Future Technology Hubs or Backwater?
Lessons on Structural Change from Germany's Coal Regions

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This paper studies the structural adjustment from natural resource-intensive industry- to knowledge-based growth. The closure of coal mines in Germany over 1975-2017 produces local labor market shocks that reveal how the presence of natural resources and international competition may affect the rise and fall of regions. Employing register data on all workers and establishments from Germany and geo-coded data on patents, coal mines and universities, we show that the loss of mining jobs triggers massive employment reductions in the entire manufacturing sector, especially in steel, but also in services industries. This is evidence for both input- and demand linkages through mining that create local agglomeration benefits. Second, mine closures lead to accelerated local restructuring in some but not all regions. Heterogeneity in the performance of former mining regions has increased. Generally, firms become more nimble, with average plant size falling, and mine closures lead to rapid job growth in IT and R&D. Moreover, employing linked patent-patentee data we show that mine closures can increase regional innovative activity. Preliminary findings indicate that knowledge-based growth is generated especially in regions that newly create universities of applied sciences. We outline a specific-factors, Rosen (1979)- Roback (1982) model to quantify aggregate implications.

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1 Introduction

As most countries exhibit vast differences in income across their cities and regions, the shift from industry to knowledge-based growth has led to an increase in global competition in which old sources of advantage are destroyed while new sources are created. Why has globalization contributed to urban decline in some cities and urban renaissance in others? Coal deposits, as a low-cost source of nearby energy supply, have been a key advantage during the era industry-led growth. In this paper, we use the German coal regions as a lens to study how international competition affects the rise and fall of regions in a world in which the nature of economic growth is changing.

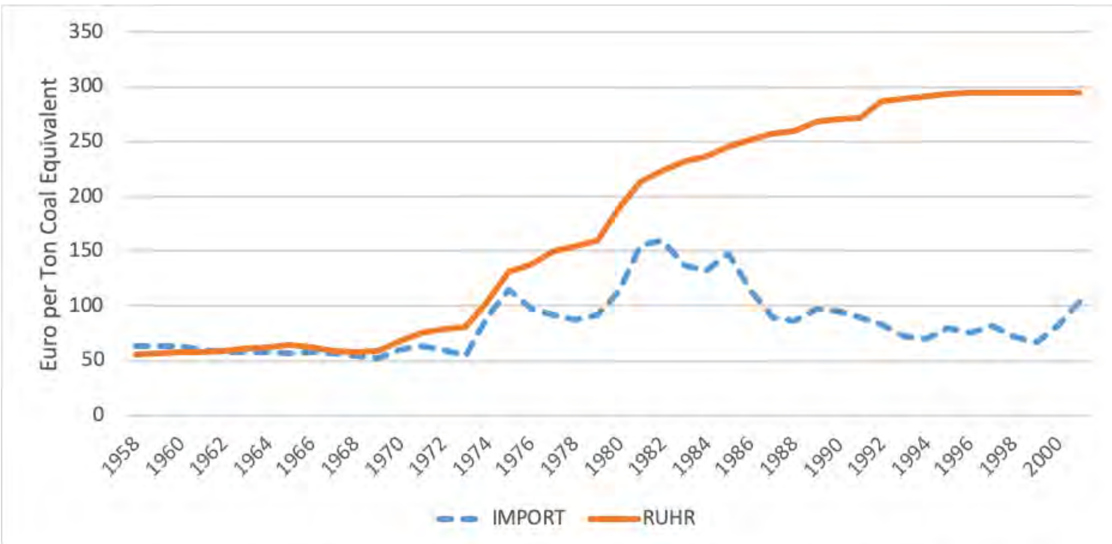

Figure 1: Domestic versus Imported Price of Coal in Germany
Source: Storchmann (2005). Constant 2000 prices of hard coal.

Take Essen, in Germany's Ruhr area, for example. Coal was produced at its *Zeche Zollverein* for almost 150 years. In the early 20th century the *Zeche* played its part in moving Germany ahead of Britain as Europe's largest economy, after WWII it quickly re-took its position as largest German coal mine to help fuel Germany‘s post-WWII economic miracle, and in 1986, it closed.[1]

German coal production declined since the mid-1950s to essentially zero today because it was internationally not competitive. Coal had generated regional clusters of energy-intensive heavy industries. A comprehensive system of coal and steel subsidies together with outright trade protection supported the sector until there was significant opposition in the 1990s– from Germany's supreme court, the European Union, and some politicians–, leading to the gradual removal of subsidies and import quotas. By this time, the price of domestic coal was three times that of imported coal (see Figure 1), and the futility of domestic coal production was increasingly accepted. Treating coal production– strongly predicted by the availability of coal reserves and hence exogenously

[1] Today, the *Zeche Zollverein* is a museum attracting 1.5 million visitors annually. Historical GDP data from Maddison (2009).

given–as a source of local regional advantage, this paper examines the impact of coal mine closures on regional economies using register data from 1975 to 2017.

For this study we combine three unique data sources. First, to measure employment and wage outcomes, we use detailed administrative data from the Establishment History Panel (*Betriebshistorikpanel*, BHP) that allow us to follow the entire population of German workers and firms for more than 40 years.[2] Thus, unlike most previous studies that had to rely on cross-sections of aggregated data on the county or municipality level (e.g., Black, McKinnish and Sanders, 2005; Feyrer, Mansur and Sacerdote, 2017), we can analyze to which extent worker mobility and the creation and destruction of firms contribute to any agglomeration spillovers mine closures might have. Second, we employ historical data on all coal mines that ever existed in Germany to create a novel geo-coded data source containing detailed information about the exact location and the foundation and closing dates of all German coal mines.[3] Third, we use the *Linked Inventor Biography Data*, a novel data set on the quantity and quality of all patents that have been issued to German employees between 1999 and 2011, which provides direct information on how the disappearance of coal mines has influenced entrepreneurship and innovation in the regions.

We find that coal mining plays an important role for the transition from the era of industrial to knowledge-based growth. First, we demonstrate that mine closures lead to lower employment in other sectors. In particular, as Figure 11 shows, employment reductions in response to mine closures are strongest in iron and steel manufacturing, a sector where traditionally coal is intensively used. However, mine closures also lead to employment reductions in other manufacturing sectors, the construction sector, and the service sector.

Given that the Ruhr area is among the top-3 most densely populated areas of Europe, the finding of negative employment effects for non-mining is striking and points to the importance of industry- and occupation-specific human capital affecting moving costs. Consistent with agglomeration spillovers, the complementarity of mining with other local activity is relatively strong before the year 1995, when mining accounted for a larger part of total employment. In section 6 we formalize this in a framework that marries elements of the specific-factors (Ricardo-Viner) and Rosen (1979) - Roback (1982) models to quantify aggregate implications. There is evidence of inter-sectoral complementary both for highly skilled and less skilled workers, and in future versions of this paper we will assess the role of migration for this using a large linked employer-employee data from Germany's Federal Employment Agency.[4]

Second, the closing of coal mines leads to lower plant size, measured by employment, see Figure 2. Moreover, our results confirm that the structural transformation away from mining particularly

[2]The data contains information about all German establishments with at least one employee subject to social security contributions except civil servants and the self-employed.

[3]We focus on non-lignite coal in this analysis.

[4]This is the Integrated Employment Biographies (IEB) data set of the IAB. The authors are currently in the process of securing access to this data.

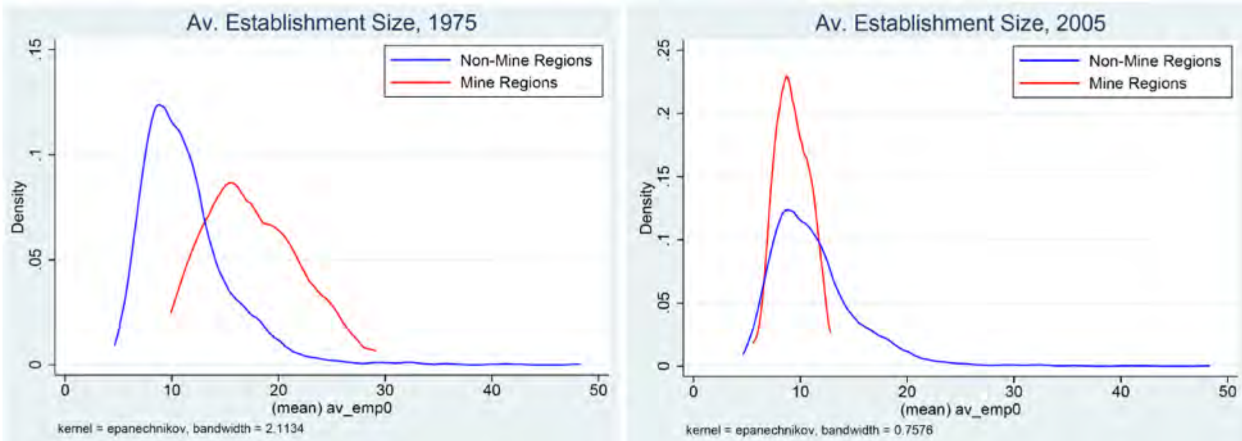

Figure 2: Change in Average Plant Size in Different Regions
Source: BHP data set, see section 3.

reduced the size of larger plants. Smaller plant size suggests that mining regions are increasingly home to more start-up companies, where entrepreneurship and innovation flourishes.

Consistent with the decline of coal mining in some regions paving the way to a successfully transitions into the knowledge-based economy, we find that mine closures increase, not decrease, growth in top skill jobs such as information technology (IT) and research and development (R&D). Furthermore, employing matched patent-patentee data geo-coded to local labor markets, we show that regions in which plant size has come down more have higher rates of patenting during 1999-2011. However, within the set of mining regions, there is a considerable degree of heterogeneity in how successfully regions transition into the era of knowledge-based growth. Figure 3 shows the share of information technology plus R&D employment in two important mining cities, Duisburg and Aachen. Generally, there is a substantial degree of heterogeneity between (former) mining regions in terms of their future trajectories. Consistent with the R&D and IT figures above, we document that some former mining regions join the league of Germany's top patenting regions whereas others do not over the period of the last four decades. Our preliminary analysis indicates that one factor determining which of the former coal regions successfully transitions into knowledge-based growth is the presence of newly opened local universities of applied sciences and technical colleges.

To sum up, as long as the mining sector is sufficiently large it serves as a regional anchor, providing agglomeration benefits for a broad range of other sectors, and the closure of mines takes down with them some part of the regional economy. At the same time, these changes yield new opportunities, because we find also evidence for lower plant size, more entrepreneurship, and innovation.

This paper, first, contributes to the literature on identifying agglomeration spillovers (Marshall 1890, Ellison and Glaeser 1997). By studying the closing of coal mines whose existence and productivity is due to exogenously given coal reserve depths, we follow recent work using natural

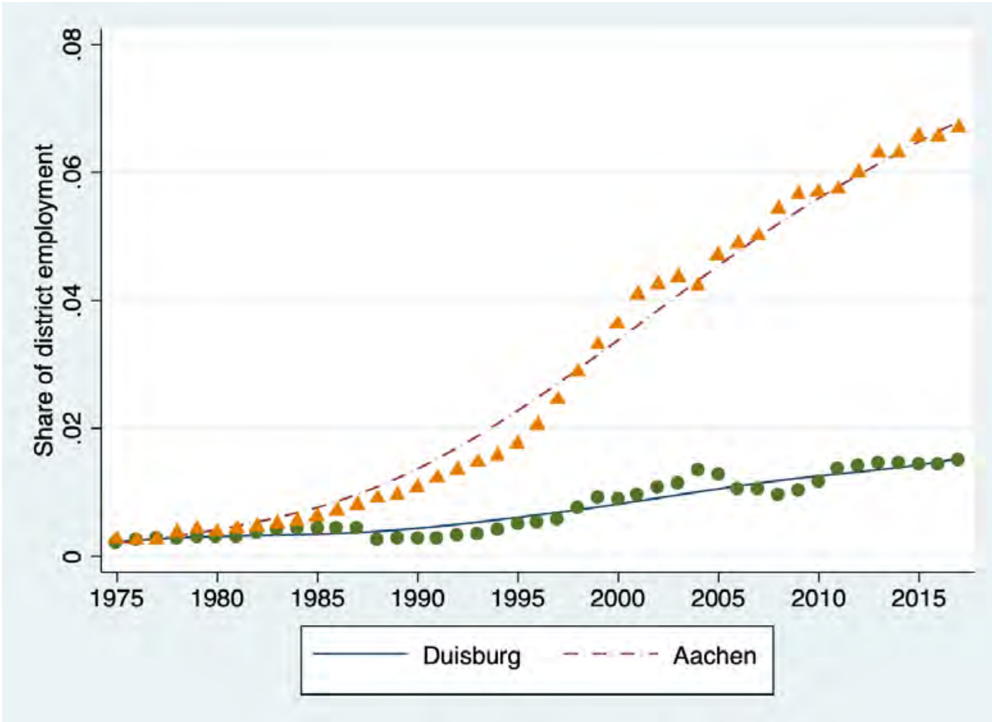

Figure 3: Evolution of IT and R&D Employment in two Mining Regions
Source: BHP data set, see section 3.

experiments (Greenstone, Hornbeck and Moretti, 2010; Allcott and Keniston, 2017; Bleakley and Lin, 2012). In particular, Kline and Moretti (2013) produce evidence for agglomeration benefits in manufacturing by showing that infrastructure subsidies to the Tennessee Valley Authority (TVA) raised manufacturing employment in the 20th century US South long after the subsidies had lapsed. By finding that the presence of spillovers from mining to other sectors turn on a large enough scale of the mining sector, similar to Ellison, Glaeser, and Kerr (2010) our analysis shifts the focus from agglomeration to co-agglomeration spillovers. Our analysis also extends Kline and Moretti's (2013) analysis by studying agglomeration in a densely populated urban, less rural area. In addition, German coal subsidies in per-capita terms were roughly ten times the size of the TVA transfers.[5]

Second, we contribute to a large literature on the impact of natural resources on economic outcomes, in particular, whether there is a so-called natural resource curse (Black, McKinnish and Sanders, 2005; Feyrer, Mansur and Sacerdote, 2017; Allcott and Keniston, 2017; Michaels, 2011).[6] Similar to Allcott and Keniston (2017), our analysis employs administrative micro data, although

[5]Peak coal subsidies in Germany were about 7.5 billion Euro in 2000 prices (year 1989; Storchmann 2005), which yields about 1,500 Euro per person in the coal mining areas. Kline and Moretti (2013) report per-capita transfers at the peak of the TVA (1950-55) of about $US 150 a year.

