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Research Paper

Knowledge creation and patenting by European higher education institutions–evidence from a new dataset (KC-HEI) ⋆

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ABSTRACT

Understanding how European universities convert knowledge into market-oriented innovation is crucial for EU competitiveness. However, large-scale empirical analysis has been limited due to the difficulty of linking patent data with institutional characteristics. This paper uses a novel micro-level database to shed new light on the role of European universities in patented innovation. It provides comprehensive data on the direct patenting activities of higher education institutions (HEIs) across 31 European countries (1980–2019), including patent counts, citation records and patent quality indicators, across 128 technological sectors and in artificial intelligence (AI) field. Our unique PATSTAT-ETER crosswalk matches patent and institutional data, enabling micro-level comparisons between 866 patenting institutions and over 2,100 non-patenting higher education institutions (HEIs) in Europe. We reveal extreme concentration in university patenting: three-quarters of European universities (and half of STEM institutions) have no direct patent activity with the top five global patent offices, while institutions from just five countries (the UK, Germany, France, Belgium and Switzerland) account for 70% of all university patent applications. Academic patenting clusters regionally, mirroring Europe's economic disparities. The key institutional factors related to universities' patenting success, taking region- and country-specific factors into account, are their age (experience/tradition), size, wealth, research orientation, and teaching load.

1. Introduction

The creation of new knowledge and innovation has long been analysed through patenting activity, which reflects the market-oriented knowledge developed by firms (Aiello et al., 2024; Behrens & Trunschke, 2020; Caviggioli et al., 2023a; Lotti & Marin, 2013) and/or by universities/research institutions (Angori et al., 2024; Caviggioli et al., 2023a,b; Coupé, 2003; Duarte et al., 2020; Gurmu et al., 2010; Henderson et al., 1998; Saragossi & van Pottelsberghe de la Potterie, 2003; Squicciarini et al., 2012; Whalley & Hicks, 2014) and co-patenting between private firms and universities (Meier et al., 2023; Wolszczak-Derlacz, 2025). However, despite the fundamental role of universities in knowledge production (European Patent Office, 2024) and the increasing emphasis placed on their third mission activities (Compagnucci & Spigarelli, 2020; Etzkowitz & Leydesdorff, 1997), which aligns with current

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EU innovation strategies that aim to strengthen universities as 'drivers of the EU's global role and leadership' (Draghi, 2024; European Commission, 2022a,b), the evidence is a cause for concern.

The European Patent Office (EPO)[1] reports that in European countries, universities and public research organisations account for only 8% of patent applications, compared to 69% from large companies and 23% from SMEs and individual inventors.[2] European universities lag behind the global leaders in terms of patenting: of the world's top 50 patenting universities between 2020 and 2022,[3] 18 were based in the United States (led by the University of California) and 18 in China but only two in Europe (both in the UK).[4] The top 10 in the Sciamago 2025 innovation ranking[5] include nine Chinese universities and one US university, but none from Europe. Furthermore, fewer than 10% of patents in Europe are jointly filed by firms and universities.[6] Consequently, the debate on the 'European paradox' remains open. The term was coined by the European Commission (European Commission, 1995) to describe the inability of European countries to translate excellent research into market-oriented innovations and competitive advantages. Whether this paradox exists remains a subject of debate (see Argyropoulou et al. 2019 and Nagar et al. 2024 for recent reviews), as several authors have noted that Europe lags behind global competitors such as the US not only in knowledge commercialisation and university–industry cooperation, but also in the quality of scientific output and publications (Conti & Gaulé, 2011; Dosi et al., 2006; Rodríguez-Navarro & Narin, 2018). Nevertheless, even the flagship EU research programme (the European Research Council, ERC), whilst accruing a greater number of patent citations, faces challenges associated with the European paradox when it comes to spillover effects and the transformation of excellent science into inventive activities (Nagar et al., 2024).

These observations raise two fundamental research questions that could help us to understand the patent landscape in the European higher education sector. Firstly, are some European higher education institutions (HEIs) systematically excluded from patent-based innovation activities? Secondly, what factors (e.g. institutional, structural, financial or location-related) determine their exclusion from technology transfer processes? Thus far, precise answers to these questions, based on a Europe-wide sample of universities, have been constrained by the difficulty of linking patent data with the characteristics of universities across Europe.

We address this research gap by constructing a novel micro-level dataset called KC-HEI (knowledge creation by higher education institutions). KC-HEI provides information on the patenting activity of nearly 900 universities in 31 European countries over four decades (1980–2019), which we then compare with a large sample of around 2100 non-patenting universities. Creating our dataset involved complex matching between granular (i.e. institution-level) patent records and the characteristics of university units. This was no trivial task, as patent-level records from sources such as PATSTAT do not provide a coherent way to identify universities among the patent assignees that can be merged with existing datasets containing characteristics of university units, such as the European Tertiary Education Register (ETER) database (Lepori et al., 2023). We have overcome this limitation by creating a unique crosswalk between the codes (and names) of universities as patent assignees in PATSTAT and the identifiers of universities in external datasets using the ETER ID.

