 0$) where supraindex *NB* stands for neighboring counties. Columns (1) to (4) 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

received state aid during the 2010–2012 funding period experienced on average an increase in broadband coverage of about 22% (causal effect due to the public funding).

As we want to assess the impact of average broadband speed on GDP per capita, we have to translate coverage increases induced by public funding into average speed increases. For this reason, we estimate the functional relationship between coverage with bandwidth ≥ 50 Mbit/s ($HH_{50\mathrm{MBit/sec}}$) and average broadband speed (*broadband_speed*) in a bivariate fixed effects regression. The respective coefficient is about 0.3, indicating that an increase in high-speed broadband coverage by one percentage point increases average bandwidth by 0.3 Mbit/s. In order to make a conservative estimate of total benefits, we draw on the FE coefficient estimates related to the variables *broadband_speed* and *broadband_speed*^{NB} which are lower than respective IV estimates. Moreover, in order to assess costs and benefits related to the ubiquitous coverage goal of the "Digital Agenda 2014–2017", we rely on the lowest FE coefficient estimates of combined effects as reported in column (4) in Table 1 (0.0031). The percentage change in *GDP_pc* in the 2015–2018 period therefore is:

$$\%\Delta GDP\_pc = \%\Delta broadband \times 0.22 \times 0.3 \times 0.0031 \times 100 \tag{9}$$

where $\%\Delta$ broadband refers to the effective unit change in percentage points of broadband infrastructure coverage in the funding period 2015–2018. According to Fig. 2, the 50 Mbit/s coverage level was about 70% in 2015 and about 83% in 2018, hence $\%\Delta broadband$ was about 13 percentage points. For simplicity, we further assume linear coverage growth over the period 2015–2018. This percentage point increase is multiplied by 0.22 assuming that on average about 22% of the observed increase in broadband coverage was due to public funding measures, and then multiplied by 0.3 to translate coverage into average speed increases. The additional funding induced broadband deployment of 2.86 percentage points (13×0.22) and an additional increase in average bandwidth by about 0.86 Mbit/s (2.86×0.3). Evaluated at the grand mean of our outcome variable (Table A.2: $\overline{GDP\_pc} = €61646.36$) this ultimately yields an increase in average GDP per capita in the 2015–2018 period of about €164 ($0.86 \times 0.31 \times 61,646.36$. This number 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) even for our most conservative estimates. 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 – based on conservative estimates – that there is a clear case for public intervention to fund broadband deployment in German counties. The high relevance of regional spillovers also indicates the importance of coordinated funding policies in order to accrue positive externalities in neighboring rural counties.

6. 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 investigated the extent of effects due to broadband deployment both within counties and across neighboring counties. Broadband deployment in our period of analysis was largely driven by investment in high-speed broadband infrastructure enabling at least 50 Mbit/s.

Whereas spatial externalities among counties 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 neighboring counties. Whereas an increase in average bandwidth by one unit (1 Mbit/s) increases regional GDP by about 0.18%, according to our main fixed effects estimation results, this effect is almost doubled (0.31%) when we also take regional externalities into account. When comparing urban and rural counties, we find a stronger impact of broadband for rural counties, for both direct and indirect effects. In line with the previous literature, direct and indirect effects are, however, subject to diminishing returns with an optimal speed level substantially below the 50 Mbit/s policy target of the “Digital Agenda 2014–2017”. Our main findings appear to be robust with respect to different panel estimators and the definition of neighboring counties and the measurement of average bandwidth.

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 neighboring counties exceeded the cost of public subsidies for high-speed broadband expansion. 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.