[6]As is ours, the cited papers are studies exploiting regional variation within a country. There is also a large literature exploiting cross-country variation, see Humphreys, Sachs, Stiglitz, Soros and Humphreys (2007); Lederman and Maloney (2008) for an introduction. Michaels (2011) reports that discussions of a possible natural resource curse go back at least to Smith (1776).

we can study mine effects at a more disaggregated level, up to 11,000 German municipalities (*Gemeinden*), compared to the about 3,000 US counties, which is important because agglomeration forces such as knowledge spillovers operate at very local level.[7] In contrast to Black, McKinnish and Sanders (2005), we find that the decline of coal significantly reduces manufacturing employment, especially in iron and steel.[8] Furthermore, using detailed industry data, we shift the focus to the tertiary sector, especially high-tech services, by showing that some regions restructure towards high technology and entrepreneurship as mining jobs disappear. This offers a more optimistic but fully consistent perspective with the finding that regions in close proximity to mines that are dominated by steel production are no fertile ground for entrepreneurs (Glaeser, Kerr and Kerr (2015)). Across cities, we find that lower plant size increases the rate of patenting, especially in the fields of electrical and mechanical engineering but also for instruments.

Third, our analysis provides new evidence on the impact of large-scale industrial subsidies, in particular coal. During much of the 20th century, coal mining has been a large and traditional blue-collar industry that used to employ thousands of low- and medium-skilled workers worldwide. In Germany, both federal and state governments subsidized the industry heavily for decades. Even by the year 2000, more than forty years after it was clear that production costs of coal in Germany were higher than the world price of coal, German coal was subsidized by about three billion Euro (Storchmann, 2005).[9] Germany provides a unique setting that may provide important lessons for other countries, such as the United States under President Trump, that plan to subsidize their blue-collar industries going forward.

The remainder of the paper is as follows. Section 2 provides the necessary background on coal mining in Germany. The following section 3 introduces the main features of the sources of data employed in this study. Our strategy of comparing mining with non-mining regions is given in section 4, with the main results given in section 5. Section 6 introduces a multi-region specific-factors model that will be employed to quantify aggregate implications of the decline of coal. A concluding discussion is presented in section 7.

2 Coal Mining in Germany: Major Developments

Once being Western Europe's largest hard coal producer with an annual output of approximately 150 million tons, Germany closed its last hard coal mine "Prosper-Hainel" in 2018. Between 1945 and 1956 German coal production expanded from 38 millions tons to 151 million tons, and provided the needed energy for Germany's quick recovery after World War II (Storchmann, 2005).

[7] Jaffe, Trajtenberg and Henderson (1993), and Fort, Keller, Schott, Yeaple, and Zolas (2019).

[8] Our result is also different from Feyrer, Mansur and Sacerdote (2017) who do not find evidence for positive spillover effects on manufacturing from the fracking boom in the US. Our findings on construction, though, are in line with earlier findings in the literature.

[9] In the 2000s, coal subsidies accounted for more than 10 percent of all federal subsidies (Deutscher Bundestag 2017).

However, in response to declining world market prices of coal and other energy sources, such as oil and gas, Germany's coal lost its price advantage in the late 1950s, and coal production gradually fell towards zero. Figure 4 shows German coal regions in the Ruhr area between 1980 to 2015.

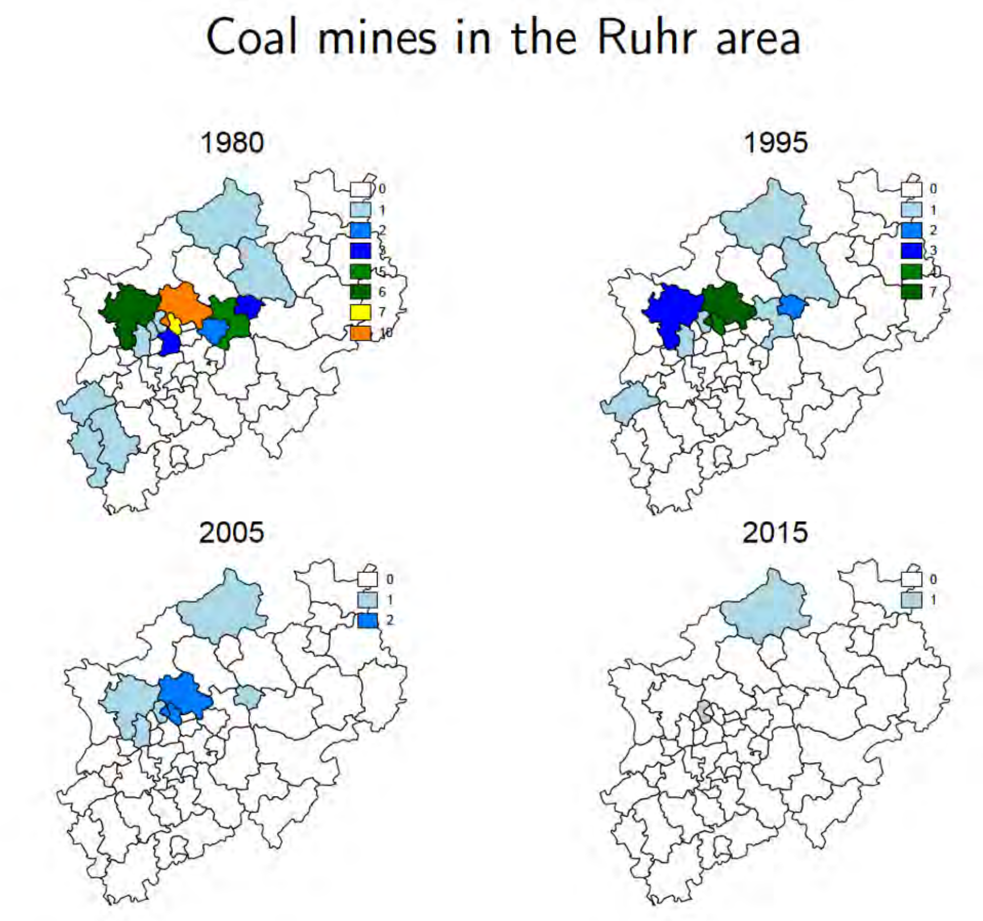

Figure 4: Coal Mines in Ruhr Area, 1980 - 2015

Although German coal production costs rose since the early 1960s to a level of triple the world market price (recall Figure 1), until 2018 Germany implemented a great variety of subsidies to keep the coal industry in operation. Figure 5 shows the evolution of coal subsidies between 1970 to 2017. They topped out during the 1990s at close to 13 billion Euros per year. These subsidies ranged from sales aids for steel mills covering the price differences between domestic and imported coal over target quantities for domestic coal in power generation to free emission certificates for energy plants using domestic hard coal. Smaller amounts of subsidies were granted for R&D in mining technology and mine closure events.

As a result, Germany had by far the largest subsidized coal production of all OECD countries. At peak times, Germany provided more than seven billion Euros of subsidies per year, and from the late 1980s to the early 1990s annual subsidies were above six billion Euros in every year. After 1995, the level of subsidies gradually declined.

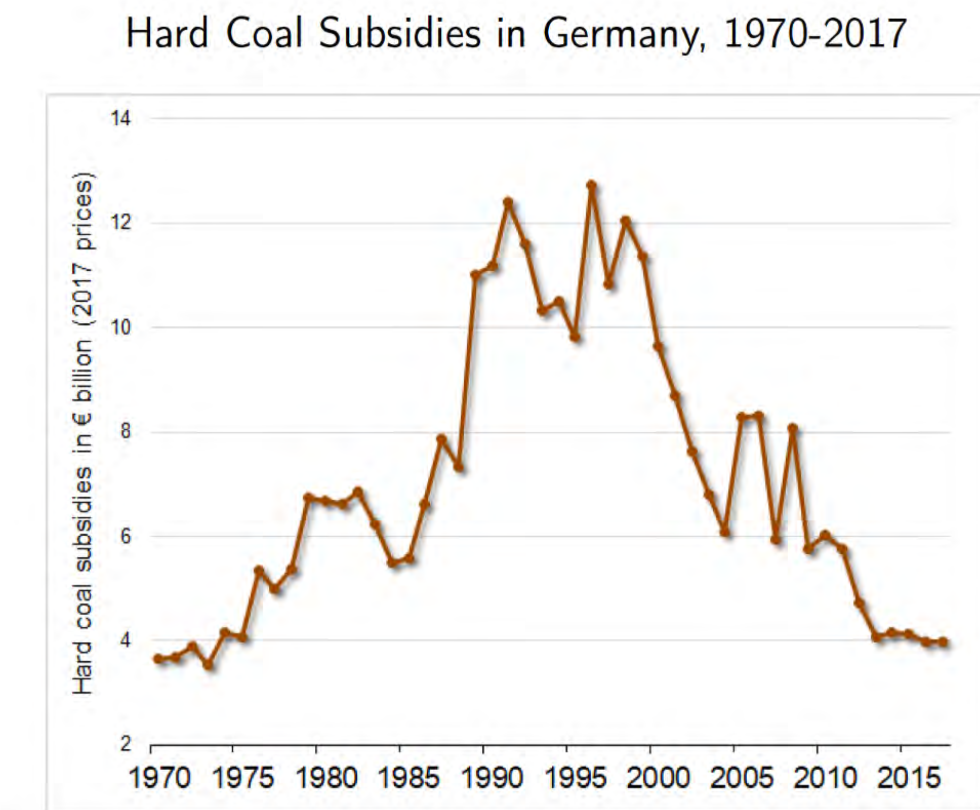

Figure 5: Subsidy Levels from 1970 to 2017

In the earlier period, subsidies were implemented after the coal crisis in 1958 to navigate the coal industry through a presumably short period of economic hardship. Although it quickly became evident that German coal mining was unlikely to resume its position in world markets, German policy makers maintained and even increased the subsidies in response to the first oil crisis of 1973 to remain self-sufficient in coal. Throughout the 1980s and 1990s subsidies tended to go up with a goal to prevent social hardship in coal mining regions (see Storchmann (2005) for more details).

After 1995, various EU regulations restricted subsidies for coal mining substantially. After 2002, the EU only allowed subsidies for mine closures, for mines that give access to new coal reserves, and to cover exceptional costs (e.g., environmental damage). However, neither the EU regulations nor a legal complaint in 1995 by *RJB mining*, a British mining company, had decisive and immediate effects on Germany's generous coal mining subsidies. Nevertheless, in the light of increasing international competition, the German government passed a bill in 2007 (*Gesetz zur Finanzierung der Beendigung des subventionierten Steinkohlenbergbaus*) to gradually remove all subsidies for hard coal mining until 2018. Germany's last coal mine closed in October of 2018.

Of these regions, the Ruhr area is by far the most important coal region, in terms of coal reserves, the size of its area, as well as the number of mining workers. Moreover, the Ruhr area is the most densely populated area in Germany, with many large cities such as Essen, Duisburg, and Dortmund.

Although Figure **??** indicates that coal mines were geographically concentrated, it also shows that the mine closures were spread out over time allowing us to rely on substantial spatio-temporal variation to identify our estimates.[10]

One important way in which we assess a region's success in terms of structural change towards knowledge-based growth is to employ geo-coded patent data (de Rassenfosse 2019). Figure 6 provides evidence on the location of innovation in Germany. While the regions around Stuttgart, Ludwigshafen-Mannheim, and Frankfurt as well as Munich clearly stand out already in the year 1980, the coal areas of Ruhr and Saar, and especially the former, are not unimportant in terms of innovation in the year 1980. Our analysis traces these trajectories with great geographic detail going forward by almost four decades.