In our analysis, we consider universities' patenting activity as one possible proxy for innovation and knowledge creation (Davies et al., 2023; Nagaoka & Motohashi, 2010) (alongside licensing, spin-offs, trademarks, university entrepreneurship, etc. – (Carmine et al., 2025)), while accounting for all its limitations (Dornbusch et al., 2013; Gambardella et al., 2008; Nagaoka & Motohashi, 2010). Our focus is on direct university patenting, i.e. patents filed by the universities themselves. This represents approximately half of all academic patenting activity (European Patent Office, 2024; Neuhäusler & Frietsch, 2024), with the remainder typically involving patents filed by other entities or individual inventors (Dornbusch et al., 2013; Geuna & Nesta, 2006). This choice is guided both by data-driven motivation (direct patents provide a harmonised and relatively more easily observable measure across the large sample of European HEIs in our dataset) and by research motivation (direct patents allow us to examine university-owned technology transfer and the performance of HEIs not only in terms of research leading to patents, but also their institutional capacity as patent applicants). Indirect patents, where researchers (including university employees) file in their own name or via firms, require alignment of inventor names in patent documents with researcher names in academic publications – an approach taken by the (European Patent Office, 2024) report comparing direct and indirect university patents in Europe, to which we provide complementary evidence. This comes at a cost: the exclusion of indirect patents may understate total academic patenting in countries where indirect patent filing is common. This is particularly relevant for Nordic countries such as Finland, Sweden and Norway, where the 'professor's privilege' was in place (European Patent Office, 2024, p. 55). However, although we focus on direct patent applications, our approach remains valuable given that these applications are becoming an increasingly significant part of European universities' patent portfolios, with the ratio

[1] https://www.epo.org/en/about-us/statistics/patent-index-2023/statistics-and-indicators/applicants/categories [date of access: March 7, 2025].

[2] In the RISIS Patent database the university share is about 10%. The small share of HEIs among patent applicants is a global tendency: almost 88% of all Patent Cooperation Treaty (PCT) applications filed in 2022 came from the business sector (WIPO, 2023).

[3] Top 50 university PCT applicants, 2020–2022. Source: WIPO Statistics Database, March 2023 (https://www3.wipo.int/ipstats/key-search/indicator).

[4] Namely: technology commercialisation and investment companies linked to the Imperial College of London (Imperial College Innovations Ltd) and Oxford University (Oxford University Innovation Limited).

[5] The Sciamago innovation ranking counts the number of patent applications by institutions and the citations that its research output receives from patents: https://www.scimagoir.com/rankings.php?sector=Higher+educ.&ranking=Innovation&country=all [date of access: March 05, 2025].

[6] Own calculations based on a sample of HEIs from 17 European countries (AT, BE, CH, CZ, DE, ES, FI, FR, HU, IE, IT, LT, LV, NL, PL, PT, UK) between 2011 and 2018. Primary data source: RISIS Patent database.

of indirect to direct patents decreasing from 4:1 between 2000 and 2019 (European Patent Office, 2024, p. 35).[7] Moreover, the focus on direct patents allows us to establish the proper identification of European universities as applicants in PATSTAT, which resulted in a unique PATSTAT–ETER crosswalk (one of the main contributions of our study).

Our research complements studies using surveys or bibliometric-patent linkages to identify university-affiliated inventors (European Patent Office, 2024; Hottenrott & Thorwarth, 2011; Lissoni et al., 2009; Neuhäusler & Frietsch, 2024). Our new dataset, KC-HEI, provides an alternative entity-level data source for patenting by universities, extending the coverage and level of detail of existing sources such as RISIS Patent[8] and OrgReg.[9] KC-HEI provides 30 alternative university-level indicators of the quality of patented knowledge, based on patent citations, breakthroughness, or originality.[10] Orduña Malea et al. (2017) show that patent URL citations are useful for ranking major US and the top few UK universities. Kousha and Thelwall (2017) add that citations from patents to scientific publications provide a useful indicator of the commercial impact of academic research. We also provide parallel indicators based on universities' activity in alternative patent offices (IP5, EPO and USPTO), considering either all patent applications or only successful (granted) ones. What is more, KC-HEI allows the innovation performance of institutions to be analysed in 128 internationally comparable technological sectors. We also enhance the technological detail of the data by providing separate university-level indicators of artificial intelligence (AI) patenting (to the best of our knowledge, this is the first attempt to quantify AI patenting by universities in such a large sample of institutions in different countries). Denter et al. (2025) develop a 'science-driven novelty' indicator for assessing the impact of science on patents.

