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Universities that matter for regional knowledge base renewal – the role of multilevel embeddedness

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Abstract

We analyze the role of universities or, more generally higher education institutions (HEIs), in terms of their regional and international embeddedness for regional knowledge base renewal. We assume that the introduction of radical patents in the sense of novel technological combinations contributes to the renewal of the knowledge base. For our empirical study, we combine information from patent applications, scientific publications and higher education statistics. We find that HEIs contribute most to knowledge base renewal if they have a strong research output and are locally embedded. International research embeddedness of HEIs benefits regional development only if combined with a central position in the regional network.

Keywords: higher education institutions, universities, knowledge base renewal, radical innovation, SNA, embeddedness

JEL: I20, I23, I25, O3, R11

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1 Introduction

The regional impact of universities, or more generally, higher education institutions (HEI) has been discussed since the 1970s (Schubert and Kroll 2016). Since then, it has been highlighted that HEIs are highly relevant actors for regional development and innovation (e.g. Drucker 2016; Valero and Van Reenen 2019), which resulted in a continuous increase in the number of HEIs worldwide; with 20.000 HEIs in 196 countries in 2021 (Marrocu, Paci, and Usai 2022). Through their three main missions (teaching, research and 'third mission'), universities contribute via well-educated graduates (e.g. Schartinger, Rammer, and Fröhlich 2006), knowledge spillovers from their research activities (e.g. Jaffe 1989), as well as strategically engaged university-industry relationships (e.g. Lehmann and Menter 2016) to regional innovation and wealth.

Despite the rich literature on the impact of HEIs on regional innovation (e.g. Uyarra 2008), their role in renewing the regional knowledge base is only poorly understood. Surprisingly little is known about their role in the underlying process of unique and novel knowledge recombination that leads to incremental, but more importantly, radical innovation (Plunket and Starosta de Waldemar 2022; Weitzman 1998). In light of this research gap and the importance of radical innovations for regional development (e.g. Castaldi, Frenken, and Los 2015), we focus on novel knowledge combinations in regions, i.e. regional knowledge base renewal, and the corresponding role of HEIs. Moreover, despite some notable exceptions (Hegde 2005; Huggins and Johnston 2009), previous research on the role of HEIs for regional development has largely disregarded their characteristics. Therefore, we follow the suggestion by Uyarra (2008) and take a more nuanced approach by investigating the following research question: How are HEIs characterized that contribute the most to the knowledge base renewal of regions? Inspired by the recent findings by Graf and Menter (2022), we particularly expect that HEIs' embeddedness in their respective regional and international knowledge networks is of great importance for their contribution to the renewal of the regional knowledge base.

In order to examine the (potentially heterogeneous) role of HEIs for regional knowledge base renewal, we perform a quantitative empirical analysis on the organizational level (HEIs) in Germany for the period between 2000 and 2018. Our underlying unique database consists of three main sources: i) Detailed information (e.g. non-monetary and monetary) about all public universities and polytechnics in Germany obtained from the Federal Statistical Office of Germany (Destatis); ii) Publication data from Scopus; iii) OECD patent data. Since, we are interested in regional knowledge base renewal, we follow previous studies (e.g. Castaldi, Frenken, and Los 2015) and use new combinations of previously unconnected technology domains (new dyads) as our dependent variable. A combination is considered new to the region if it had not existed in the corresponding region in the previous years since 1978. Apart from controlling for several university level variables (e.g. number of students, third-party funds), we are particularly interested in two main types of embeddedness, which have been shown to play a role in innovation related contexts: i) the regional network embeddedness of HEIs (as in Graf and Menter 2022); ii) embeddedness and visibility in the international academic network (based on publication data) (Wagner, Park, and Leydesdorff 2015; Graf and Kalthaus 2018).

By empirically investigating the favorable conditions for HEIs to foster regional knowledge base renewal, we enrich the current scientific debate about the contribution of HEIs to the re-

gional economic development (e.g. Brekke 2021) in two important aspects. First, we examine the influence of HEIs on the regional knowledge base renewal, which, despite its economic and political importance (Castaldi, Frenken, and Los 2015; Grashof, Hesse, and Fornahl 2019), has not yet been done, particularly with an empirical approach. Second, following suggestions by previous studies (e.g. Carrascal Incera, Kitsos, and Posada 2022; Uyarra 2008), we also consider the heterogeneity between HEIs as well as regions (e.g. structural strong vs. weak regions). With respect to the former, we extend the previous insights by Graf and Menter (2022) and investigate the role of multilevel embeddedness, namely the regional network embeddedness, the embeddedness in the international academic network as well as their potential interaction. Besides contributing to the current scientific discussion about HEIs and regional economic development, our study also provides highly relevant practical insights for (regional) policy-makers to fully comprehend the heterogeneity of HEIs and thus fully exploit the potential of HEIs for knowledge renewal in the region.

The remainder of this paper is structured as follows: In section 2, we review the corresponding literature and derive our central hypotheses. In section 3, we describe the data sources, methods for variable construction and the corresponding main variables for the empirical analysis. Thereafter, section 4 outlines descriptive results with respect to the role of HEIs for the regional knowledge base renewal. In section 5, we outline our econometric approach and present our empirical findings regarding the characteristics of HEIs that contribute the most to the knowledge base renewal of regions, thereby focusing in particular on the multilevel embeddedness. The paper ends with the conclusion in section 6, including limitations and promising future research avenues.

2 Literature review

2.1 A regional perspective on the contribution of HEIs

There is consensus that HEIs play a crucial role in regional economies (Blume, Brenner, and Buenstorf 2017; Fritsch and Slavtchev 2007; Marrocu, Paci, and Usai 2022; Schubert and Kroll 2016). In addition to their role as employers and purchasers (demand-side), they also contribute through their three main missions (teaching, research and 'third mission') to regional innovation and thereby ultimately wealth (Uyarra 2008).[1]

As a *provider of academic education* (e.g. Caniëls and Van den Bosch 2011), HEIs can for instance contribute to regional development by providing and upgrading the regional human capital (Breznitz, Lawton Smith, and Bagchi-Sen 2022; Schartinger, Rammer, and Fröhlich 2006; Stephan 2015). Furthermore, HEIs have been shown to positively influence the regional innovation system (RIS) by being a *provider of academic and scientific knowledge* (e.g. Caniëls and Van den Bosch 2011; Fritsch and Slavtchev 2007). Regional actors can thereby profit from

1. Goldstein, Maier, and Luger (1995) identified eight different functions of research universities that can potentially influence the economic development: (1.) creation of knowledge, (2.) human capital creation, (3.) transfer of existing know-how, (4.) technological innovation, (5.) capital investment, (6.) regional leadership, (7.) influence on regional milieu and (8.) knowledge infrastructure. However, these can in turn be assigned to the corresponding missions.

the accumulated knowledge of HEIs through knowledge spillovers (e.g. labour mobility, collaboration, informal meetings or publications). These knowledge spillovers, which are spatially concentrated, enable companies located in the immediate vicinity of higher education institutions to introduce innovations more quickly, thereby making them more competitive (Feldman 1999; R. Henderson, Jaffe, and Trajtenberg 1998; Jaffe 1989). In this regard, Hegde (2005) further emphasizes that the quality of academic research enhances the localization of the resulting spillovers. In addition to these two rather "traditional" missions, HEIs are also increasingly taking on entrepreneurial roles, focusing on the commercialization of research for instance in the form of patents, spin-offs but also industry collaborations (Etzkowitz et al. 2000; Etzkowitz and Leydesdorff 2000; Perkmann et al. 2013). Regarding the latter, university-industry collaboration has been shown to influence regional wealth (Lehmann and Menter 2016) as well firms' innovation performance (Belderbos et al. 2015). Recent evidence also provides some insights about the promising role of university-industry collaboration for the emergence of radical innovations, at least on the firm-level (Arant et al. 2019; Wirsich et al. 2016). In sum, there exist some empirical studies that have already examined the relationship between higher education institutions and regional innovation from the perspective of different channels (i.e. missions). Nevertheless, we are here interested in one specific type of innovation, namely radical innovation[2], which has so far not been empirically investigated yet – especially with respect to the corresponding RIS.