Figure 7 shows that overall, regions in the Ruhr area that never had any mines experienced higher patenting growth than the Ruhr's coal mining regions. This is consistent with the idea that mining is slowing down the transition to post-industrial, knowledge-based growth.

At the same time, mining regions are far from being the same in terms of their success in structural change. Figure 8 shows a trend towards increasing heterogeneity among mining regions in terms of their innovativeness. According to this figure heterogeneity might have peaked around the year 2010.

3 Data Sources and Summary Statistics

3.1 Data

We use three main data sources in this analysis. First, to identify foundations and closures of coal mines, we create a novel geo-coded dataset that contains information about all coal mines that ever existed in Germany. Second, we use the Establishment History Panel (BHP, Betriebshistorik Panel, see Spengler (n.d.) for more details) to measure employment and wage outcomes. Third, to measure the innovativeness of regions we merge the BHP data to the *Linked Inventor Biography Data*, a novel data set that contains information about all inventors in German patents between 1999 and 2011 (see (Dorner et al., 2019) for more details).

The geo-coded coal mine data set matched to our employment data allows us to infer how the presence of coal mines has influenced the development of local labor markets. Moreover, the data contains precise information on opening and closing dates for all mines such that we do not have to rely on information of our register data to identify the closure of coal mines (see following section for more detail). For the purpose of our study, we restrict the data to hard coal mines that closed in the year 1975 or later. For some part of the analysis we exclude all coal mines in the former East

[10] We also account for mine closures that occurred before 1975, see below.

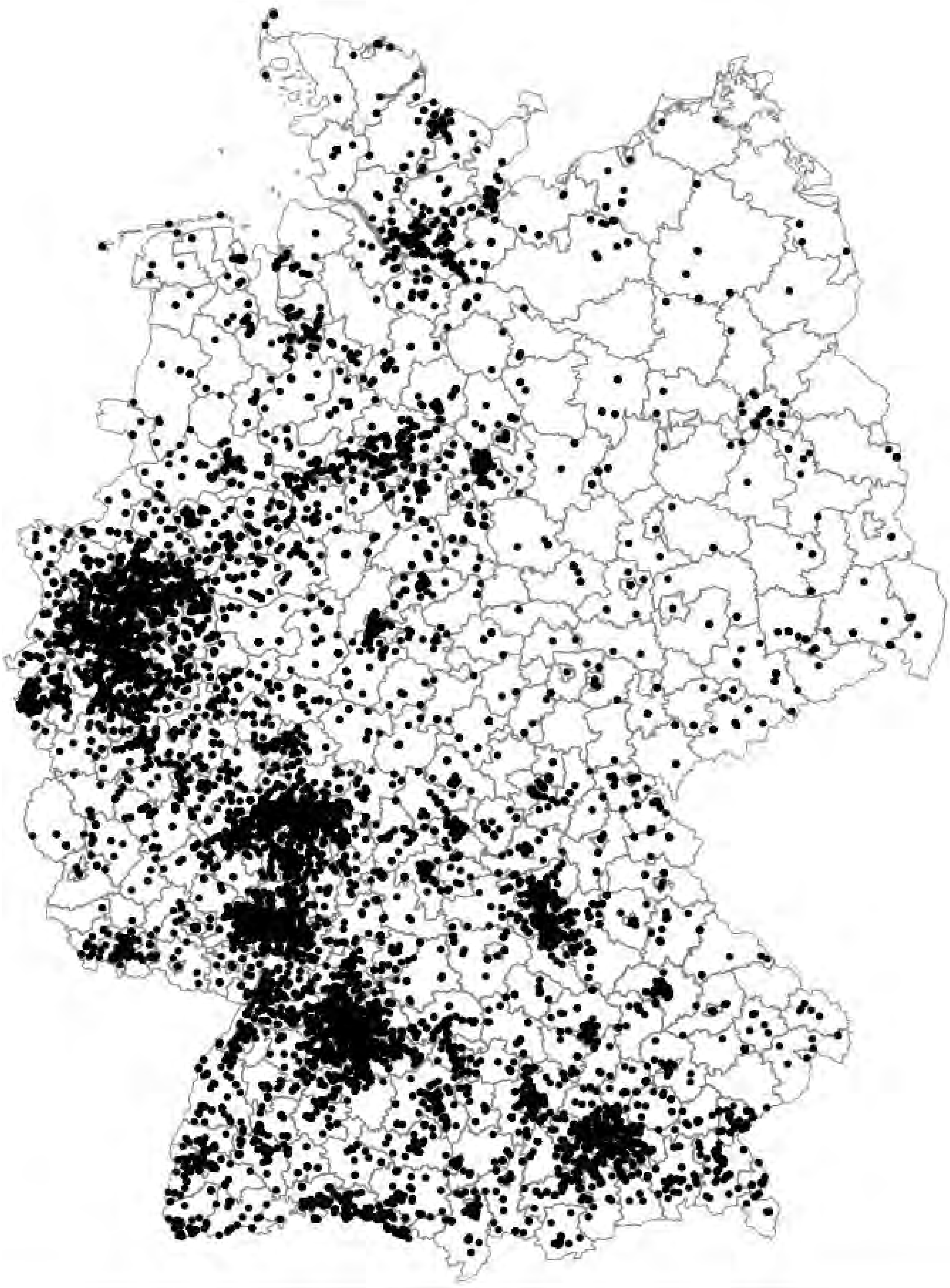

Figure 6: Patenting in Germany, 1980. Inventor Location

Germany because all of them closed before the time of German reunification (1991), and our labor market data only contains information for regions in Germany's east only after 1990.

The second data set contains register data from the Establishment History Panel (BHP, Betriebshistorik Panel, see Spengler (n.d.) for more details) provided by the German Federal Employment Agency. The BHP contains information about the universe of German establishments with

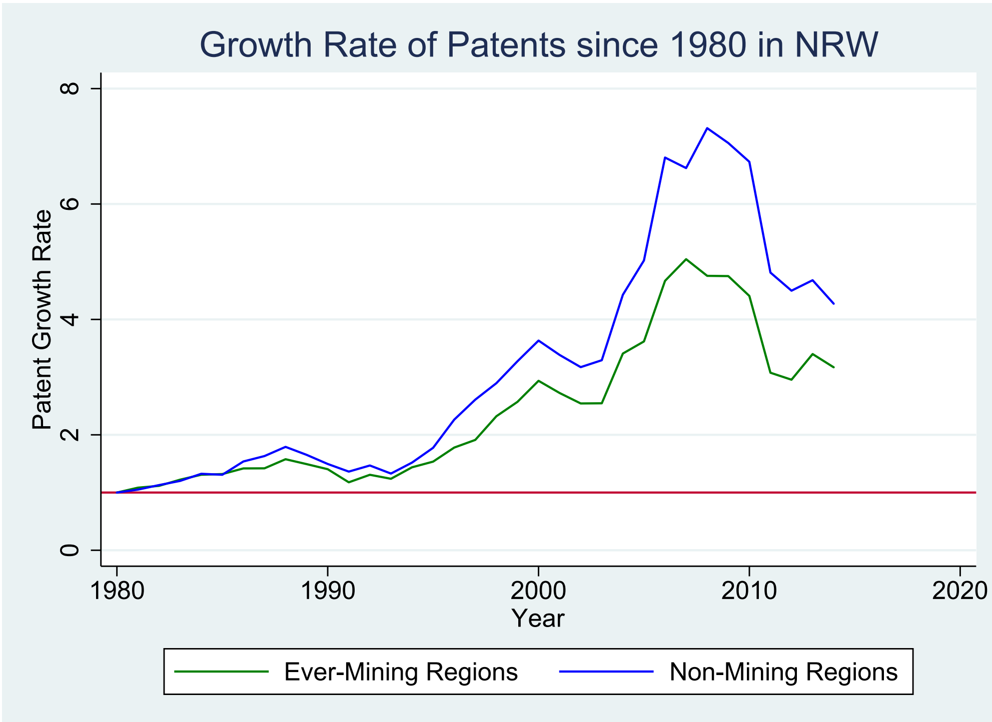

Figure 7: Patenting Growth: Mining versus Non-mining Areas in Northrhine-Westphalia

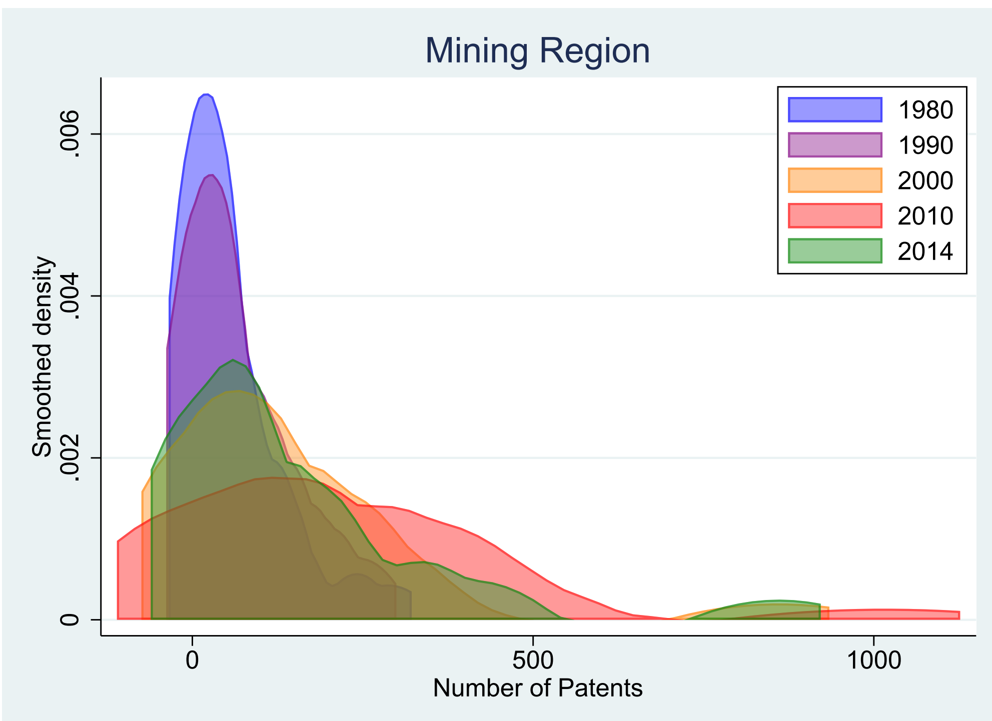

Figure 8: Diversity among Mining Regions: Evolution of Patent Densities

at least one employee subject to social security contributions from 1975 through 2017. As the data contains aggregated information from mandatory notification to social security, it provides highly reliable information about worker and firm characteristics of approximately 2.7 million establishments per year. A major advantage of using the universe of German establishments is that we can observe all firms rather than only the relatively large businesses of specific sectors—, as is the case in most micro-level data sets, e.g., the US Annual Survey of Manufacturers. This matters because most firms are small, with fewer than 20 employees, and it is particularly important for anaylyzing start-up firms, considered to be key for innovation.

The purpose of our study is to analyze how mine closures affect the development of regions. To this end the data contains detailed information about the firms' location, such that we can precisely describe the developments of local labor markets at a relatively disaggregated level. For the purpose of this study, we analyze local labor markets at various levels of disaggregation. We begin our analysis at the level of approximately $11,000$ municipalities. In addition, to take worker mobility and geographic spillover effects into account, we also perform analyses at the more aggregated level of districts and local labor markets that take commuter flows into account.

The detailed information in our data does not only allow us to analyze the overall employment and wage developments of regions. We also examine employment in different industries and for specific educational groups. In addition, a unique firm identifier allows us to consistently follow all firms over time such that we can analyze how mine closures influence local firm creation, destruction, and the distribution of firm size. As a number of studies have shown that small and fast growing firms are important for entrepreneurship and economic growth, our analysis allows us to shed new light on the long-term consequences of mine closures.

The third data set is the *Linked Inventor Biography Data* that contains patent data that is based on filings of the European Patent Office (EPO) between 1999 and 2011. The data base allows us to merge patents that have been issues by German employees throughout this period to their firms, and it gives us a measure of how innovative firms in different regions are. This information gives is a great tool for measuring regional innovation, and in particular, we do not have to solely rely on analyzing the development of average firms size given that that we know the entire firm size distribution at the local level.[11] The data set contains information on more than 150,000 inventors that we merge to their firms observed in the BHP data.

Tables 1 throughout 3 show a number of descriptive statistics for our estimation sample. The first column of each table refers to coal mining regions and the second one to non-mining regions. We see that, on average, mining regions are much larger than non-mining regions in terms of overall employment. In 1975, mining regions particularly differ from non-mining regions with respect to their employment in the iron and metal sector which is much larger than in non-mining regions.