Moreover, our analysis likely underestimates the true welfare gains related to broadband expansion for the following reasons: first, the future impacts of high-speed 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*). 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. We captured this aspect only indirectly using availability related data and introducing the variable *years_since*. 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). Finally, the current pandemic COVID-19 crisis shows the utmost importance of the digital economy to mitigate the massive damage of global economic and social shutdowns. Apparently, the economic loss would be much higher, if economic transactions could not be realized or substituted via online platforms (e-government, e-learning, tele-working, etc.) based on sufficient broadband quality and underlying digital infrastructures. Although the extent of digital economies varies significantly among industries, digital platforms and underlying infrastructures provide another major source of a positive externality during an economic crisis. Whereas this externality might be massive it has not been considered in the literature focusing on “normal” economic times. Taking this particular externality into account, however, provides another strong reason for public funding and lending to invest in digital infrastructures and networks. This might also include funding for investments in substantial and high-quality back-up capacities in view of peak usage and internet traffic in another upcoming similar crisis.

Future research should also 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.

CRediT authorship contribution statement

Wolfgang Briglauer: Conceptualization, Methodology, Writing - original draft. **Niklas Dürr:** Data curation, Software, Visualization. **Klaus Gugler:** Conceptualization, Methodology.

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Appendix

Tables A.1–A.5

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_speed	Average broadband household access in a certain county, where household coverage is averaged with respect to specific ranges of bandwidth (≥ 1 Mbit/s, ≥ 2Mbit/s, ≥ 6 Mbit/s, ≥16 Mbit/s, ≥50 Mbit/s)	Breitbandatlas/TÜV Rheinland
broadband_speed ^{NB}	Average broadband household access of the five closest neighboring counties, where household coverage is averaged with respect to specific ranges of bandwidth (≥ 1 Mbit/s, ≥ 2Mbit/s, ≥ 6 Mbit/s, ≥16 Mbit/s, ≥50 Mbit/s). Individual neighboring counties are weighted by their inverse linear distance (beeline) to center of focal county	Breitbandatlas/TÜV Rheinland
years_since	Number of years that have passed since the share of households with access to at least 16 Mbit/s exceeds the first quartile	
Control variables		
capital	Capital accumulation defined as gross value added minus labor income divided by GDP	INKAR
labor	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	4,868,360,000	7,768,240,000	578,105,088	88,095,793,152
GDP_pc	2406	61646.4	11366.7	41,100	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
labor	2406	72678.3	97919.7	11,879	1,311,413
log(labor)	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_speed	2406	29.63	11.64	1.81	49.96
broadband_speed ^{NB}	2406	30.48	8.35	8.00	48.49
years_since	2406	2.346	1.963	0	6
apartments_share	2406	54.51	19.54	10.40	88.50

Table A.3
FE and IV estimation results with worst case measure of average speed.