2.2 HEIs and regional knowledge base renewal

Innovation is generally understood to be the result of (re)combining existing knowledge in a unique way to create something new (Arthur 2007; Basalla 1988; Castaldi, Frenken, and Los 2015). This common understanding of innovation has its roots in Schumpeter´s idea of "Neue Kombinationen" (Schumpeter 1912) and the related work by Weitzman (1998) introducing the concept of "recombinant innovation", which is defined as "[...] the way that old ideas can be reconfigured in new ways to make new ideas." (p. 333).

However, the corresponding degree of novelty can thereby be quite different (Plunket and Starosta de Waldemar 2022; Verhoeven, Bakker, and Veugelers 2016). On the one hand, incremental innovations typically involve the reuse and refinement of existing combinations through exploitative search processes (March 1991; Mewes 2019). They follow established trajectories and are thus considered the usual approach (Dosi 1982; W. Schoenmakers and Duysters 2010; Verhoeven, Bakker, and Veugelers 2016). While these innovations usually have rather marginal novelty and impact, over time they can ultimately have significant effects on the economy (R. M. Henderson and Clark 1990; Lundvall 2016; W. Schoenmakers and Duysters 2010). On the other hand, radical innovations are based on an exploratory search for and development of novel combinations of knowledge pieces that have not been previously combined (March 1991; Fleming 2001; Mewes 2019).[3] Due to the increased costs and risks (in technological as well as commercial

2. Following Castaldi, Frenken, and Los (2015), we use the terms "innovation" and "invention" interchangeably, because the theoretical framework of recombinant innovation also uses the term "innovation". But, it is highlighted that the present study focuses on technological achievements rather than their successful commercialization.

3. Due to the lack of a standardized definition for radical innovations in the literature (Shkolnykova and Kudic 2022), they have also been described as "technological breakthroughs" (Castaldi, Frenken,

terms) associated with exploring new and previously unknown knowledge combinations (Ayres 1988; Fleming 2007; Strumsky and Lobo 2015), radical innovations are relatively rare compared to incremental innovations (Fleming 2001; Hesse and Fornahl 2020; Mewes 2019). However, if they prove successful, radical innovations have the potential to establish entirely new technological approaches (Arthur 2007; Verhoeven, Bakker, and Veugelers 2016) that lead to strong competitive advantages (e.g. Castaldi, Frenken, and Los 2015) and the creation of entirely new markets and industries (e.g. R. M. Henderson and Clark 1990; Tushman and Anderson 1986). Building on the concept of urbanization economies (Jacobs 1969) and the further refinement of related/unrelated variety (Frenken, Van Oort, and Verburg 2007), scholars, so far, primarily stressed the catalyst role of regional variety for searching and finding these new knowledge combinations. However, there is still an ongoing discussion whether unrelated variety (e.g. Castaldi, Frenken, and Los 2015), related variety (Boschma et al. 2022), or both variety measures (Hesse and Fornahl 2020; Miguelez and Moreno 2018) drive the emergence of these novel combinations.

Despite their potential for knowledge renewal and path development within RIS, the influence of HEIs has largely been ignored in this context (Hassink, Isaksen, and Trippl 2019; Nieth and Radinger-Peer 2022; Vallance 2016). In light of their various missions (see section 2.1), it is reasonable to assume that HEIs can act as a crucial source for regional knowledge variety (Callon 1994; Vallance 2016). This broader knowledge base makes it more likely to foster exploratory innovative capabilities (Quintana-García and Benavides-Velasco 2008) and to gain from cross-fertilization (Granstrand 1998; Leten, Belderbos, and Van Looy 2007), both of which can facilitate the combination of previously unconnected pieces of knowledge (Fleming 2001; Nerkar 2003).

2.3 Heterogeneous role of HEIs in renewing the regional knowledge base

Despite the assumed and still to be verified importance of HEIs for regional knowledge renewal, it is not sufficient that a HEI is merely located in a particular region (Bramwell and Wolfe 2008; Fritsch and Slavtchev 2007). HEIs cannot be regarded as a homogeneous group, instead they differ in terms of size, financial resources, reputation, organizational structure and strategic orientation (e.g. focus on research vs. teaching), among other things (Schubert and Kroll 2016; Uyarra 2008; Vallance 2016). Consequently, it is also likely that their contribution to the RIS differs (Huggins and Johnston 2009; Marrocu, Paci, and Usai 2022). So far, however, this heterogeneity has been largely ignored, with a few exceptions (e.g. Huggins and Johnston 2009; Schubert and Kroll 2016), particularly with respect to radical innovations. It therefore remains unclear under which conditions higher education institutions can contribute most to the renewal of the regional knowledge base.

Since the successful creation of radical innovations can hardly be achieved by only relying on *internal* knowledge and capabilities (Christensen 1997; R. Henderson 1993), access to *external* knowledge that can be recombined with internal knowledge is necessary (Dong, McCarthy,

and Los 2015), "disruptive innovations" (Tushman and Anderson 1986) or "atypical innovations" (Uzzi et al. 2013). Nonetheless, in line with recent approaches (such as Grashof and Kopka (2022) and Rizzo et al. (2020)), we refer to them as radical innovations if they introduce new combinations of knowledge.

and W. W. Schoenmakers 2017; Faems, Van Looy, and Debackere 2005; Fornahl, Grashof, and Kopka 2021). The relational perspective is therefore often regarded to be important for understanding the emergence of radical innovations (e.g. Breschi and Lenzi 2014; Hesse and Fornahl 2020). In line with the underlying idea of knowledge spillovers (Griliches 1992; Jaffe 1989), the embeddedness of HEIs within the regional knowledge network may be one very relevant factor in this regard (Graf and Menter 2022). In the specific context of HEIs, regional linkages are assumed to be highly important for an effective knowledge diffusion and thereby ultimately an influence on the regional knowledge base (Huggins and Johnston 2009; Smith 2007; Vallance 2016). However, the degree of regional embeddedness varies between HEIs (Tijssen, Edwards, and Jonkers 2021). Hence, there is indeed the risk of HEIs becoming "cathedrals in the desert", meaning that they interact very little with local industry so that they are of limited use for the regional economy (Morgan 2007; Uyarra 2008). Also in terms of renewing the regional knowledge base, it is reasonable to assume that HEIs with a higher engagement in the regional knowledge network are also the ones that contribute the most (Vallance 2016). As described in section 2.2, HEIs can act as a crucial source for regional knowledge variety, which ultimately can facilitate the emergence of novel knowledge combinations. A high degree of regional network embeddedness would facilitate the local diffusion of the knowledge variety offered by HEIs in this context (Graf and Menter 2022). In that case, a large number of actors in the RIS could use and exploit this knowledge, provided that they have sufficient absorptive capacities (Cohen and Levinthal 1990; Grashof 2021). Consequently, the following hypothesis is proposed:

Hypothesis 1 *The more regionally focused a HEI's relationships are, the more it contributes to regional knowledge base renewal.*

Besides the regional focus of HEI's relationships, especially the network literature has emphasized the promising role of a central network position for the innovation performance in general (Owen-Smith and Powell 2004; Powell, Koput, and Smith-Doerr 1996; Whittington, Owen-Smith, and Powell 2009). However, in the case of radical innovations, despite some recent efforts (Fornahl, Grashof, and Kopka 2021; Graf and Menter 2022), this widely accepted notion still needs to be properly researched, particularly with respect to HEIs. From a theoretical point of view, two possible directions are conceivable with regard to the influence of a central network position of HEIs on the regional knowledge base renewal. On the one hand, a central network position provides access to diverse knowledge sources, which, given sufficient absorptive capacities, can increase the likelihood of creating novel knowledge combinations (Fornahl, Grashof, and Kopka 2021; Gnyawali and Madhavan 2001). Moreover, since centrality measures capture the influential role of network entities, HEIs occupying a central network position also have a relatively high influence on communication flows and thereby on the diffusion of knowledge, which – in line with our Hypothesis 1 – could be relevant for the regional knowledge base renewal (Graf and Menter 2022). Nevertheless, on the other hand, a highly central network position might cause a cognitive overload, meaning that it becomes quite complicated and resource-intensive to absorb, process and integrate the corresponding knowledge, particularly in the case of too much non-redundant knowledge (Ahuja and Katila 2004; Fleming and Sorenson 2001). For example, based on panel data for about 116 firms in the pharmaceutical, chemical and automotive industries, Gilsing et al. (2008) find evidence for an inverted-U shaped influence of network centrality

and explorative patent activities. Furthermore, to secure their central position in the knowledge network, central network entities also tend to avoid rather radical innovations that could cannibalize their existing technologies and associated business models (Amason and Mooney 2008; Chandy and Tellis 2000; Fornahl, Grashof, and Kopka 2021). As a result, they are more likely to suffer from competency traps, as they tend to favor their established routines and the use of related technologies over experimentation with new ones, reducing the opportunities to develop radically new ideas (Ahuja and Morris Lampert 2001; Chang et al. 2012; Fornahl, Grashof, and Kopka 2021; Levitt and March 1988). Since HEIs are of course structurally different from firms, it is unclear whether this also applies to HEIs. However, it is also not completely unrealistic that due to their comparatively strong risk aversion (Benneworth 2007; Swamidass 2013) HEIs might face similar problems. While both theoretical directions are generally conceivable, in light of recent empirical findings stressing the relevance of a central network position for the creation of radical innovations (Fornahl, Grashof, and Kopka 2021; Graf and Menter 2022)[4], we propose the following hypothesis:

Hypothesis 2 *The more centrally a HEI is embedded in the regional knowledge network, the more it contributes to regional knowledge base renewal.*

However, HEIs are actors that operate within multi-level institutional networks (Benneworth and Hospers 2007; Marrocu, Paci, and Usai 2022). The (international) academic research network seems to be particularly relevant in this context (Benneworth, Pinheiro, and Karlsen 2017), given that high-quality research-oriented HEIs also appear to contribute more to the development of the RIS (Malva and Carree 2013; Marques et al. 2019). Following the concept of "local buzz" and "global pipelines" (Bathelt, Malmberg, and Maskell 2004), HEIs are not only important to the "local buzz", but through their engagement in international academic research networks they also provide access to non-local knowledge from "global pipelines" (Benneworth and Hospers 2007; Bramwell and Wolfe 2008). By having access to cutting edge research on a global basis, HEIs can upgrade and renew their own knowledge base, thereby avoiding a potential lock-in situation. Through their different missions (see section 2.1), they should ultimately be more likely to reshape the regional knowledge base (Bramwell and Wolfe 2008). Consequently, the following hypothesis is proposed:

Hypothesis 3 *The higher its international research embeddedness, the more a HEI contributes to regional knowledge base renewal.*

Nevertheless, it is reasonable to assume that these benefits from accessing the international academic network are more pronounced for HEIs that also have a central position in the regional knowledge network. In other words, similar to previous studies (e.g. Gilsing et al. 2008; Breschi and Lenzi 2014), the different types of network embeddedness might interact with each other. Several authors speak in this context of the "antenna" or "gatekeeper" function of public research whereby new knowledge is absorbed from external sources and diffused within the local or

4. The study by Graf and Menter (2022) indeed find different influences of network centrality depending on the type of organization. However, in the case of universities they find a higher likelihood for radical patents irrespective of their network position.

regional system (Fritsch and Schwirten 1998; Graf 2011; Kauffeld-Monz and Fritsch 2013). As such, by occupying a central network position, HEIs can be expected to influence to a high degree knowledge diffusion within the regional knowledge network (Graf and Menter 2022), which makes it more likely that other regional actors can also access the non-local knowledge coming from the engagement in the international academic network. In general, the diffusion of non-local knowledge has been shown to foster the emergence of radical innovations within the corresponding regions (Hesse and Fornahl 2020; Miguelez and Moreno 2018). The geographical distant knowledge is likely to provide new perspectives and routines (even if it comes from a similar technological field)[5], which can spur the generation of radically new ideas and reduce the risk of a potential regional lock-in situation (Arant et al. 2019; Boschma 2005; Hesse and Fornahl 2020). Consequently, the following hypothesis is proposed:

Hypothesis 4 *Centrality in the regional knowledge network and the international research embeddedness complement each other in HEIs' contribution to regional knowledge base renewal.*

3 Data and variables

3.1 Data sources

To empirically examine these hypotheses, we use three main data sources: (i.) German higher education statistics, (ii.) patent and (iii.) publication data. Since we focus on the contribution of HEIs to the renewal of the regional knowledge base, one of our main data sources is the German higher education statistics provided by the Federal Statistical Office in Germany (Destatis). It contains official and detailed information about all higher education institutions in Germany. In general, the German higher education statistics can be divided into non-monetary (e.g. number of students, graduates, employees) and monetary higher education statistics (e.g. personnel expenses, third-party funding), which we both use in our empirical analysis. However, in order to avoid potential distorting effects, we focus on public institutions and leave out the relatively few cases of privately owned HEIs. In total, we have detailed non-monetary and monetary information for 163 public HEIs in Germany (for the time period between 2000 and 2018), from which 45.4% (74) are universities and 54.5% (89) are polytechnics.

In a second step, we link this database with information on scientific publications. We retrieved publication data from Scopus in summer 2022. We accessed the data through the cleaned and enhanced relational database offered by the Competence Centre for Bibliometrics for Germany. The advantage of this data is the comprehensive disambiguation of institution names[6], which outperforms disambiguation systems offered by Scopus or Web of Science (Donner, Rimmert, and Eck 2020). Hence, it has also been used in previous studies investigating the research and science system in Germany (e.g. Krieger et al. 2021). However, since the disambiguation of institutions is critical to the accuracy of bibliometric indicators (Donner, Rimmert, and Eck

5. In fact, previous studies have found that geographical distant knowledge has a higher influence on the emergence of radical innovations if it is cognitively related (Hesse and Fornahl 2020; Miguelez and Moreno 2018).