[11]The data excludes all patent applications that are filed by foreign entities and all information of inventors with a residential address from abroad.

However, the relative size of the iron and metal sector decreases substantially between 1975 and 2017 where the difference between mining and non-mining regions remains only marginally significant at the 10 percent level. In contrast, the relative shares of service sector jobs and of the retail and maintenance sector of mining versus non-mining regionsincreases substantially over time. Tables 1 to 3 also reveal that the relative importance of IT and R&D jobs increased more in mining than in other regions. However, the differences are nnot significant at conventional levels.

Table 1: Mine Regions vs. Non-Mining Regions in 1975; Averages

	Mining	Non-Mining	Difference	p-value
Total employment (regular)	38,369.526	2,105.264	36,264.263	0.000
Employment in manufacturing	0.282	0.332	-0.050	0.240
Employment in the iron and metal sector	0.058	0.007	0.050	0.000
Employment in the electricity supply sector	0.010	0.006	0.004	0.529
Employment in services	0.292	0.275	0.017	0.618
Employment in the construction sector	0.103	0.190	-0.087	0.007
Employment in the retail and maintenance sector	0.134	0.108	0.026	0.228
Employment in the IT sector	0.000	0.001	-0.001	0.834
Employment in R&D sector	0.001	0.001	-0.001	0.850
High-skilled employment outside coal mining	0.015	0.009	0.005	0.060
Medium-skilled employment outside coal mining	0.405	0.480	-0.075	0.005
Log Mean Real Wage, non-mining	3.966	3.904	0.062	0.066
Observations	8,181			

Table 2: Mine Regions vs. Non-Mining Regions in 1995; Averages

	Mining	Non-Mining	Difference	p-value
Total employment (regular)	32,960.237	2,355.770	30,604.466	0.000
Employment in manufacturing	0.224	0.277	-0.053	0.161
Employment in the iron and metal sector	0.025	0.007	0.018	0.010
Employment in the electricity supply sector	0.014	0.004	0.010	0.042
Employment in services	0.430	0.377	0.054	0.132
Employment in the construction sector	0.104	0.190	-0.086	0.005
Employment in the retail and maintenance sector	0.156	0.126	0.030	0.151
Employment in the IT sector	0.003	0.002	0.001	0.774
Employment in R&D sector	0.002	0.001	0.000	0.931
High-skilled employment outside coal mining	0.050	0.033	0.017	0.011
Low-skilled employment outside coal mining	0.077	0.098	-0.020	0.105
Medium-skilled employment outside coal mining	0.560	0.655	-0.095	0.000
Log Mean Real Wage, non-mining	4.259	4.235	0.024	0.410
Observations	8,239			

Table 3: Mine Regions vs. Non-Mining Regions in 2017; Averages

	Mining	Non-Mining	Difference	p-value
Total employment (regular)	34,404.763	2,803.324	31,601.439	0.000
Employment in manufacturing	0.173	0.220	-0.048	0.170
Employment in the iron and metal sector	0.018	0.006	0.012	0.077
Employment in the electricity supply sector	0.007	0.003	0.004	0.408
Employment in services	0.651	0.468	0.183	0.000
Employment in the construction sector	0.072	0.145	-0.073	0.008
Employment in the retail and maintenance sector	0.189	0.136	0.053	0.016
Employment in the IT sector	0.011	0.007	0.004	0.406
Employment in R&D sector	0.003	0.002	0.001	0.816
High-skilled employment outside coal mining	0.090	0.060	0.030	0.001
Low-skilled employment outside coal mining	0.052	0.045	0.007	0.297
Medium-skilled employment outside coal mining	0.483	0.496	-0.013	0.551
Log Mean Real Wage, non-mining	4.357	4.311	0.045	0.112
Observations	8,384			

4 Empirical Strategy

This section introduces our econometric approach and shows results from comparing mining with non-mining regions. We employ both relatively wide and more narrow comparison groups to examine the robustness of our results (all of German regions, versus regions in states with mining regions).

In order study the impact of mine closures to the local economy we employ two complementary approaches. First, we use time event analysis, as in Jacobson, LaLonde, and Sullivan (1993), and focus on the closure of the last mine in the local market to estimate the following equation:

$$lnY_{it} = \alpha_i + \lambda_t + \sum_k D_{it}^k \delta^k + \varepsilon_{it} \tag{1}$$

where i indicates a local market which we take as a municipality, and t represents the calendar time in years.[12] D_{it}^k is a set of dummy variables equal to 1 in the $k'th$ year before or after the mine closure. Thus δ^k represents the effect of mine closures in the k'th year before or after the mine closure. We follow all mining municipalities throughout a period between five years before the closure of their mine until ten years after it. For non-mining regions, D_{it}^k is always 0. Regression 1 is very flexible because it follows the trajectories of the treated regions without imposing a functional structure for the pre- and post-treatment period.

The parameter λ_t represents a set of coefficients for each year in the observation period. The

[12] We also employ our analysis at district level and obtain similar results.

municipality fixed effect a_i capture all observable and unobservable persistent differences across local markets. We assume ε_{it} to have constant variance and to be uncorrelated with municipality and time effects. lnY_{it} represents the logarithm of the dependent variable of municipality i at time t. In particular, Y_{it} is the total employment in different sectors.

An important challenge in estimating the effect of mine closures on the development of local economy is that researchers have no information on how the mining regions would have developed in the absence of the mine closure. A common solution to this problem is to compare the mining regions to a counterfactual group of comparable non-mining regions. To estimate the counterfactual trends, we rely on two different samples of control regions. First, we use all municipalities of the former West Germany without coal mines as control regions. Doing so allows to exploit the largest possible variation to identify our effects. Second, we follow an approach along the lines of Dustmann, Schönberg and Stuhler (2017) and use propensity score matching to select regions that had similar observable characteristics as the mining regions in 1975 but were located reasonably far away from them.

As our sample of all formerly West German municipalities includes regions that differ substantially from our treatment (mining) municipalities, the control regions might exhibit very different trends than the treatment regions. As a result, our main identification assumption, parallel trends in the absence of treatment, might be violated. Moreover, the first sample also includes regions that may be exposed to spillovers, positive and/or negative, from mine closures, because they are located geographically close to the mining regions. The presence of such spillovers would violate Rubin's (1974) stable unit treatment value assumption (SUTVA). To overcome both problems we create a sample of control municipalities that are reasonably far away from the mining regions but were otherwise very similar to them at the beginning of our observation period.

We follow Dustmann, Schönberg and Stuhler (2017) and use the following variables in 1975 for our propensity score matching: total employment in the region, share of manufacturing employment, share of service employment, share of low, medium and high skilled employment outside mining, and the logarithm of the average wage in the region.[13] Figure 9 displays the treatment and counterfactual regions that evolve from this approach.

In addition to event-study graphs, an extended set of regression results will be shown in tabular form.

While the time event approach is useful and transparently shows any evidence on pre-trends, especially in regions with more than one coal mine the dynamics of the local economy may be influenced by the entire history of mine closures. To take into account such dynamics we complement the event-study approach using the following regression equation:

[13]Our measure of skill here is education. High-skilled workers are college-educated, medium-skilled workers have a vocational education degree, and low-skilled workers have neither college nor vocational education.

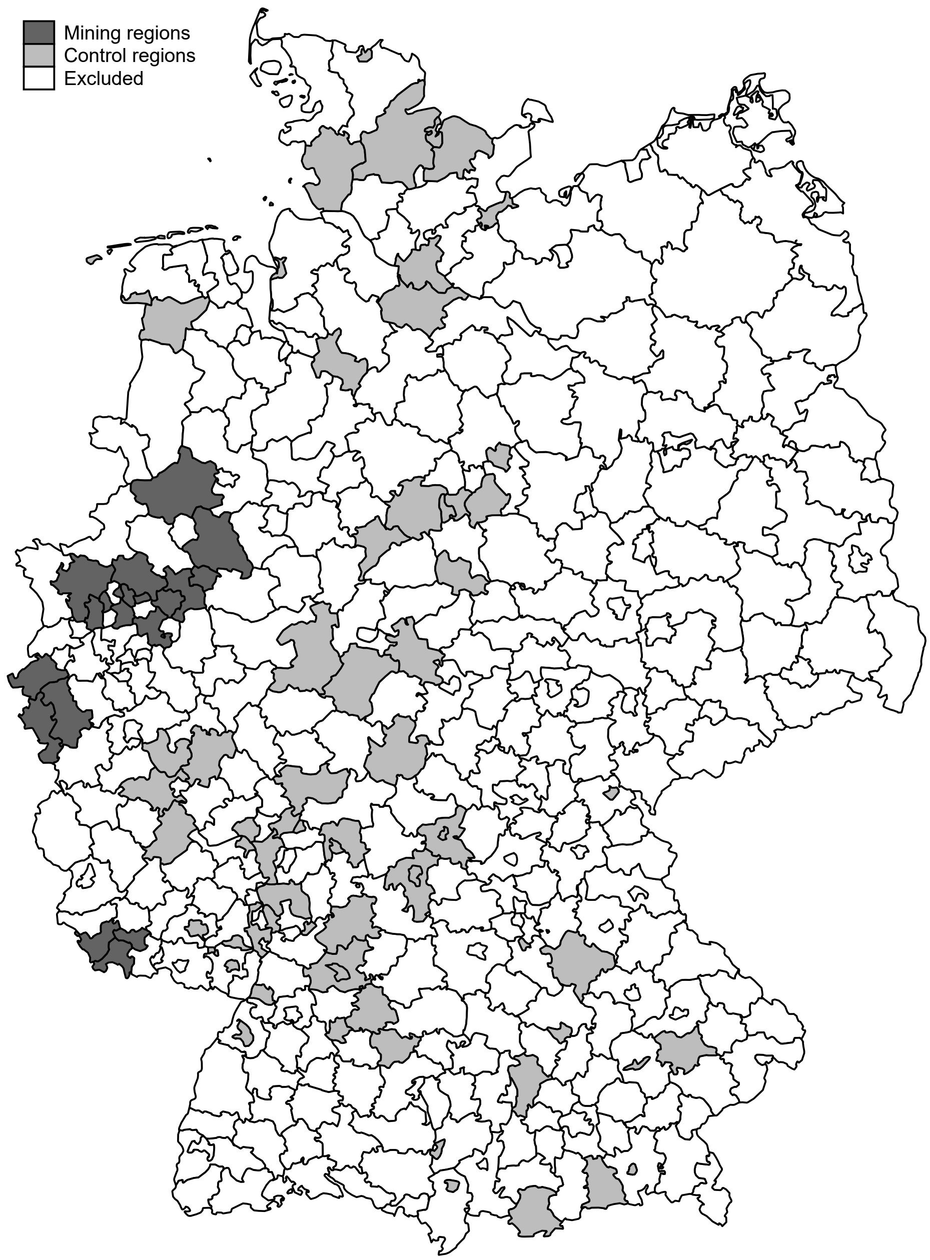

Figure 9: Mining regions vs. control regions

Control regions are selected by propensity score matching using the following variables in the base year 1975: total employment in the region, share of manufacturing employment, share of service employment, share of low, medium and high skilled employment outside mining, and the logarithm of the average wage in the region

$$lnY_{ist} = \gamma_0 + \gamma_1 CMineClosure_{ist} + \tau_{st} + \alpha_i + \varepsilon_{ist} \quad (2)$$

$CMineClosure_{ist}$ is the cumulated number of mine closures in local market i located in state s

in year t. In order to better capture the dynamic impact we discounted the mine closures with an annual discount factor 0.99.[14] In equation 2 as before we draw from a longitudinal data and focus on within local market (municipality) variation to eliminate the possibility that unobservable characteristics of a region's location affect the results. The term τ_{st} denotes the state, s, by time, t, fixed effects, which control for the aggregate shocks that may differ across states such as the state-specific public spending.

5 Empirical Results

5.1 Event-Study Analysis

We begin by illustrating the impact of mine closings on employment in a number of sectors using event-study analysis. The following shows event-study plots for the closing of the last coal mine in a region. It is based on all *Gemeinden* in the former West Germany.[15] Included in the sample are all last-mine closing regions for which we have at least five years in the pre- and at least ten years in the post-closing era within the overall sample period of 1975 to 2017.

Figure 10 shows the impact of mine closings of the last mine in a municipality on employment in the hard coal mining industry. Closing the last mine has the expected long-term negative effect on coal mining employment. Virtually all coefficient estimates of the post-treatment period are very close to one indicating a drop of 100 percent in coal mining employment in the long-run, i.e., as expected coal mining municipalities retain virtually no coal-mining employment after having closed their last coal mine.[16]

As a few municipalities had more than just one coal mine, and policy makers often tried to smooth the closing process to avoid social hardship by providing aid for job search and early retirement programs, some coefficient estimates for the pre-treatment period are positive and significantly different from zero. However, the effects are astonishingly small given that one might have expected substantial *shadow of death effects* in an industry that is a major political priority. Thus, the results on pre-trends do not only support the validity of the parallel trends assumption—even within a sample that does not impose further restriction on our counterfactual regions—they also reveal that mine closures constitute substantial shocks to the local economies despite the strong political involvement in the sector.