	(1) FE no neighbors	(2) IV no neighbors	(3) FE no neighbors	(4) FE 5 neighbors	(5) IV 5 neighbors	(6) FE 5 neighbors
broadband_speed	0.0010***	0.0041***	0.0023***	0.0001	0.0049***	0.0019***
	(0.0001)	(0.0014)	(0.0004)	(0.0001)	(0.0012)	(0.0004)
broadband_speed ^{NB}				0.0019***	0.0029***	0.0039***
				(0.0003)	(0.0009)	(0.0007)
$\beta + \beta^{NB,}= 0$				0.0021***	0.0078***	0.0058***
				(0.0002)	(0.0009)	(0.0005)
broadband_speed ^{2}			−0.0000***			−0.0000***
			(0.0000)			(0.0000)
broadband_speed ^{2,NB}						−0.0001***
						(0.0000)
log(capital/GPD)	0.8818***	1.0549***	0.8829***	0.8851***	1.0434***	0.8738***
	(0.0276)	(0.0862)	(0.0278)	(0.0283)	(0.0929)	(0.0278)
log(higher education)	0.0050	0.0054	0.0053*	0.0011	0.0122	0.0009
	(0.0031)	(0.0111)	(0.0031)	(0.0051)	(0.0133)	(0.0048)
log(labor)	0.4588***	0.0483***	0.4517***	0.1650***	0.0512***	0.1408***
	(0.0429)	(0.0098)	(0.0427)	(0.0443)	(0.0102)	(0.0462)
years_since	0.0135***	0.0181***	0.0145***	0.0089***	0.0064	0.0122***
	(0.0010)	(0.0058)	(0.0010)	(0.0011)	(0.0040)	(0.0011)
log(capital/GPD) ^{NB}				0.0466	0.0532	0.0200
				(0.0384)	(0.1175)	(0.0370)
log(higher education) ^{NB}				0.0091	−0.0566***	0.0141**
				(0.0060)	(0.0208)	(0.0056)
log(labor) ^{NB}				0.3812***	−0.0216	0.3222***
				(0.0639)	(0.0146)	(0.0617)
constant	6.6922***	11.2141***	6.7672***	5.7414***	11.5588***	6.5661***
	(0.4594)	(0.1328)	(0.4574)	(0.5781)	(0.1908)	(0.5739)
R^2 (within)	0.8237	0.6006	0.8251	0.8547	0.6304	0.8678
DWH (*p*-value)		0.00			0.04	
CDW		80.93			96.45	
KPW		157.86			255.53	
F-test (excl. instr.)		157.14			253.94	
F-test (overall)		127.73			99.82	
F-test (*p*-value)	0.0000		0.0000	0.0000		0.0000
Hausman test (*p*-value)	0.0000		0.0000	0.0000		0.0000
# Observations	2406	2406	2406	2406	2406	2406
# Clusters	401	401	401	401	401	401

Notes: Fixed effects and IV estimation estimation for 401 German counties for the period 2010–2015. All FE regressions include county fixed effects and an alternative measure of average broadband speed. For the variables *broadband_speed* and *broadband_speed*^{NB} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta + \beta^{NB} = 0$) where supraindex *NB* stands for neighboring counties. Significance at * 10%, ** 5% and *** 1% levels. Average broadband speed for the worst case based on lower bandwidth bounds (*broadband_speed*^{lb}) is calculated as follows: *broadband_speed*^{lb} $= \{(HH_{50MBit/s} \times 50) + ((HH_{16MBit/s} - HH_{50MBit/s}) \times 16)$
$+((HH_{6MBit/s} - HH_{16MBit/s}) \times 6)$
$+((HH_{2MBit/s} - HH_{6MBit/s}) \times 2)$
$+((HH_{1MBit/s} - HH_{2MBit/s}) \times 1) + ((100 - HH_{1MBit/s}) \times 0)\} \times 0.01$.

Table A.4
FE and IV estimation results with different number of neighboring counties.

	(1) FE 15 neighbors	(2) IV 15 neighbors	(3) FE 15 neighbors
broadband_speed	0.0002	0.0060***	0.0026***
	(0.0001)	(0.0013)	(0.0005)
broadband_speed ^{NB}	0.0034***	0.0047***	0.0066***
	(0.0003)	(0.0010)	(0.0007)
$\beta + \beta^{NB}= 0$	0.0036***	0.0106***	0.0091***
	(0.0003)	(0.0010)	(0.0007)
log(capital/GPD)	0.8927***	1.0508***	0.8869***
	(0.0285)	(0.0903)	(0.0285)
log(higher education)	−0.0007	0.0221	−0.0028
	(0.0048)	(0.0151)	(0.0046)

(*continued on next page*)

Table A.4 (*continued*)