6. For a detailed description of the corresponding disambiguation system, called *KB system*, please refer to Rimmert, Schwechheimer, and Winterhager (2017)

2020), we even revise the *KB disambiguation system* by checking the HEIs with an affiliation identifier (kb_inst_id) with a official list by the *German Rectors' Conference (HRK)*[7]. In four cases (all polytechnics), we indeed found a mismatch, i.e. polytechnics were on the list by the HRK but had no kb_inst_id. Although these four polytechnics had admittedly small publication activities, we also considered them by assigning them an identifier (based on the affiliation identifier by Scopus). Based on this updated kb_inst_id, we could identify publications (including articles, books and conference proceedings) where at least one author is affiliated to one of the 163 public HEIs in Germany (from 2000 until 2018). As a result, we identified 2,468.669 publications in total.

To finally enrich our database with patent data, we identified patents of all German HEIs from the OECD Regpat and HAN databases (August 2022). In the Regpat database, many applicants appear with different versions of their organization name, which makes identification of all patents of an organization challenging. The HAN database offers a solution to this problem by providing common applicant IDs for organizations that appear with different spellings or typos. However, even after consulting the HAN database, there are still many different variants of names for unique applicants. We performed a manual search to identify all HAN IDs referring to each German public HEI to establish consistency within our data. We then collected all patents from HAN and additional information on the patent from Regpat, considering the geographical location (NUTS 3 regions) of the applicant. To avoid a possible bias, we excluded all HEIs that did not have a single patent during the entire period (2000-2018).[8] As a consequence, in total 12 HEIs are excluded so that our final sample for the analysis consists of 151 public HEIs in Germany.

For further control variables on the regional level (e.g. GDP per capita), we collect regional data from the INKAR (in German: "Indikatoren und Karten zur Raum- und Stadtentwicklung") database of the BBSR (in German: "Bundesamt für Bauwesen und Raumordnung").

3.2 Dependent variable

To examine the influence of HEIs on the regional knowledge base renewal, we calculate the share of regional radical patents[9] (new to the region) coming from HEIs. There exist different ways for the identification of radical patents, such as backward citations or forward citations (Fornahl, Grashof, and Kopka 2021; Hesse and Fornahl 2020). Taking into account the fundamental idea of recombinant innovation (Weitzman 1998), which recognizes that innovation arises from the (re)combination of pre-existing knowledge elements in a new and unique manner (Arthur 2007; Basalla 1988; Castaldi, Frenken, and Los 2015), we measure radical patents by the pioneering combination of technology classes listed on patents (e.g. Grashof, Hesse, and Fornahl 2019; Verhoeven, Bakker, and Veugelers 2016). In doing so, we follow previous studies (e.g. Hesse and

7. The corresponding list can be accessed under: www.hochschulkompass.de/en/higher-education-institutions.html.

8. As a first robustness check, we also kept these HEIs in our sample. The corresponding results remain stable and can be provided upon request.

9. Despite some commonly acknowledged limitations (Griliches 1998), the majority of current research utilizes patent-based metrics in this context (Arant et al. 2019; Hesse and Fornahl 2020).

Fornahl 2020) and identify in a first step all combinations of 4-digit codes[10] of the International Patent Classification (IPC) that appear on patent filings per region and year (priority year) between 2000 and 2018. In a second step, we compare these annual IPC combinations to all previously existing ones (between 1978 and the preceding year) in each NUTS 3 region in Germany. In other words, an IPC combination that appears for the first time is considered completely new to the corresponding NUTS 3 region in Germany (since 1978) and therefore deemed radical (Grashof, Hesse, and Fornahl 2019; Hesse and Fornahl 2020). Our main dependent variable (*rad_share_hei*) is then calculated by dividing the number of radical patents (new to the region) created by HEIs by the total number of radical patents in the respective NUTS 3 region.

3.3 Independent and control variables

For our measures of regional network embeddedness, we follow Graf (2017) and reconstruct the knowledge networks for 5-year moving windows[11] through applicants linked by common inventors. As indicated in 2.2, we are interested in two different indicators in this context: (i.) To capture the regional orientation of HEI's relationships, we calculate the share of internal linkages of the HEI within the regional network (*share_internal*). (ii.) We calculate the degree centrality to determine the centrality of HEIs in the corresponding regional knowledge network (*deg_cent*). However, since HEIs operate within multi-level institutional networks (Benneworth and Hospers 2007; Marrocu, Paci, and Usai 2022), we also consider relations to the international academic research community. Based on publication data, we therefore calculate the share of international co-publications (i.e. at least one co-author needs to be affiliated to an organization based outside Germany) for each HEI (*copub_share_int*).

Moreover, we also control for further characteristics of HEIs. In order to capture the research substance of HEIs we calculate the number of publications per research associate (*pub_pe*). Research associates include all professors (permanent/temporary), lecturers and assistants/teaching staff (permanent). In addition, we use the number of patent applications (*epo_applns*) as a proxy for the overall capacity to produce ideas with potential for industrial application. In this context, we also capture the industry-orientation of HEIs by computing the share of third-party funding from the industry in total third-party funding (*third_indust_share*). More in line with the traditional "mission" of HEIs, we additionally consider the number of students per research associate (*studis_pe*). Furthermore, we control for potential regional influences. Since it might be easier for HEIs to generate knowledge combinations that are new to the region, if the corresponding region has overall a small number of new combinations, we calculate the share of radical patents in total patents within NUTS 3 regions in Germany (*rad_share*). Lastly, since the relevance of HEIs for regional development might differ between structurally strong and weak regions (Kempton 2015), we also control for these structural differences in terms of economic performance. In line with previous studies (e.g. Iammarino, Rodriguez-Pose, and Storper 2019; Kopka and Grashof 2022), we create a dummy variable that equals one if regions

10. Consistent with earlier research (e.g. Mewes and Broekel 2020; Hesse and Fornahl 2020), the aggregation of technology classes at the 4-digit IPC level is argued to be the most appropriate approach, as it provides a maximum number of technologies while also ensuring a sufficiently large number of patents.

11. This means the network for the year 2000 is based on patents filed from 1996 to 2000, thereby assuming a link decay of five years.