What is the relationship between mine closings and employment in other sectors? Using the same event-study approach, Figure 12 shows the results for all employment outside of mining. We find

[14] Results without discounting are similar, see below.

[15] Results are qualitatively the same at the district- and local labor market level.

[16] Closed mines would sometime retain for a while some administrative staff, or if particularly significant the mine might be turned into a museum.

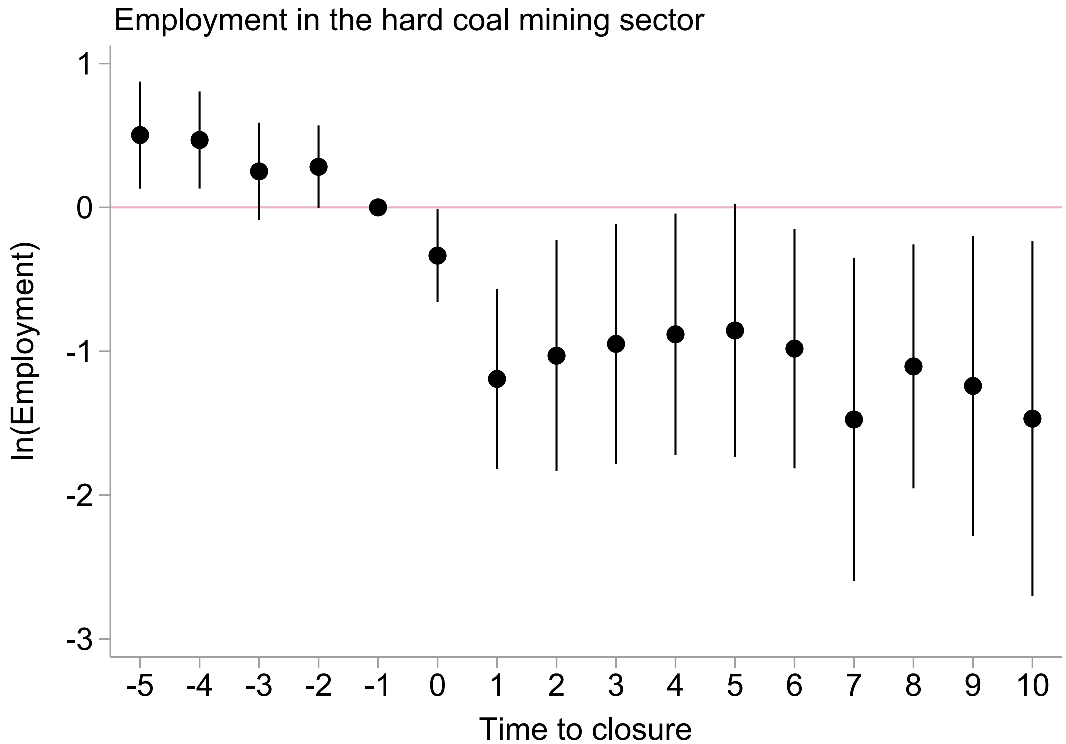

Figure 10: Coal Mining Employment. Event-study regression for Last Mine Closure
Year of closure of last mine normalized to -1. Estimation by OLS with municipality and year fixed effects. Treatment group are all mining regions, control group are all non-mining regions of the former West Germany. Confidence bands at the 5% level with clustering at the municipality level shown.

a negative impact on non-mining employment of about five percent. The point estimate does not change very much after five years of closing of the mine, and it is roughly the same ten years after closing. This is evidence that mine closures have long run effects on regional employment. Also notice that there is no evidence for significant pre-trends in non-mining employment before the closure of the last mine. Again, the pre-trend results suggest that the mine closures constituted substantial shocks to local labor markets.

As noted above, mine closure may have positive or negative spillovers on other regions, in particular ones that are in the geographic vicinity of our mining municipalities. To address these potential issues, Figure 13 shows results on the matched sample including only distant control regions with a similar employment structure as the mining regions. Comparing Figures 12 and 13, although there are small differences, the results remain qualitatively and quantitatively very similar. This result is very reassuring and also suggests that our fixed effect structure performs well in containing the influence of regional spillovers on our results.

In the following we expand on the event-study analysis with regression results on a broader range

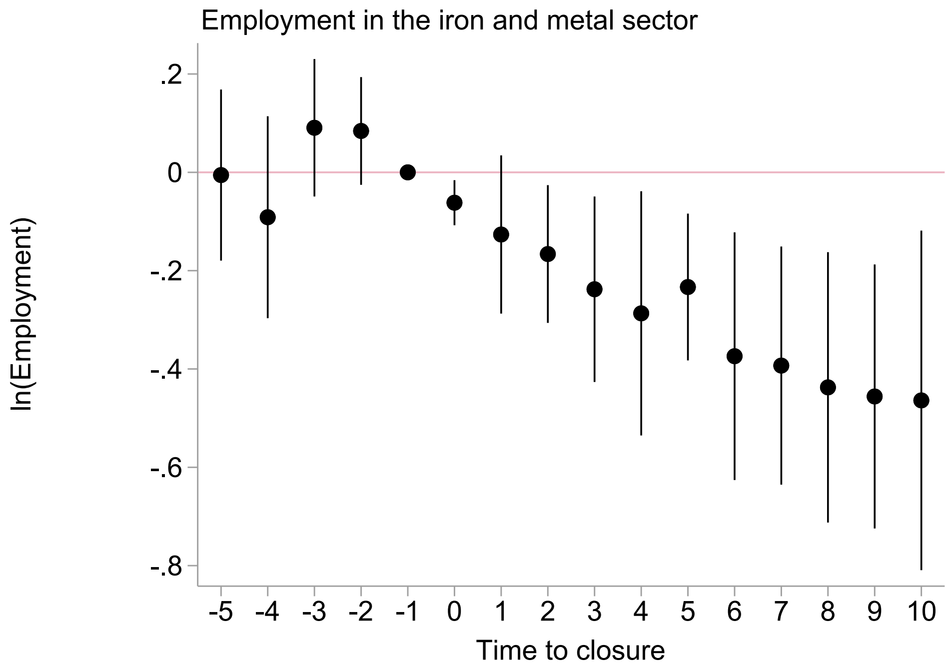

Figure 11: Iron & Steel Sector Event-Time Regression for Mine Closure
Regression contains municipality and time fixed effects (see section 4). Treatment group is all mining regions, control group all non-mining regions in West Germany. Confidence intervals (95%) with clustering at the municipality level shown.

of outcomes. The first section studies the effect of mine closings on sectoral employment in local labor markets for the period between 1975 and 2017. The second part analyzes the temporal heterogeneity by distinguishing two sub-periods of roughly twenty years, 1975-1995 versus 1995-2017. As noted above, by the mid-1990s it had become clear that domestic coal production in Germany faced insurmountable international competition, and the system of subsidies and protectionism was scaled back.

The following section turns to the impact of mine closings on plant size, a proxy for entrepreneurship and economic dynamism in the local economy. Furthermore, we provide direct evidence that changes in plant size affect local rates of innovation as measured by patenting. We conclude this section by examining heterogeneity in regional performance within the set of mining regions to shed light on the factors that facilitate the transition into the era of knowledge-based growth.

5.2 Employment, Skill Composition, and Mine Closures, 1975-2017

Table 4 shows results of estimation of equation 2. This analysis compares mining with non-mining regions in all of the former West Germany; results for other sets of control regions will be shown below.

Table 4: Mine Closures and Employment Spillovers

	(1) Coal	(2) Outside Coal	(3) Manufacturing	(4) Iron & Steel	(5) Services	(6) IT	(7) R&D
Mine Closures	-1.001***	-0.112***	-0.171***	-0.448***	-0.116***	0.206*	0.559**
	(0.266)	(0.029)	(0.043)	(0.137)	(0.027)	(0.117)	(0.272)
Observations	1,465	354,516	303,503	51,647	335,961	87,281	26,737
R-squared	0.883	0.971	0.943	0.889	0.963	0.813	0.852
Municipality Fixed Effects	✓	✓	✓	✓	✓	✓	✓
State x Time Fixed Effects	✓	✓	✓	✓	✓	✓	✓

Notes: Dependent variable is log employment in the sector given at top of column. Mine closures variable is the discounted number of mine closures between 1975 and year t in municipality i. Estimation by OLS of equation 2. Robust standard errors, reported in parentheses, are clustered by municipality. *, ** and *** indicate significance at the 10 %, 5% and 1% levels respectively.

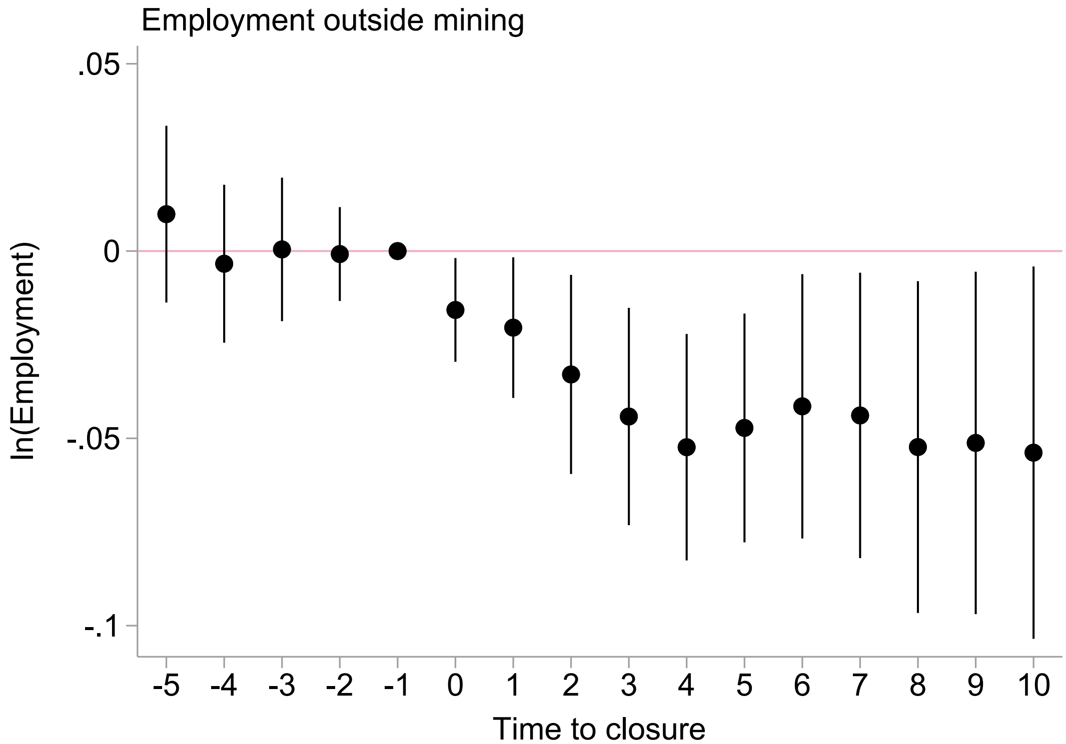

Figure 12: Non-Mining Employment. Event-study Regression for Last Mine Closure
Year of closure of last mine normalized to -1. Estimation by OLS with municipality and year fixed effects. Treatment group are all mining regions, control group are all non-mining regions of the former West Germany. N = 354,516. Confidence intervals (95%) with clustering at the municipality level shown.

Starting with column (1), the results confirm the event-study result that mine closings significantly reduce mining employment. In column 2 the dependent variable is the logarithm of employment in all sectors except the mining sector. We find significant and negative impact of mine closures on non-mining sector employment. With competitive markets and constant returns to scale, one would expect to see an *increase*, not decrease in non-mining employment if mine workers would rapidly find re-employment in another local sector after the closing of their mine. The fact that there is no evidence that local non-mining employment is increasing is evidence for a complementary relationship between coal mining and other local employment. Moreover, the results suggest that workers face high transition costs and cannot easily switch to other occupations and sectors to find new employment.