	(1) FE 15 neighbors	(2) IV 15 neighbors	(3) FE 15 neighbors
log(labor)	0.1317***	0.0540***	0.1092**
	(0.0428)	(0.0099)	(0.0447)
years_since	0.0077***	0.0005	0.0120***
	(0.0010)	(0.0041)	(0.0011)
log(capital/GPD) ^{NB}	0.0393	0.0625	0.0281
	(0.0471)	(0.1398)	(0.0472)
log(higher education) ^{NB}	0.0135**	−0.1011***	0.0188***
	(0.0057)	(0.0272)	(0.0056)
log(labor) ^{NB}	0.2999***	−0.0259	0.3288***
	(0.0708)	(0.0162)	(0.0650)
broadband ^{2}			−0.0000***
			(0.0000)
broadband ^{2NB}			−0.0001***
			(0.0000)
constant	6.9290***	11.5948***	6.7804***
	(0.6063)	(0.2054)	(0.5931)
R^2 (within)	0.8735	0.6378	0.8848
F-test (all $\alpha_i = 0$) (p-value)	0.0000	0.0000	0.0000
Hausman test ($E(\alpha_i \vert \boldsymbol{x}_i) = 0$) ($p$-value)	0.0000	0.0000	0.0000
# Observations	2406	2406	2406
# Clusters	401	401	401

Notes: Columns (1) and (2) report FE estimation results whereas column (2) reports IV estimation restuls for 401 German counties for the period 2010–2015 with an alternative number of neigbouring counties. For the variables *broadband_speed* and *broadband_speed*^{NB} point estimates and standard errors are provided for the linear combinations of respective parameters ($\beta + \beta^{NB} = 0$) where supraindex *NB* stands for neighboring counties (15 instead of 5). Columns (1) and (3) 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 A.5
Arellano–Bond (AB) system-GMM estimation results.

Dependent variable: *log(GDP_pc)*	(1) AB no neighbors	(2) AB no neighbors	(3) AB no neighbors	(4) AB 5 neighbors
broadband_speed	0.0053***	0.0049***	0.0031***	0.0018***
	(0.0012)	(0.0011)	(0.0006)	(0.0006)
broadband_speed ^{NB}				0.0026**
				(0.0013)
broadband_speed ^{2}		−0.0000**		
		(0.0000)		
$\beta + \beta^{NB} = 0$				0.0044***
				(0.0010)
log(capital/GPD)	1.1116***	1.0214***	1.0422***	1.2019***
	(0.1160)	(0.0373)	(0.0586)	(0.1466)
log(higher education)	0.0660**	0.0238**	0.0156	0.2663***
	(0.0286)	(0.0106)	(0.0160)	(0.0979)
log(labor)	0.1129***	0.1082***	0.0962***	0.0732**
	(0.0153)	(0.0115)	(0.0134)	(0.0309)
years_since	0.0127***	0.0192***	0.0170***	0.0130***
	(0.0026)	(0.0009)	(0.0014)	(0.0024)
log(capital/GPD) ^{NB}				−0.2413
				(0.1984)
log(higher education) ^{NB}				−0.2353**
				(0.1021)

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Table A.5 (*continued*)

Dependent variable: *log(GDP_pc)*	(1) AB no neighbors	(2) AB no neighbors	(3) AB no neighbors	(4) AB 5 neighbors
log(labor) ^{NB}				0.0402
				(0.0375)
constant	10.3068***	10.4715***	10.6616***	10.3220***
	(0.2080)	(0.1390)	(0.1542)	(0.3122)
Hansen (*p*-value)	0.520	0.994	0.051	0.423
AR(1) (*p*-value)	0.000	0.016	0.080	0.002
AR(2) (*p*-value)	0.605	0.162	0.777	0.116
# Clusters	401	401	401	401
# Observations	2406	2406	2406	2406

Notes: Columns (1) to (4) use system-GMM estimation (Arellano and Bover, 1995; Blundell and Bond, 1998) for 401 German counties for the period 2010–2015. Individual fixed effects are differenced out and a constant term is added as in FE regressions. For the variables *broadband_speed* and *broadband_speed*^{NB} point estimates and standard errors are provided for the test $\beta + \beta^{NB} = 0$. Broadband coverage variables in first differences are instrumented with their own lagged levels and first differences. Column (3) additionally employs our external instrumental variable *apartments_share*. 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.

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