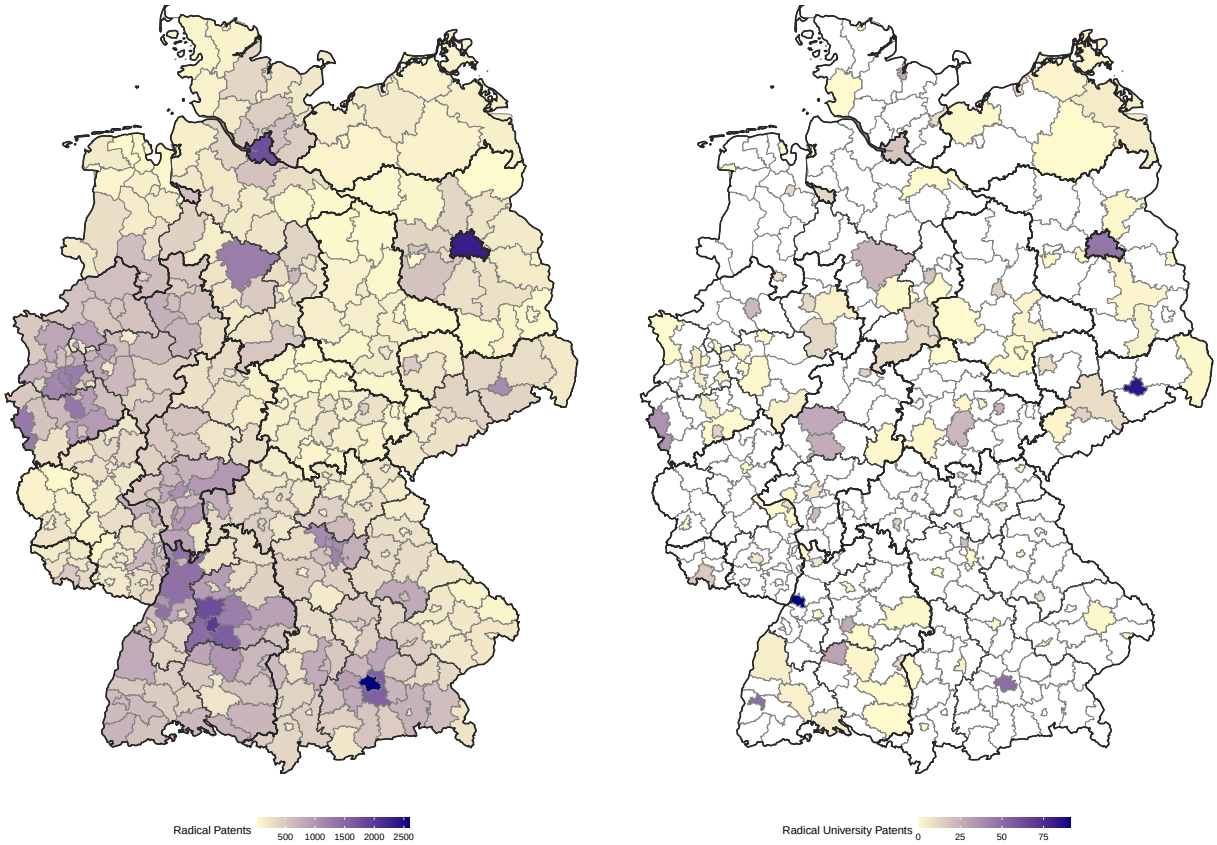
have (equal or) more than 75% of the national average, indicating that they are structural strong regions, or zero if regions have less than 75% of the national average (*GDP_strong*).

4 Descriptive analysis

Our definition of radical patents (see Section 2.2) implies that any radical patent changes the structure of the regional knowledge space by adding novel combinations to the network of technologies. Figure 1a shows a map of Germany where NUTS 3 regions are filled with darker colors the more radical patents (new to the region) they produced in the period 2000 to 2018. We observe that the highly innovative large cities, such as Munich, Berlin, Stuttgart and Hamburg produce most radical patents. There are other hotspot regions in the Southwest of Germany around Stuttgart and Karlsruhe as well as in the West (Cologne, Aachen) and North-center (Hanover). Despite some notable exceptions (e.g. Berlin, Dresden), most regions from Eastern Germany tend to be less active in generating radical patents. Focusing on the HEIs in Germany, Figure 1b shows the number of radical patents filed by the local universities and polytechnics. Regions in white do not host any of the HEIs in our sample, for the other regions, a higher number of radical patents corresponds to darker colors. While the general pattern looks similar compared with the overall distribution of radical patents, there are some striking differences. Instead of Munich, we can identify Karlsruhe and Dresden as regions with the highest number of radical patents by HEIs, followed by Munich, Freiburg (Breisgau) and Berlin. Moreover, if we focus on the radical patents filed by HEIs, the Eastern German regions generally seem to perform somewhat better than in the case of the total number of radical patents, suggesting their particular importance to the knowledge renewal in these regions.

Looking more closely into the HEIs producing these radical patents (see Table 3), we find only universities at the top of the ranking (U Karlsruhe (KIT), TU Dresden, U Freiburg, etc.). It is noteworthy that in the list technical universities are over-represented, e.g. in large cities with several HEIs, such as Munich or Berlin, we find the respective technical universities among the top 10. To better understand the magnitude, it is important to know that our sample includes only 11 technical universities in total. Of these 11 technical universities, no less than 5 technical universities made it into the top 10 list of HEIs with the highest average number of radical patents (between 2000 and 2018). In terms of their relative importance for renewing the regional knowledge base (see Table 4 with the HEIs ranked according to their share in all regional radical patents), we find several smaller regions in the top spots. In the Ilm-Kreis, almost 10% of all radical patents are filed by the local university (TU Ilmenau). In Magdeburg, Oldenburg, Rostock or Goslar, regions which, apparently, do not produce many radical patents, less than one patent per year is sufficient to account for 5 to 7% of all radical patents. However, we also find a high HEI share in some of the strong (in terms of the number of radical patents) regions, in particular, Karsruhe, Freiburg (Breisgau) and Dresden.

Apparently, the role of HEIs for regional knowledge base renewal can be important in different types of regions. To scrutinize this issue further and observe changes over time, we plot the average share of radical patents by HEIs over time in Figure 2. In Figure 2a, we distinguish between weak and strong regions (according to the definition provided in Section 3.3) and observe



(a) Overall **(b)** by HEIs

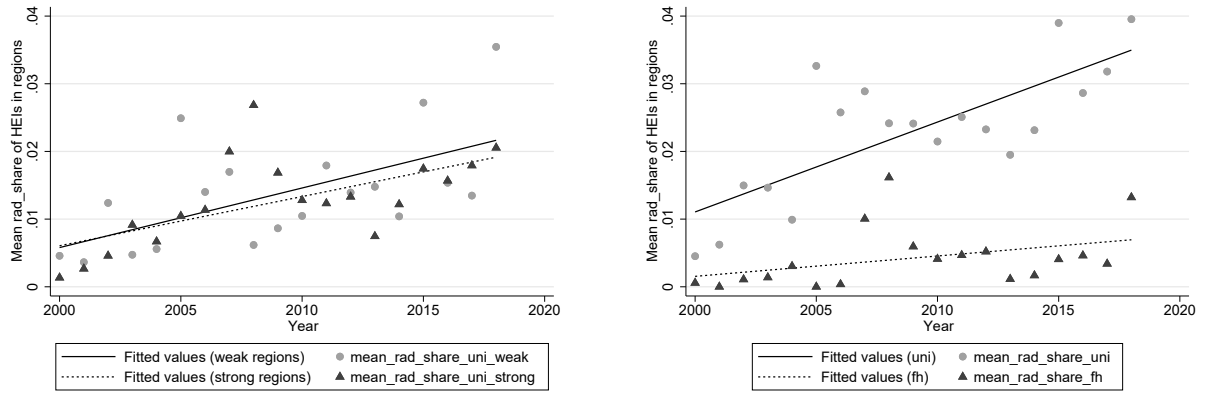
Figure 1: Number of radical patents (new to the region) in German NUTS3 regions (2000–2018)

rather low absolute values but a strong positive trend for both types of regions, albeit slightly more pronounced in the case of structurally weak regions. Based on the fitted trend, in all regions, the share of radical patents by HEIs increased significantly from less than 1% in the year 2000 to about 2% in 2018. Figure 2b shows differences between HEI types, i.e. universities (uni) and polytechnics (fh), in their contribution to regional knowledge base renewal. The difference between the two HEI types is quite striking in terms of absolute shares but also in terms of their average developments. The fitted trend for universities shows their shares to more than triple from 1% in 2000 to more than 3% in 2018 whereas polytechnics, remain below 1% despite a positive trend. This indicates the historically rooted difference between these two types of HEIs within the German research and teaching landscape. The polytechnics have a relatively stronger focus on teaching but also on applied research often in collaboration with (local) industry. Universities, on the other hand, strive for research excellence quite often with a focus on basic research.