Coal mining may create spillovers both via manufacturing and service sectors. We find significant spillovers from coal mining on manufacturing (see column 3 Table 4) . This is an important result for at least two reasons. First, there is no significant impact from coal booms & busts or fracking on local manufacturing in studies employing US county level data (Black et al., 2005; Feyrer et al.,

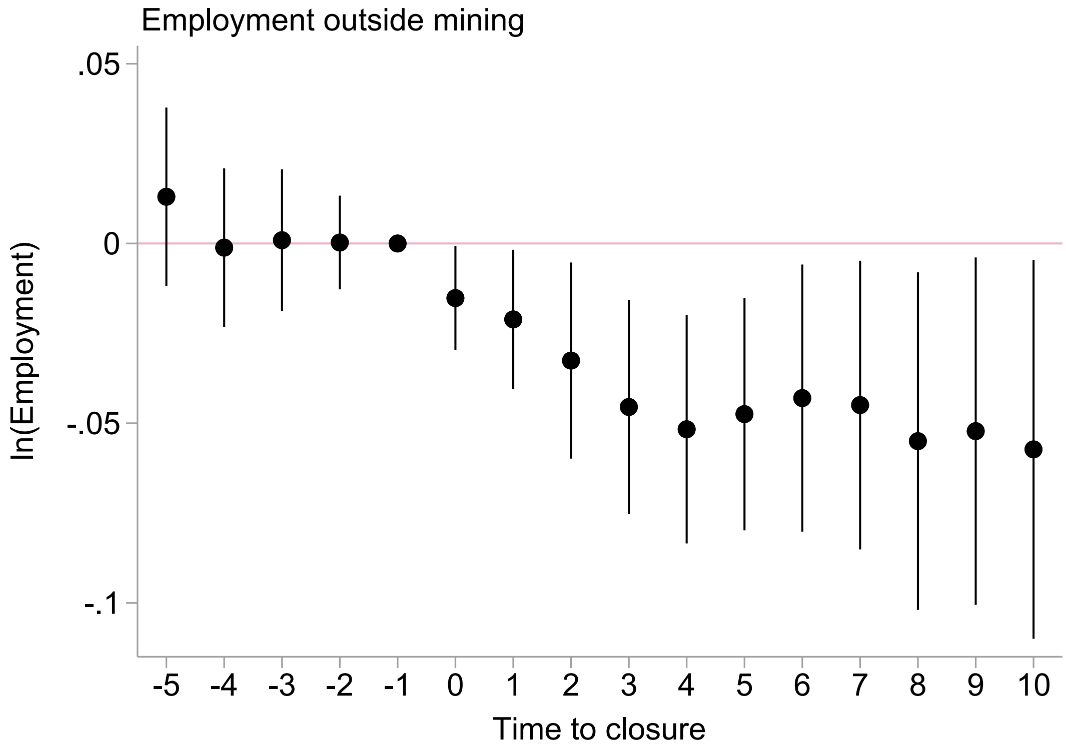

Figure 13: Non-Mining Employment Event-study Regression—Matched Sample
Year of closure of last mine normalized to -1. Estimation by OLS with municipality and year fixed effects. Treatment group are all mining regions, control group are those shown in Figure 9. Confidence intervals (95%) with clustering at the municipality level shown.

2017). One might think that this is due to the more granular size of the local areas that we study (there are roughly 11,000 *Gemeinden* in Germany, compared to about 3,000 counties in the US). [17] We believe that our finding of significant spillovers on manufacturing is due to a combination of spatial dis-aggregation of the local labor market combined with precise geo-coding of mines, and the timing of mine closures.

Second, the negative impact of mine closures on local manufacturing employment matters because manufacturing generates positive agglomeration spillovers (Kline and Moretti, 2013; Moretti, 2010). If local coal mining matters for the scale of manufacturing production even during the years 1975-2017 when costs of shipping energy had fallen dramatically relative to earlier periods then instead of agglomeration spillovers in manufacturing we should perhaps think of them arising through the co-location of mining and manufacturing.[18] More generally, our result indicates that it is important

[17]This cannot be the only reason, however, because we find also significant evidence for spillovers on manufacturing at the more aggregate *Kreis* level (not shown). There are about 400 *Kreise* in Germany.

[18]The importance of access to coal for industry is well-known to students of long-run development. Pomeranz (2001), for example, argues that access to coal explains why Britain industrialized in the late 18th century while China did only much later.

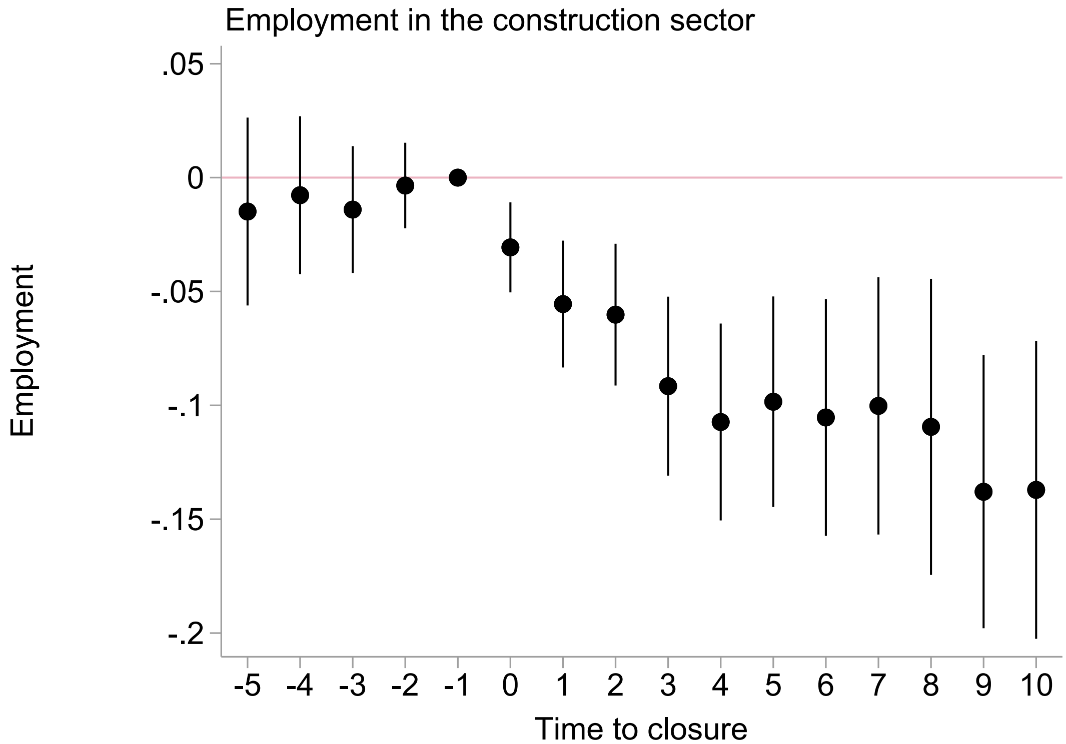

Figure 14: Construction Sector Employment. Event-time Regressions for Last Mine Closure
Year of closure of last mine normalized to -1. Estimation by OLS with municipality and year fixed effects. Treatment group are all mining regions, control group are all non-mining regions of the former West Germany. Confidence intervals (95%) with clustering at the municipality level shown.

to think about agglomeration benefits arising from the co-location of industries.

Due to agglomeration forces traditional heavy industries that rely on hard coal, such as iron and steel may be an important link between coal mining and the overall manufacturing. Therefore, we study the impact of coal mine closures on the iron and steel employment in column 4. A lower level of mining activity spills over strongly to the iron and steel sector. The impact is substantially higher on iron and steel than the entire manufacturing suggest that the employment spillover effect on manufacturing is happening via the input linkages as the steel industry has been a major user of coal inputs, in particular coking products.

Coal mining closings have also a negative impact on service employment, see Table 4, column 5. However, input linkages may not be the only channel as we see that the employment effects from mining spill over significantly to the local service economy, see column 5.

Using the event-study results we find the negative effect concentrated on the retail industry particularly. Figure 15 shows that the closing of the last coal mine has a significant negative effect on

Figure 15: Retail Trade and Maintenance Sector Employment. Event-time Regressions for Last Mine Closure

Year of closure of last mine normalized to -1. Estimation by OLS with municipality and year fixed effects. Treatment group are all mining regions, control group are all non-mining regions of the former West Germany. Confidence intervals (95%) with clustering at the municipality level shown.

employment in the retail sector particularly. This provides additional evidence that mine closings have far-reaching employment consequence in very different parts of the local economy.

Next, we break down non-mining employment by turning to the construction sector. As seen from Figure 14, there is evidence that the closing of the last coal mine has a significantly negative impact on construction employment. After five years there is a loss of five percent, and at ten years a loss of ten percent of employment. The significant negative impact on retail and construction employment suggest that another channel through which lower mining activities spill over to local economy is the demand channel. The sharp decline in relatively high-paid mining jobs is likely affecting the local economy via reduced demand. [19] That is, we find mine closures influence a major part of the local economy (the share of employment in services goes from roughly 40 to just under 70 percent in Germany during our sample period).

[19] Our findings of spillovers to the construction sector are in line with employment spillover effects found in the case of the coal bust in local labor markets of the US after the OPEC-induced energy price increases of the 1970s (Black et al., 2005), and also to finding of spillovers from mining to construction in the recent fracking boom (Feyrer et al., 2017).

Turning back to Table 4, the last two columns of the table show evidence on the impact of mine closings on employment in the information technology (IT) and R&D sectors. Recall from above that employment in these high-tech industries accounts for a relatively small share of total employment, and there is also a substantial number of municipalities that has no IT or R&D worker at all, as the lower number of observations indicates. Nevertheless, the results show that mine closings have a positive impact on IT and R&D employment (with the latter more precisely estimated). This is some rare evidence for positive spillovers from coal mine closings. It provides initial evidence that at least in some cities the decline of coal gives rise to industries that are by all accounts important in a knowledge-based economy.

Results summarized in the following Table 5 speak to the robustness of these results in a number of important dimensions. First, consider the specific measure of mining activity. Table 5 shows results for four alternative measures: (i) discounted number of mine closings, (ii) number of mine closings, (iii) number of operating coal mines, and (iv) an indicator for having at least one operating coal mine in the municipality. The results indicate that irrespective of the particular measure of mining activity, non-mining employment is decreasing in the number of mine closings, or equivalently, non-mining employment is higher the higher is the number of operating coal mines.

Second, it is important to examine the role of the set of control regions for our results. In the specifications summarized in columns 1 to 4 we employ all municipalities of the former West Germany as control regions. Instead, results shown in columns 7 and 8 employ only municipalities from North-Rhine Westphalia (NRW) and the Saar states. On the one hand, control regions in these states are likely to be more similar to our mining regions than control regions from all of the former West Germany. In particular, the share of municipalities in NRW and Saar with coal mines that were closed *before* our sample period starts, in 1975, is substantially higher than for all municipalities of the former West Germany. On the other hand, due to their relative geographic proximity, control regions from NRW and Saar are more likely to be affected by spillover effects from mine closings than the typical non-mining municipality of the former West Germany.[20] However, our results indicate that the particular choice of control regions does not strongly affect our results (compare column 7 with column 1, and column 8 with column 3). In line with this finding, we have seen above that mine closings also significantly reduce non-mining employment in a matched sample of regions that are located throughout the former West Germany (see Figures 7 and 9).

Third, it is important to examine the role of spatial aggregation for our results. One reason for this is that region size may affect the likelihood of cross-region migration in response to the mine closings. Another is comparability with existing studies where typically larger regions are examined. In columns (5) and (6) of Table 5, then, we compare the impact of mine closings on regional manufacturing employment, with regions being either municipalities or districts. We see that while in both cases mine closings depress manufacturing employment, the point estimate at the munici-

[20]See Feyrer, Mansur and Sacerdote (2017) for an analysis of such geographic spillovers in a related setting.

Table 5: Robustness Checks - Mine Closures and Employment Outside Coal Mining

	Former West Germany						Mining Regions	
	(1)	(2)	(3)	(4)	(5) Manuf'g	(6) Manuf'g	(7)	(8)
DCumMineClosure	−0.112***				−0.171***	−0.060***	−0.110***	
	(0.029)				(0.043)	(0.023)	(0.028)	
CumMineClosure		−0.089***						
		(0.022)						
Number of Coal Mines			0.068***					−0.088***
			(0.016)					(0.022)
At least 1 Operating Coal Mine				0.087**				
				(0.034)				
Observations	354,516	354,516	354,516	354,516	303,503	15,865	19,135	19,135
R-squared	0.971	0.971	0.971	0.971	0.943	0.970	0.979	0.979
Municipality Fixed Effects	✓	✓	✓	✓	✓	✓	✓	
State x Time Fixed Effects	✓	✓	✓	✓			✓	✓
Time Fixed Effects					✓	✓		
Districts Fixed Effects								✓

Notes: The sample in columns (1)-(6) is former West German regions and in (7)-(8) only the mining regions. Dependent variable in all specifications is log employment outside coal, except in (5) and (6) where it is log manufacturing employment. *DCumMineClosure* is the discounted cumulative number of mine closures between 1975 and year t in municipality i. Independent variable $CumMineClose_{it}$ is the cumulative number of mine closures between 1975 and year t in municipality i. Estimation by OLS of equation 2. Robust standard errors, reported in parentheses, are clustered by municipality. *, ** and *** indicate significance at the 10 %, 5% and 1% levels respectively.

pality level is about three times the estimate at the district level. This suggests that research based on relatively large spatial units may be missing part of the local impact because, for example, the within-district migration response is not observed.