Consequently, our contribution is the new database and evidence it provides, so in the paper we focus on the dataset construction methodology and demonstrate its research potential, whilst reserving detailed analysis of university-level patenting behaviour for future research utilising the KC-HEI. In particular, we use KC-HEI to highlight the significant geographical concentration of university patenting in Europe. The top patenting universities are located in the economic heartland of Western Europe (Fig. 1), and (the extreme polarisation of university patenting in Europe is a cause for concern: 70% of all direct university patents come from five Western European countries, whilst over 70% of European HEIs do not appear amongst patent applicants at all. Fifty universities account for almost 27% of all university patent applications to the 'big five' patent offices.[11] Even within STEM institutions,[12] which should theoretically be better equipped to deliver market-oriented innovation in patentable technological fields, only 50% are active in patenting.

The rest of the paper is structured as follows. Section 2 describes the construction of the database. Section 3 demonstrates the potential of KC-HEI, presenting a set of stylised facts on the core-periphery pattern of university patenting in Europe (1980–2019). Section 4 concludes and indicates the possible directions of future research using the newly developed database. The Supplementary materials set forth details on the creation and content of KC-HEI (Appendix A), a detailed description of the procedure leading to ETER-PATSTAT crosswalk (Appendix B), and additional tables and figures (Appendix C).

2. KC-HEI Dataset construction[13]

2.1. Data sources[14]

To quantify the creation of knowledge by universities, we use granular patent statistics from the Worldwide Statistical Patent Database (PATSTAT Global, Autumn 2022 edition),[15] which gives bibliographical and legal event patent data from leading industrialised and developing countries. PATSTAT provides patent-level records allowing the quantification of innovation activity by firms (Aiello et al., 2024; Behrens & Trunschke, 2020; Caviggioli et al., 2023a; Lotti & Marin, 2013) and universities (Angori et al., 2024; Caviggioli et al., 2023a,b; Squicciarini et al., 2012).

University identifiers and names come from the European Tertiary Education Register database (ETER)[16] (Lepori et al., 2023). We also use ETER to create, as an integral part of the KC-HEI, a crosswalk that relates university units in PATSTAT with external university-level datasets, using the *eter_id* identifier (details in Section 2.2 and Appendix B).

[7] A systemic shift toward university ownership of academic inventions has occurred across most EU countries (European Patent Office, 2024, p. 13) and the sectoral distribution of academic patents exhibits similar patterns across technology fields regardless of whether patents are filed directly by universities or indirectly, by firms or individual inventors (European Patent Office, 2024, p. 39).

[8] Research Infrastructure for Science and Innovation Studies. RISIS Patent is managed by the Research Infrastructure for Science and Innovation Policy Studies (RISIS2.EU) project (https://www.risis2.eu/risis-datasets/) (Laurens, 2022).

[9] Register of Research and Higher Education Organizations (https://www.risis2.eu/orgreg-data/) (Lepori, 2022).

[10] For details on all the indicators in KC-HEI see Supplementary materials, Appendix A.

[11] Accounting for fractional apportionment. Numbers based on KC-HEI – see Section 3 for details.

[12] STEM (Science, Technology, Engineering, Mathematics) institutions are identified in line with ETER (Lepori et al., 2023, p. 119) as HEIs with positive shares of students and graduates in science and technology, i.e. in the following fields: 05 (Natural sciences, mathematics and statistics), 06 (Information and communication technologies) and 07 (Engineering, manufacturing and construction).

[13] a complete replication package accompanying this paper is available at: . more complete, extensive description of the database construction is provided in the working paper version of this paper

[14] for details on provenance and availability of all the data, see the ReadmeFile (replication package).

[15] We thank Ronald Davies for his help in providing PATSTAT source files.

[16] Data source: ETER project. Download date: September 18, 2023. Data has been provided by the European Tertiary Education Register (ETER) funded by the European Commission under the contracts EAC-2013-0308, EAC-2015-0280, 934533-2017 A08-CH and EAC-2021-0170.