5 Econometric approach and regression results

5.1 Fixed effects regression approach

Since our database has a (unbalanced) panel structure of 151 public HEIs in Germany from 2000 to 2018, we conduct a panel regression analysis on the HEI level in order to test our proposed



(a) by region type **(b)** by HEI type

Figure 2: Average share of radical innovations in regions of higher education institutions

hypotheses (see section 2.2). Based on the results of the robust Hausman test (e.g. Schaffer and Stillman 2016; Wooldridge 2002), we choose to estimate a fixed effect panel regression (with robust standard errors). The stylized model has thereby the following form:

$$rad\_share\_hei_{i,t} = \beta_0 + \beta_1 deg\_cent_{i,t-1} + \beta_2 share\_internal_{i,t-1} + \beta_3 copub\_share\_int_{i,t-1} + \beta_4 copub\_share\_int\#deg\_cent_{i,t-1} + \beta_5 Controls_{i,t-1} + \omega_i + \alpha_t + \mu_{i,t} \quad (1)$$

where $rad\_share\_hei_{i,t}$ refers to the share of radical innovations within NUTS 3 regions for each HEI (i) and each time period (t). $deg\_cent_{i,t-1}$, $share\_internal_{i,t-1}$ and $copub\_share\_int_{i,t-1}$ are our three main independent variables. They capture the degree centrality, share of internal linkages within the regional network and the share of international co-publications respectively. $Controls_{i,t-1}$ stands for a set of control variables (presented in section 3.3) which potentially influence our dependent variable. To mitigate possible endogeneity problems in the regressions, all independent and control variables are lagged by one year, denoted by $t-1$. Moreover, we include university (ω_i) and time (α_t) fixed effects in order to control for unobserved heterogeneity at these two dimensions. Finally, $\mu_{i,t}$ represents the residuals.

Table 1 provides an overview, including summary statistics, for all used variables.[12] In line with previous studies (e.g. Grashof, Hesse, and Fornahl 2019), we see that radical innovations in terms of new 4-digit IPC combinations, are not that frequent (on average the considered NUTS 3 regions in Germany have a share of radical patents (rad_share) of 23.7%), even when they are only new to the region and not to the whole country or world. Moreover, as expected, HEIs differ in terms of of their mission orientation as well as their size. While the average ratio of research associates to students is just under 36, there are relatively strong deviations, where on a maximum one HEI even has a ratio of 818. Similar disparities can also be observed with regard to publication and patent activities of HEIs.

12. As indicated by the pairwise correlation matrix (see Table 5 in the appendix), the correlation between our variables is rather low. Thus, multicollinearity does not appear to be a problem for our empirical analysis.

Table 1: Descriptive statistics

Variable	Description	Obs	Mean	Std. Dev.	Min	Max	Data source
rad_share_hei	Share of radical patents by HEI	2809	0.014	0.047	0	1	OECD Patent
copub_share_int	Share of international co-publications	2770	0.35	0.157	0	1	Scopus
share_internal	Share of internal links in the regional network	1294	0.216	0.256	0	1	OECD Patent
deg_cent	Degree centrality in the regional network	1661	0.037	0.048	0	0.317	OECD Patent
pub_pe	Scientific publications per research associate	2831	1.212	1.511	0	11.688	Scopus & Destatis
epo_applns	Number of EPO applications (annual)	2831	2.816	6.297	0	65	OECD Patent
third_indust_share	Share of third party funding from industry	2824	0.259	0.188	0	1	Destatis
studis_pe	Number of students per research associate	2831	36.141	36.088	7.508	817.584	Destatis
rad_share	Share of radical patents in all regional patents	2830	0.237	0.12	0	1	OECD Patent
GDP_strong	Regional dummy: 1 if per capita GDP in top 25%, zero otherwise	2831	0.656	0.475	0	1	INKAR

5.2 The role of (multilevel) embeddedness of HEI in renewing the regional knowledge base

In this section, we present and interpret the results of our fixed effects regression approach. In total, we estimated four different models, subsequently adding measures of HEI embeddedness on different levels. Model 1 is the baseline model, including only the control variables. In Model 2, we capture regional embeddedness by including the share of HEI's internal relationships within the regional knowledge network (*share_internal*) and the degree centrality of HEI's (*deg_cent*) in order to test hypotheses 1 and 2. Subsequently, Model 3 adds embeddedness in the international research community by including the share of international co-publications (*copub_share_int*). Lastly, in Model 4 we include an interaction term between *copub_share_int* and *deg_cent*. The results of these four models are presented in Table 2. We can already observe interesting results in the baseline model (Model 1), which also remain robust throughout all other models. First, we find evidence that the degree of research activities of HEIs also matters for the creation of radical patents that are new to the region. HEIs with a high number of publications per research associate also create more knowledge combinations that are novel to the region. This result goes in line with previous studies emphasizing the relevance of high-quality research-oriented HEIs for the overall development of the RIS (e.g. Malva and Carree 2013; Marques et al. 2019). Second, we find a significant influence of the number of patent applications, indicating that a higher capacity to produce ideas with potential for industrial applications is conducive to the creation of rather radical patents. In view of both results, it can therefore be summarized that the overall

research activities (expressed by publications and patents) are supporting the capacity of HEIs to renew the regional knowledge base. Third, our results also show that the regional context matters, in particular the total share of radical innovations within a region. In regions that are characterized by a comparatively small share of this type of innovation, HEIs appear to play a even more relevant role for the knowledge renewal than in regional innovation systems where new combinations are relatively more frequent. In other words, on average, HEIs particularly contribute to knowledge renewal in regions where incremental innovation along established paths is predominant. This goes in line with previous theoretical and case study contributions that stress the relevance of HEIs for regional development and innovation patterns in less developed regions (e.g. Kempton 2015; Marques et al. 2019).