Table 6: Mining Closures and Skill Composition

	(1) Medium-Skilled	(2) Low-Skilled	(3) High-Skilled
Mine Closures	-0.022***	0.019***	0.000
	(0.005)	(0.004)	(0.002)
Observations	354,516	354,516	354,516
R-squared	0.440	0.643	0.528
Municipality Fixed Effects	✓	✓	✓
State x Time Fixed Effects	✓	✓	✓

Notes: Dependent variable is the employment share outside of coal mining of the skill group given at top of column. Mine Closures variable is the discounted number of mine closures between 1975 and year t in municipality i. Estimation by OLS of equation 2. Robust standard errors, reported in parentheses, are clustered by municipality. *, ** and *** indicate significance at the 10 %, 5% and 1% levels respectively.

The next set of results examines the impact of mine closings on the skill composition of the local labor force. Results are shown in Table 6. Three levels of skill are distinguished by education: high-skilled workers have college education, medium-skilled have a vocational degree, and low-skilled workers have neither. We estimate a negative impact of mine closings on the share of medium-skilled workers, see column 1. At the same time, mine closings increase the share of low-skilled workers, while the share of high-skilled workers remains flat (columns 2 and 3, respectively). On average, the net effect of mine closings is to shift the local skill distribution down towards lower skills. Mine closings have a weakly polarizing effect that has been associated with certain forms of technical change and rising import competition (see Autor and Dorn (2013) and Keller and Utar (2016), respectively).

5.3 Agglomeration Effects from Mining

In this section we distinguish two sub-periods during the overall sample period of 1975-2017, namely before and after 1995. We take the year 1995 as the approximate turning point at which due to increased international competition the system of trade protection and subsidies for coal was scaled back (see section 2). In Table 7 we show results for the specifications employed before separately for two sub-periods, 1975 to 1995 and 1995 to 2017.

Table 7 shows the impact of mine closings on employment in three sectors: manufacturing, ser-

Table 7: Mine Closures and Employment Spillovers: Changing Patterns over Time

	1975-1995			1995-2017		
	(1) Outside Coal	(2) Manufacturing	(3) Services	(4) Outside Coal	(5) Manufacturing	(6) Services
Mine Closures	−0.106***	−0.158***	−0.128***	−0.028	−0.002	−0.038
	(0.028)	(0.044)	(0.018)	(0.030)	(0.031)	(0.029)
Observations	172,674	149,304	161,020	181,828	154,085	174,868
R-squared	0.983	0.970	0.977	0.984	0.968	0.978
Municipality Fixed Effects	✓	✓	✓	✓	✓	✓
State x Time Fixed Effects	✓	✓	✓	✓	✓	✓

Notes: The sample in columns (1)-(3) refers to the period 1975-1995 and in the columns (4)-(6) to the period 1995-2017. Dependent variable is log employment of the sector given at top of column. Independent variable Mine Closures is the discounted cumulative number of mine closures between 1975 and year t in Panel A and between 1995 and year t in Panel B in municipality i. Estimation by OLS of equation 2. Robust standard errors, reported in parentheses, are clustered by municipality. *, ** and *** indicate significance at the 10 %, 5% and 1% levels respectively.

vices, and all non-mining. We have seen above that over the entire sample period, mine closings lead to negative employment effects in all three parts of the local economy. The key insight from the present analysis is that the negative employment effect of mine closings is concentrated in the first two decades of our sample, from 1975 to 1995. From the mid-1990s onwards, mine closings do not have a (significant) negative impact on employment in other sectors anymore (compare the left with the right side of Table 7).

This is a key result of our analysis because it indicates that the spillovers from mining to other sectors of the local economy depend on the scale of mining production. During the first twenty years of our sample, coal mining accounted for about 10 percent of local employment on average, and during this time, the closing of mines leads to lower employment in other sectors. By the year 1995, however, the employment share of coal mining has fallen to around 5 percent in mining regions, and the results of Table 7 show that then, mine closings do not matter anymore for other sectors. One concern is that there is no impact on non-mining employment after 1995 because there are simply very few coal mines left. That, however, turns out to not be the case. While the number of mine closings is somewhat larger before 1995 than after 1995, with 40 versus 33 the figures are not too different.

In sum, mine closings have only negative employment spillover effects if the scale of mining is large enough. Once employment has fallen below a certain threshold mine closings do not affect employment in other sectors. The result indicates that coal mining in these regions has a certain anchor effect, and the co-agglomeration benefits that coal mining generates depend on it being sufficiently large.

5.4 Entrepreneurship and the Growth of High-Tech Plants

In the following we examine the impact of mine closures on plant size. The level of entrepreneurship is directly related to start-up firms and the entry (and exit) of firms. Thus, plant size is a well-known proxy for entrepreneurship and innovation that is available in certain micro level data sets (e.g., Glaeser et al., 2015). Table 8 shows results on the impact of mine closings on measures of plant size at the municipality level.

Panel A on top shows results for the years 1975 to 1995. Notice that mine closings lead to a lower average plant size (column 1). The result is primarily driven by large plants, captured in our analysis with the 75th percentile of plant size (column 2). In contrast, there is no impact of mine closings on the size of relatively small plants (column 3). In the lower part, we see the same qualitative results for the later part of the sample, see Part B, columns 1 to 3.

The finding that mine closures lead to lower plant size is consistent with a move towards smaller, more nimble firms, and increased levels of entrepreneurship. At the same time, mining plants tend

Table 8: Mine Closures, Firm Size, and High-Tech Plant Growth

Panel A: 1975 to 1995

	(1) Average Size	(2) Large Plant Size	(3) Small Plant Size	(4) Average Size (Manuf.)	(5) Large Plant Size (Manuf.)	(6) No. IT Plants	(7) No. R&D Plants
Mine Closures	−0.184***	−0.048***	0.002	−0.089**	0.055*	0.357***	0.117*
	(0.054)	(0.011)	(0.020)	(0.043)	(0.032)	(0.091)	(0.061)
Observations	172,718	172,718	172,718	149,304	149,304	172,718	172,718
R-squared	0.896	0.725	0.416	0.905	0.799	0.793	0.870
Municipality Fixed Effects	✓	✓	✓	✓	✓	✓	✓
State x Time Fixed Effects	✓	✓	✓	✓	✓	✓	✓

Panel B: 1995 to 2017

	(1) Average Size	(2) Large Plant Size	(3) Small Plant Size	(4) Average Size (Manuf.)	(5) Large Plant Size (Manuf.)	(6) No. IT Plants	(7) No. R&D Plants
Mine Closures	−0.193***	−0.017*	0.018	−0.012	−0.067**	0.120**	0.194***
	(0.058)	(0.010)	(0.025)	(0.025)	(0.032)	(0.056)	(0.074)
Observations	181,874	183,697	183,697	154,085	154,079	183,697	183,697
R-squared	0.898	0.700	0.323	0.894	0.792	0.909	0.860
Municipality Fixed Effects	✓	✓	✓	✓	✓	✓	✓
State x Time Fixed Effects	✓	✓	✓	✓	✓	✓	✓

Notes: Dependent variables are given at top of column. Log average plant size results given in columns 1 and 4, log of the 75th percentile of plant size given in columns 2 and 5, and log of the 25th percentile of plant size given in column 3. Dependent variables in columns 6 and 7 are the log number of plants in IT and R&D, respectively. Mine Closures is the discounted cumulative number of mine closures between 1975 and year t in Panel A and between 1995 and year t in Panel B in municipality i. Estimation by OLS of equation 2. Robust standard errors, reported in parentheses, are clustered by municipality. *, ** and *** indicate significance at the 10 %, 5% and 1% levels respectively.

to be large in size, and it is important to see whether this drives our results.[21] To shed light on this we examine the impact of mine closings on the size of manufacturing plants. During the first twenty years, the average size of manufacturing plants decreases with mine closings (column 4, Panel). There is considerable heterogeneity though, because the size of large manufacturing plants actually increases as mines are closed (column 5; marginally significant). In contrast, during the later period of 1995-2017, the size of large manufacturing plants declines as mines are closed (Panel B, column 5). This is consistent with the impact of mine closings on manufacturing plant size following the same pattern as for non-manufacturing plants with a delayed response.

Overall, we find that the closing of mines has led to a substantial reduction in plant size. The effect is present in large parts of the local non-mining economy, including in manufacturing.

We have seen above that mine closings have increased employment in the IT and R&D sectors. Here, we complement that evidence by showing evidence on the number of IT and R&D establishments in the local labor markets. As seen on the right side of Table 8, the number of IT and R&D establishments is increasing as mines are closed. For IT establishments, the growth caused by mine closings is larger during the years 1975-95, while for R&D plants growth is stronger during the later sub-period. This confirms earlier results that for some of the cities the closing of coal mines was the beginning of a new focus on high-tech activities.

5.5 Mine Closings and Innovation: Evidence from Local Patenting

This section employs linked patent-patentee information to obtain direct evidence on innovation at the local level. While a limitation is that we have this information only for the years 1999 to 2011, an advantage is that we cover regions both in the former West and East Germany. Since patenting at the most disaggregated spatial level is a rare event, we perform the following analysis at the district level. As we have seen above, the impact of mining closings on employment in other sectors at the municipality and district level is similar. Table 9 shows the results.

We find that the closing of mines has increased patenting at the local level, see column 1. The coefficient indicates that closing one mine leads on average to about two more patents at the regional level. The finding is qualitatively similar when we focus on districts of the former West Germany or districts in North-Rhine Westphalia and the Saar areas (columns 2 and 3, respectively).

Furthermore, we also find that among coal mining regions, patenting is increasing as the average size of the local plant decreases (not reported). This provides evidence that differences in patenting is related to variation in average plant size across mining regions. The result is in line with our finding above that mine closings decrease plant size and increase patenting in the sample of all

[21] However, recall that the average size of mining plants does not change dramatically over our sample period; section 3

Table 9: Mine Closures and Innovation

	Regions			Tech. Fields & Quality			
Dependent Variable: Number of Patents	(1) East & West Germany	(2) West Germany	(3) NRW & Saar	(4) Elect. Engineering	(5) Instruments	(6) Chemical	(7) Quality
Number of Operating Mines	−1.947**	−1.356*	−1.351**	−0.556**	−0.370**	−0.140	−0.006
	(0.758)	(0.717)	(0.665)	(0.237)	(0.149)	(0.131)	(0.027)
Observations	5,213	4,212	767	5,213	5,213	5,213	1,454
R-squared	0.507	0.357	0.216	0.534	0.476	0.323	0.303
District Fixed Effects	✓	✓	✓	✓	✓	✓	✓
Time Fixed Effects	✓	✓	✓	✓	✓	✓	✓

Notes: The sample in the columns (4)-(7) consists of East and West Germany. Dependent variable is the number of patents by regions in columns (1)-(3), and by branches in columns (4)-(6). Column (7) measure the quality of a patent denoted by its originality. Independent variable *zNumber* is the number of operating mines. Estimation by OLS of equation 2. Robust standard errors reported in parentheses. *, ** and *** indicate significance at the 10 %, 5% and 1% levels respectively.

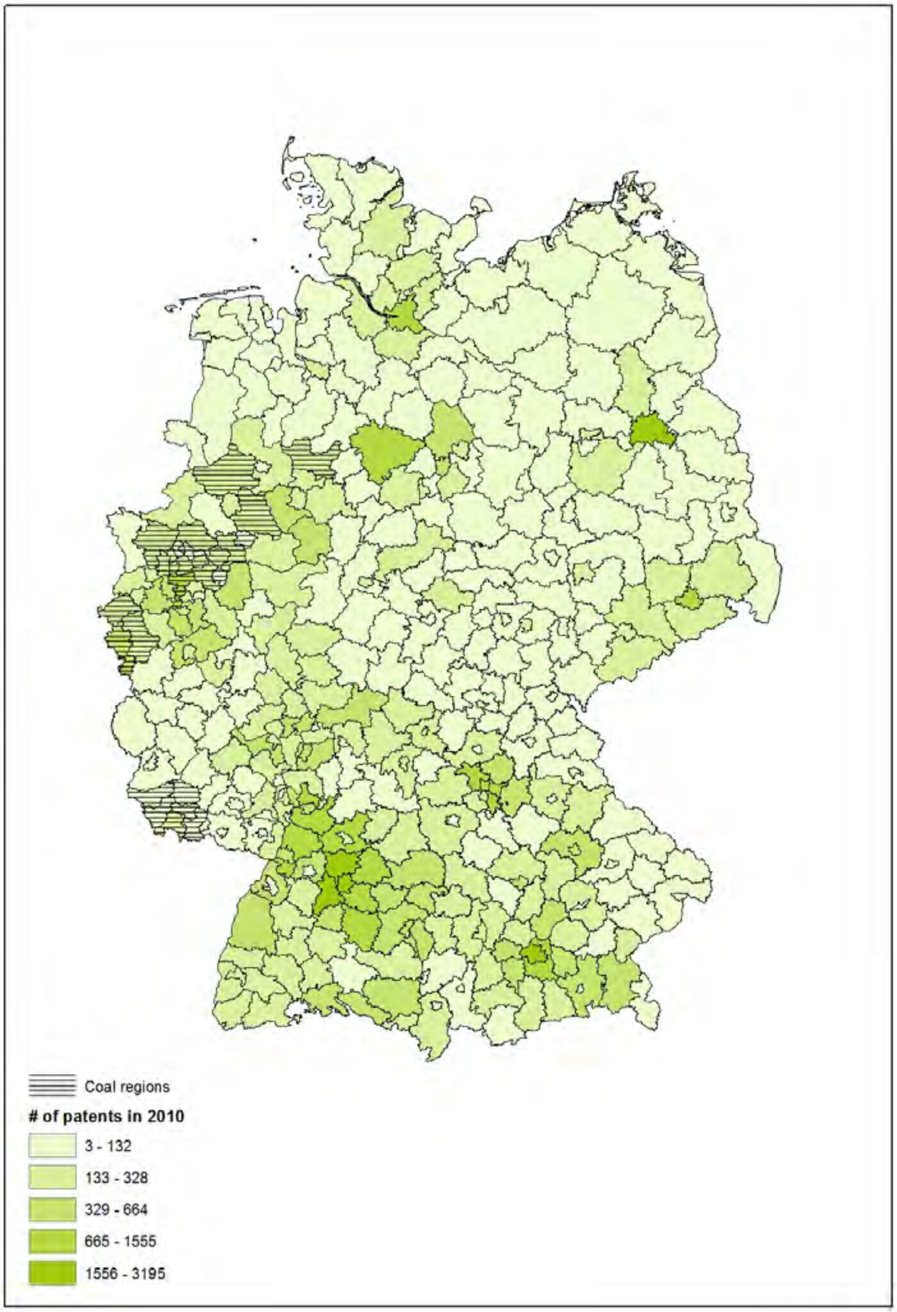

Figure 16: Patenting in Mining and Non-mining Regions by 2010

German regions.[22]