Table 2: Regression results: The role of multilevel embeddednesss

VARIABLES	(1) rad_share_hei	(2) rad_share_hei	(3) rad_share_hei	(4) rad_share_hei
l.deg_cent		-0.282**	-0.283**	-0.807***
		(0.121)	(0.121)	(0.268)
l.share_internal		0.0377*	0.0377*	0.0364*
		(0.0203)	(0.0203)	(0.0199)
l.copub_share_int			0.00671	-0.0322
			(0.0240)	(0.0216)
l.copub_share_int#l.deg_cent				1.262**
				(0.632)
l.pub_pe	0.00412***	0.00740**	0.00736**	0.00721**
	(0.00147)	(0.00362)	(0.00359)	(0.00344)
l.epo_applns	0.00062**	0.000928***	0.000927***	0.000834***
	(0.000266)	(0.000337)	(0.000338)	(0.000317)
l.third_indust_share	0.00584	0.0470	0.0466	0.0438
	(0.00464)	(0.0387)	(0.0381)	(0.0373)
l.studis_pe	-0.000014	-0.000339	-0.000339	-0.000298
	(0.000022)	(0.000231)	(0.000230)	(0.000198)
l.rad_share	-0.02165*	-0.0579*	-0.0580*	-0.0618*
	(0.0117)	(0.0302)	(0.0303)	(0.0313)
l.GDP_strong	0.0109	0.0149	0.0150	0.0165
	(0.00732)	(0.00973)	(0.00980)	(0.0104)
Constant	-0.0019	-0.0103	-0.0120	0.00244
	(0.00488)	(0.0208)	(0.0233)	(0.0204)
Year Fixed Effects	Yes	Yes	Yes	Yes
University Fixed effects	Yes	Yes	Yes	Yes
Observations	2,651	1,208	1,208	1,208
Number of groups	151	112	112	112
R-squared (within)	0.030	0.078	0.078	0.083

Note: Robust standard errors in parentheses *p<0.1; **p<0.05; ***p<0.01

Coming to our main explanatory variables of interest, in Model 2 we investigate the influence of the degree centrality as well as the regional focus of HEIs relationships. Regarding the latter, we find evidence for a significant positive influence ($\beta = 0.0377; p < 0.1$), which remains robust throughout all models. Hence, the more regionally focused the relationships of HEIs are, the more they contribute to the regional knowledge base renewal. A higher regional engagement of HEIs can facilitate the local diffusion of their knowledge variety and it can provide them access to the regional knowledge base, which makes it more likely that they find knowledge

combinations that are new to the region. Thus, there is no evidence to reject hypothesis 1.

Nevertheless, with respect to the degree centrality of HEIs, we find that a highly central network position seems to negatively affect the capacity of HEIs to contribute to the regional knowledge base renewal ($\beta = -0.282; p < 0.05$).[13] We therefore have to reject our second hypothesis that HEIs benefit from a central network position within the regional knowledge network in terms of generating novel knowledge combinations to the corresponding regional knowledge space. Instead, our results tend to provide evidence to potential disadvantages of a highly central position within a regional network in terms of coming up with radically new ideas, e.g. cognitive overload (Ahuja and Katila 2004; Fleming and Sorenson 2001) and competency traps (Ahuja and Morris Lampert 2001; Fornahl, Grashof, and Kopka 2021; Levitt and March 1988).

Since HEIs are actors operating within multi-level institutional networks (Benneworth and Hospers 2007; Marrocu, Paci, and Usai 2022), in Model 3 we investigate the influence of the share of international co-publications. Our results indicate that there is no significant influence in this regard. HEIs with a higher share of international co-publications, so being more engaged within the international academic research network, thus do not contribute significantly more to the renewal of the regional knowledge base. No direct effect of the share of international co-publications can therefore be detected, so we have to reject hypothesis 3.

Although we do not find evidence for a direct effect of the engagement in the international academic research network, we can detect an indirect effect (see Model 4). We find a significant and positive interaction term between the share of international co-publications and the degree centrality of a HEI ($\beta = -1.262; p < 0.05$). The centrality in the regional knowledge network and the international research connections of HEIs therefore complement each other in contributing to the regional knowledge base renewal. For a better interpretation of this result, the interaction between the two continuous variables is illustrated in a contour plot (see Figure 3).

Having a highly central network position and almost no links to the international academic research network decreases the share of radical patents of HEIs. This goes in line with our findings with respect to the overall negative influence of the degree centrality. However, when such a central position within the regional knowledge network is accompanied with a elaborated access to the international academic research network HEIs are more likely to come up with knowledge that is radically new to the corresponding region. Hence, while a highly central position in the regional network is rather detrimental to the emergence of radical patents through HEIs (e.g. competency traps), combined with a relatively strong degree of international research connections the capacity of HEIs to renew the regional knowledge base is reinforced. In this regard, we provide empirical evidence to the "antenna" or "gatekeeper" function of public research (Fritsch and Schwirten 1998; Graf 2011; Kauffeld-Monz and Fritsch 2013). Given our results, we can therefore not reject hypothesis 4.

Overall, the findings of our study imply that generalized statements about the role of HEIs in regional knowledge renewal are inappropriate and might be misleading. Instead, the influence

13. Since it might make a difference if HEIs are central in a more inward or outward oriented region, as a robustness check, we additionally control for the overall external orientation of the regional network by including the share of outside linkages of the regional knowledge network. The corresponding results remain stable and can be provided upon request.

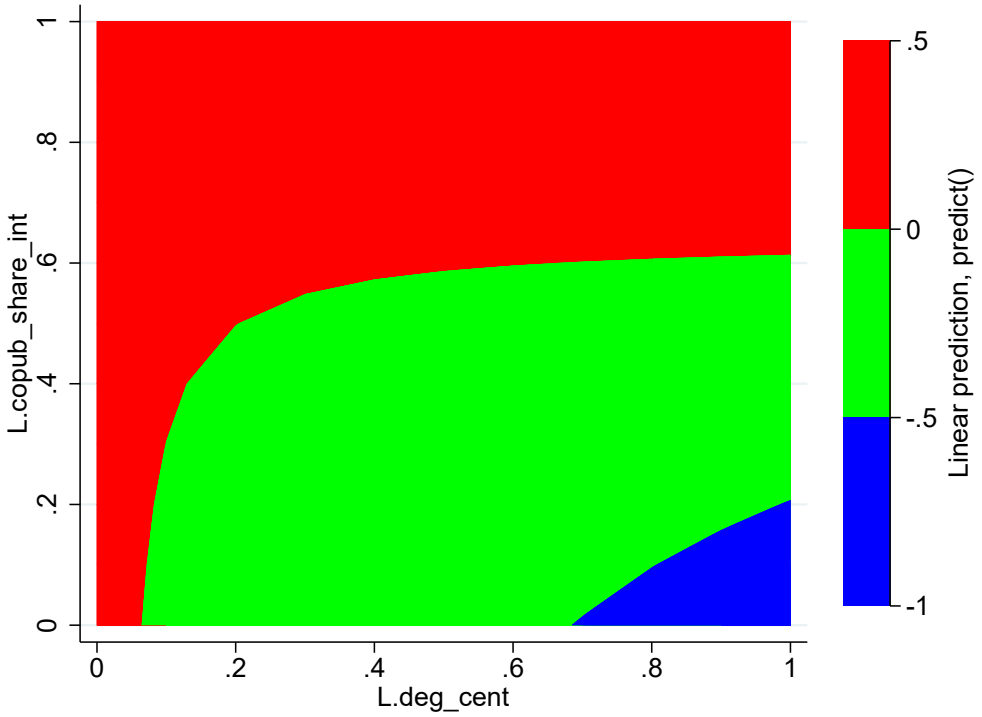


Figure 3: Predicted probability of rad_share_hei by l_copub_share_int and l_deg_cent

of HEI is quite heterogeneous, depending on the respective characteristics of HEI as well as on the regional context. With respect to the former, our results indicate that a central position in the regional network can prevent the emergence of radical innovations, when the corresponding HEI does not have sufficient external linkages to the international academic research community. In addition, our results also indicate a positive impact of more regionally focused relationships of HEIs.

6 Conclusion

There is no doubt about the supportive or even critical role of institutes of higher education (HEI), such as universities and polytechnics, for regional development and innovation (e.g. Drucker 2016; Valero and Van Reenen 2019). The channels for this impact are multiple and correspond to the three missions of HEIs, teaching, research and knowledge transfer (Uyarra 2008). With this study we do not challenge this conventional wisdom but rather aim at contributing to a more nuanced picture. The way HEIs contribute to regional knowledge base renewal, as one piece of the puzzle in regional development, depends on characteristics and strategies of the HEI but also on the broader innovation systems in which they are embedded.

We hypothesized that HEIs with a regional focus and a central position in the regional network (i.e. many local linkages) should have the highest potential in shaping and redirecting the knowledge base of a region. While we find support for our hypothesis regarding the regional focus, our results indicate that linkages with many different partners in the knowledge network (irrespective of their location) are associated with a lower share of radical patents in the region.

This finding might be explained by cognitive overload or competency traps. One might also argue that many linkages indicate an abundance of other actors in the respective region who also develop radical patents so that the role of the individual HEI is relatively weaker. As we saw in the descriptive analysis, the strongest HEIs in terms of the number of radical patents are not necessarily the ones with the largest regional contribution. In terms of their embeddedness in international research communities, we expected that due to the inflow of diverse knowledge, openness would contribute to knowledge base renewal. However, our results indicate that this is only the case if such "global pipelines" are combined with many partners in the regional network ("local buzz") who are able to absorb this external knowledge. In that sense, HEIs that act as gatekeepers in the regional network contribute most to regional knowledge base renewal. We also find that HEIs with strong research output in terms of publications and patents contribute relatively more to renewing the knowledge base. These positive effects of HEIs are stronger in regions where radical novelties are relatively rare.

The plurality of our results therefore support the view of HEIs as heterogeneous actors in the regional innovation system (RIS) (Huggins and Johnston 2009). Not all HEIs contribute equally to the renewal of the regional knowledge base, instead it depends on their characteristics as well as on the regional context. Consequently, this heterogeneity should also be reflected in the corresponding higher education and regional policy approaches. Besides further supporting the research excellence of HEIs, our results indicate that a pure focus on promoting the international research collaboration will not improve the capacity of HEIs to introduce radical patents to the corresponding RIS. Instead of this rather narrow relational focus, it is crucial to simultaneously consider the regional embeddedness. When promoting international research cooperation of HEIs [14], the connection to the regional knowledge network should therefore be considered (and eventually supported) at the same.

However, when considering our results, some limitations need to be discussed, which can also serve as starting points for future scientific work. First, we operationalise knowledge renewal and regional embeddedness through patent data, which has some well-known drawbacks, such as the fact that not all inventions are also patented (e.g. Griliches 1998). Related to this, in line with previous studies (e.g. Grashof, Hesse, and Fornahl 2019) we measure radical patents based on new combinations of IPCs. While this is a widely used approach, there are other measures for radical patents based on their citation structure or textual content (e.g. Shane 2001; Squicciarini, Dernis, and Criscuolo 2013; Arts, Hou, and Gomez 2021), but also non-patent-based indicators (e.g. Hervas-Oliver et al. 2019) that could be used in future studies in this context. Third, in the case of our embeddedness measures we do not explicitly consider the partner configurations in terms of their diversity, characteristics or their stability over time. For future research, a more nuanced network analysis with respect to the partner configuration and the stability might therefore be quite promising in order to get further insights about the role of HEI's embeddedness. Lastly, due to data limitations (with respect to the detailed information about HEIs) our analysis is only conducted for Germany and public HEIs. Since the German Higher Education system might be different from other countries, additional studies are needed

14. In 2020, the Federal Ministery of Education and Research in Germany alone spent 1.283 billion EUR on international research cooperation (BMBF 2021).

to allow for generalizations. Moreover, the potential influence of private HEIs might also be worth to investigate in future studies not only in the U.S. (e.g. Hegde 2005) but also in the European higher education context.

Despite these limitations, this paper makes a valuable contribution to the ongoing debate about the relevance of HEIs for regional development by providing empirical evidence of their heterogeneous role in regional knowledge base renewal. Specifically, we emphasize the promising influence of multilevel embeddedness, which involves being embedded in both the regional knowledge network and the international academic research network. Our findings suggest that HEIs should not be regarded as universal drivers of regional knowledge base renewal, but instead their specific capacities and potentials should be acknowledged and supported.

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A Tables

Table 3: Top 10 HEIs by their number of radical patents

Top 10 HEI	NUTS 3 region	Federal state	Radical patents (new to region)	
			number	regional share
U Karlsruhe (KIT)	Karlsruhe	Baden-Wuerttemberg	90	8.7%
TU Dresden	Dresden	Sachsen	80	7.1%
U Freiburg i.Br.	Freiburg im Breisgau	Baden-Wuerttemberg	50	7.8%
TU München	München	Bayern	35	1.4%
TH Aachen	Städteregion Aachen	Nordrhein-Westfalen	31	2.4%
U Marburg	Marburg-Biedenkopf	Hessen	28	4.9%
TU Berlin	Berlin	Berlin	28	1.2%
U Kiel	Kiel	Schleswig-Holstein	25	7.3%
U Hannover	Region Hannover	Niedersachsen	24	1.9%
U Gießen	Gießen	Hessen	23	4.7%
TU Ilmenau	Ilm-Kreis	Thueringen	23	9.9%

Table 4: Top 10 HEIs by their mean share of radical patents

Top 10 HEI	NUTS 3 region	Federal state	Radical patents (new to region)	
			number	regional share
TU Ilmenau	Ilm-Kreis	Thueringen	23	9.9%
U Karlsruhe (KIT)	Karlsruhe	Baden-Wuerttemberg	90	8.7%
U Freiburg i.Br.	Freiburg im Breisgau	Baden-Wuerttemberg	50	7.8%
U Kiel	Kiel	Schleswig-Holstein	25	7.3%
U Magdeburg	Magdeburg	Sachsen-Anhalt	14	7.1%
TU Dresden	Dresden	Sachsen	80	7.1%
U Oldenburg	Oldenburg	Niedersachsen	11	6.7%
U Rostock	Rostock	Mecklenburg-Vorpommern	7	5.3%
TU Clausthal	Goslar	Niedersachsen	12	5.1%
U Marburg	Marburg-Biedenkopf	Hessen	28	4.9%

Table 5: Pairwise correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) rad_share_hei	1.000									
(2) copub_share_int	0.108***	1.000								
(3) share_internal	-0.005	-0.116***	1.000							
(4) deg_cent	0.305***	0.246***	-0.121***	1.000						
(5) pub_pe	0.261***	0.313***	-0.015	0.464***	1.000					
(6) epo_applns	0.294***	0.222***	0.006	0.500***	0.625***	1.000				
(7) third_indust_share	-0.059***	-0.111***	0.024	-0.147***	-0.218***	-0.094***	1.000			
(8) studis_pe	-0.031*	0.020	-0.032	-0.069***	0.048**	-0.041**	-0.036*	1.000		
(9) rad_share	0.004	-0.130***	-0.072***	0.032	-0.218***	-0.237***	-0.011	0.005	1.000	
(10) GDP_strong	-0.003	0.054***	0.027	-0.024	0.122***	0.145***	0.039**	-0.025	-0.265***	1.000

*** p<0.01, ** p<0.05, * p<0.1

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