It is also interesting to look at variation in patenting by field. On the right side of Table 9 we see that while the point estimate for all fields indicates that mine closings tend to increase patenting,

[22]Furthermore, we have relied throughout solely on within-region variation over time.

the effect is stronger for electrical engineering and instruments and weaker (and insignificant) in the chemical industry. The last column shows results for patent quality, as measured by originality. The point estimate is negative but essentially zero, which may be in part due to the smaller sample.

To summarize, there is evidence that the closing of coal mines leads to an increase in innovation as measured by patenting. Recall from above [Figure Duisburg vs Aachen], however, that there is substantial variation in the speed with which mine regions move into high-technology sectors. It is thus important to examine any differences between (former) mining regions. The next section turns to this question.

5.6 Channels of Heterogeneity between Mining Regions

This section seeks to shed more light on what explains differences between the performance of mining regions over the sample period. We have seen above that mine closings lead to higher rates of patenting across regions. In the first part of this section we ask whether differences in average plant size between mining regions plays a role for differences in patenting of these regions. Table 10 shows the results.

What are the sources of these regional differences? Why does plant size, and patenting, change in some mining regions more than others? We employ data on the operation of all universities, including universities of applied sciences (*Fachhochschulen*), to provide some initial evidence on this. Specifically, for a given year t, we employ the total number of years that all such universities are open in a given district. Universities, in particular those of the applied sciences, are important for the development of the scientific base in a region, and often provide inputs to local firms. Of course, the creation of new universities may be endogenous, and the following results should therefore not be given a causal interpretation.

The specifications in Table 10 relate district employment in different sectors to the universities variable. The regressions also includes district and state-year fixed effects. Overall employment is decreasing in the years local universities are open, which is consistent with the idea that overall, human capital is a substitute for 'raw' labor (column 1). Also agricultural and mining employment is declining in the universities variable (columns 2 and 3), and so is manufacturing employment (column 4). The latter makes sense in the context of skill-biased technical progress. In contrast, there is a positive correlation between universities and service employment (column 5). Furthermore, the number of universities is also positively correlated with IT and R&D employment, as shown in the last two columns of Table 10.

To summarize, the opening of universities and schools of applied sciences is associated with different structures of employment growth at the local level, and there is some evidence that it plays a role in the transition of mining regions into the era of knowledge-based growth.

Table 10: Structural Change, Employment Structure, and Human Capital

	(1) Total	(2) Agriculture	(3) Outside Coal	(4) Manufacturing	(5) Services	(6) IT	(7) R& D
Universities	−123.361**	−1.644**	−61.413**	−169.791**	5.946**	40.658**	11.208**
	(20.326)	(0.297)	(4.665)	(9.734)	(0.701)	(2.197)	(1.599)
Observations	895	895	895	895	895	895	895
R-squared	0.974	0.958	0.777	0.913	0.962	0.863	0.871
District Fixed Effects	✓	✓	✓	✓	✓	✓	✓
State × Time Fixed Effects	✓	✓	✓	✓	✓	✓	✓

Notes: The sample consists of mining region. Dependent variable is employment in sector on top of column. Universities is defined as the sum of years that universities in a given region are open at year t. Estimation by OLS of equation 2. Robust standard errors reported in parentheses. *, ** and *** indicate significance at the 10 %, 5% and 1% levels respectively.

6 A Multi-Region Specific-Factors Model

[Incomplete] In this section we outline the baseline model and characterize the environment of the economy. Particularly, we draw on important features of the Ricardo-Viner (Amano, 1977; Jones, 1971) and Rosen-Roback (Rosen, 1979; Roback, 1982) models (Redding and Rossi-Hansberg 2016 give a broader overview). This connects to important aspects of agglomeration, including endogenous market size, agglomeration and dispersion forces, endogenous choice of location in the presence of differences in amenities (see, e.g., (Fujita et al., 2001; Krugman, 1991; Krugman and Venables, 1995; Ottaviano and Thisse, 2004), (Kline and Moretti, 2013; Glaeser, 2008; Glaeser and Gottlieb, 2009)). Our setup contrasts with Glaeser and Gottlieb (2009), Kline and Moretti (2013), and Greenstone et al. (2010), who consider environments with a single aggregate output, thus abstracting from important implications of inter-industrial shifts within regions.

6.1 Environment

The economy comprises two regions, A and B, populated by homogeneous workers in terms of skills.[23] Each region is characterized by a service good (Y_s), which is a constant-returns sector, and a manufacturing good (Y_m), an increasing-returns sector, that are combined to produce an aggregate consumption good Y. Moreover, service and manufacturing goods are produced in the spirit of Ricardo-Viner model. That is, each sector uses a specific-factor in addition to factor labor, which is mobile.

6.1.1 Production technology

The final consumption good combines Y_s and Y_m with a constant elasticity of substitution (CES) technology:

$$Y = \left(Y_s^{\frac{\gamma-1}{\gamma}} + Y_m^{\frac{\gamma-1}{\gamma}} \right)^{\frac{\gamma}{\gamma-1}}, \tag{3}$$

where $\gamma > 0$ is the elasticity of substitution between Y_s and Y_m. We choose the price of the final consumption good as the numeraire, and define P_s and P_m as the price index of Y_s and Y_m, respectively. By means of profit maximization subject to Eq. (3), the demand for service and manufacturing goods are given:

$$Y_j \quad = \quad Y P_j^{-\gamma} \quad (j = s, m). \tag{4}$$

Service good is produced by combining a service-specific factor (K_s), e.g. housing, and a homo-

[23] We suppress the regional parameter to simplify notation.

geneous factor labor (L_s) with a Cobb-Douglas technology:

$$Y_s = K_s^{\beta} L_s^{1-\beta}. \tag{5}$$

Let r_s be the price of service-specific factor K_s, profit maximization subject to Eq. (5) yields the demand for K_s:

$$r_s = \beta(Y_s/K_s). \tag{6}$$

Manufacturing good (Y_m) is produced by combining an industry-specific factor (Z_m), e.g. a resource-intensive input such as coal, and a composite intermediate goods (X) characterized by monopolistic competition as in Dixit and Stiglitz (1977):

$$Y_m = Z_m^{\alpha} X_m^{1-\alpha} \tag{7}$$

$$X_m = \Theta_m \left(\int_0^{N_m} x(i)^{\rho} \mathrm{d}i \right)^{1/\rho}, \tag{8}$$

where $x(i)$ is the intermediate variety i, N_m denotes the endogenous mass of monopolistic firms, $\sigma = 1/(1-\rho) > 1$ denotes the elasticity of substitution. The term

$$\Theta_m = N_m^{v-1/\rho} \tag{9}$$

denotes the agglomeration spillover, where the parameter v captures the degree of external increasing returns to scale. As in Iranzo and Peri (2009), we impose $v = 1$ to allow for increasing returns due to agglomeration. The price of the specific-factor Z_m is set internationally and exogenously given to the manufacturing good producer, $\bar{r}_z$.

Under perfect competition, profit maximization subject to Eqs. (7) and (8), gives the demand for the specific-factor:

$$Z_m = \alpha^{1/(1-\alpha)} \bar{r}_z^{1/(1-\alpha)} X_m, \tag{10}$$

and for each intermediate good:

$$p(i) = (1-\alpha) P_x (Z_m/X_m)^{\alpha} X_m^{1/\sigma} x(i)^{-1/\sigma}, \tag{11}$$

where p(i) is the price of intermediate variety $x(i)$. Combining Eqs. (7), (8) and (11) yields the the marginal price of composite intermediate goods:

$$P_x = \Theta_m \left(\int_0^{N_m} p(i)^{1-\sigma} \mathrm{d}i \right)^{1/(1-\sigma)} \tag{12}$$

Given the demand function, Eq. (11), profit maximizing monopolists sets the the price equal to a markup $\sigma/(\sigma-1)$ over marginal costs $\tilde{w}$

$$p(i)=\frac{\sigma}{\sigma-1}\tilde{w}. \tag{13}$$

Each intermediate variety requires a fixed costs (measured in terms of the numeraire), f. Labor is the sole of production, i.e. $l_m(i)=f+\tilde{w}x(i)$, where $\tilde{w}$ is the marginal costs.

By symmetry, the output and the price index of the intermediate composite good reduces to:

$$X_m = N_m^{\sigma/(\sigma-1}x \tag{14}$$
$$P_m = pN_m^{1-\sigma}. \tag{15}$$

6.1.2 Labor markets

Workers are mobile both between sectors within regions and across the regions due to endogenous choice of location. Let the economy wide number of workers (L) and the amount of workers in each region $k=A,B$ be denoted by L_k. Then, labor market clearing conditions imply

$$L = L_A+L_B \tag{16}$$
$$L_k = L_{s,k}+L_{m,k} \tag{17}$$
$$L_{m,k} = \int_0^{N_m} l_m(i)\mathrm{d}i = N_m l_m, \tag{18}$$

where the second equality in Eq. 18 results by symmetry assumption. However, we assume that region A has a technology advantage to produce an intermediate good. A firm producing one unit of intermediate good $x(i)$ in region A requires $1/H(\leq 1)$ unit of labor.

6.1.3 Workers utility

Following spatial equilibrium frameworks (Kline and Moretti, 2013; Glaeser and Gottlieb, 2009), the indirect utility level of workers in region $k=A,B$ is given by a Cobb-Douglas function:

$$U_k=\ln(w_k)-\ln(r_{sk})+\ln(a_k), \tag{19}$$

where w_k denites the nominal wage rate, r_k is the cost of service-specific factor (e.g. housing), a_k denote the amenities in region k.

Thus, the decision to move between region A and B is a function of nominal wages, costs of region-specific services, and amenities:

$$\ln(w_A/r_{sA}) > \ln(w_B/r_{sB}) + \ln(a_B/a_A). \tag{20}$$

[To be completed.]

7 Concluding Remarks

Using the closures of coal mines in Germany over 1975-2017 as local labor market shocks we study how natural resources and international competition affect the rise and fall of regions in a world in which the nature of economic growth is changing. Employing register data on all workers and establishments from Germany, we find that coal mining plays an essential role in the transition from the era of industrial to knowledge-based growth. We demonstrate that mine closures produce substantial negative employment spillovers in both the manufacturing and the service sector. For the manufacturing sector, we find that the iron and metal industries are the key manufacturing sector in creating these spillovers.

The results show mine closures lead to smaller plant sizes outside the mining sector in the local economy. Smaller plant size suggests that mining regions are increasingly home to more start-up companies, where entrepreneurship and innovation flourishes. Consistent with the decline of coal mining in some areas paving the way to a successfully transitions into the knowledge-based economy, we find that mine closures increase, not decrease, growth in top skill jobs such as information technology (IT) and research and development (RD).

The results also reveal substantial heterogeneity both across time and across mine regions. The restructuring in the traditional, heavy industries such as iron and steel due to global competition since the mid-1990s help to subside the negative effect of mine closures on the manufacturing sector. And we find the government's efforts to establish new universities an important factor deriving the cross-sectional heterogeneity within the mine region.

Our results show that as long as the mining sector is sufficiently large, it serves as a regional anchor, providing agglomeration benefits for a broad range of other sectors, and the closure of mines takes down with them some part of the regional economy. At the same time, these changes yield new opportunities, because we also find evidence for smaller plant size, more entrepreneurship, and innovation.

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8 Appendix

TBD