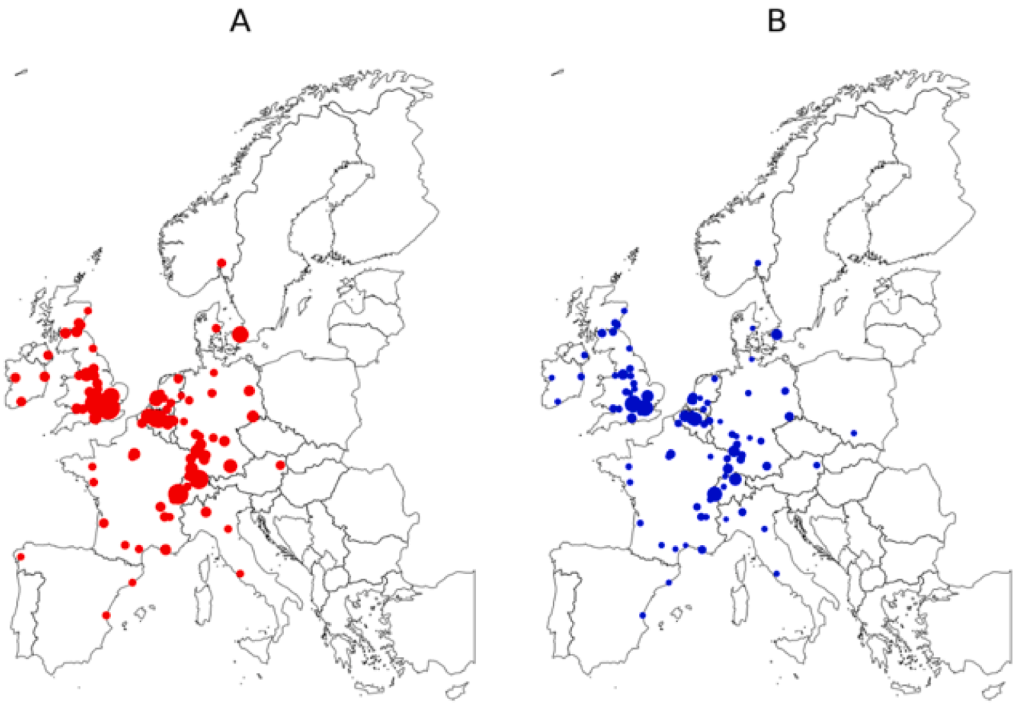

Fig. 1. Top 100 patenting universities in Europe (1980–2019).
Note: The 100 universities with the most IP5 patent applications (Fig. A) and (IP5 patents granted (Fig. B) in 1980–2019. Sample: 866 patenting HEIs in 31 European countries. IP5 patents allocated to HEIs using fractional apportionment by applicant share. Bubble size reflects the total number of patent applications/patents by university in 1980–2019. Only direct academic patents.
Source: own elaboration using KC-HEI.

Indicators of patent quality by application cohort (i.e. patents with the same filing year and technological class) are derived from the OECD Patent Quality Indicators database (version: August 2023) available at the OECD STI Micro-data Lab.[17] Technological fields of patents and their Cooperative Patent Classification (CPC) codes are sourced from PATSTAT. We also use WIPO's PATENTSCOPE Artificial Intelligence Index[18] to identify university AI patents (i.e. those ascribable to artificial intelligence technologies). Finally, we use socio-economic data on the regions in which universities are located from the Eurostat Regional Statistics, NUTS 2 and NUTS 3 level.[19]

2.2. Patent data selection

To construct KC-HEI, we use a subsample of 333,495 patent records reported in PATSTAT Global (Autumn 2022 edition) that can be ascribed to higher education units (i.e. applications with at least one university among the assignees[20]) and with at least one applicant in a European country[21] since 1980. The final number of applications that serve to derive KC-HEI is smaller (107,501) because of choices concerning patent provenance and type.

We limit the final set of 31 countries because we retain only those universities that can be identified in ETER (to merge the PATSTAT records with university-level characteristics). Second, we restrict the patent applications to those filed in the IP5 jurisdictions: European Patent Office (EPO), Japan Patent Office (JPO), Korean Intellectual Property Office (KIPO), China National Intellectual Property Administration (CNIPA) and United States Patent and Trademark Office (USPTO) because the vast majority of patent applications worldwide (according to WIPO around 85% in 2022) originate in IP5. We also provide a parallel series of indicators (i.e. patent quality) based exclusively on applications to EPO and USPTO. The next choice was between all patent applications and patents

[17] https://www.oecd.org/sti/intellectual-property-statistics-and-analysis.htm [date of access: March 27, 2024].
[18] https://www.wipo.int/tech_trends/en/artificial_intelligence/patentscope.html [date of access: March 27, 2024].
[19] https://ec.europa.eu/eurostat/web/regions/database [date of access: March 27, 2024].
[20] Records in PATSTAT that have an assignee where PSN_Sector includes UNIVERSITY, i.e. "UNIVERSITY", "GOV NON-PROFIT UNIVERSITY", "UNIVERSITY HOSPITAL", "COMPANY UNIVERSITY". Later we consider the UNIVERSITY units only.
[21] We have selected patent applications with at least one assignee from the following countries (variable `person_ctry_code` in TLS206 table in PATSTAT): AL AT BE BG CH CY CZ CS DE DD DT DL DK EE ES FI FR GR HR HU IE IL IS IT LI LT LU LV MT NL NO PL PT RO RS SE SI SK TR GB.

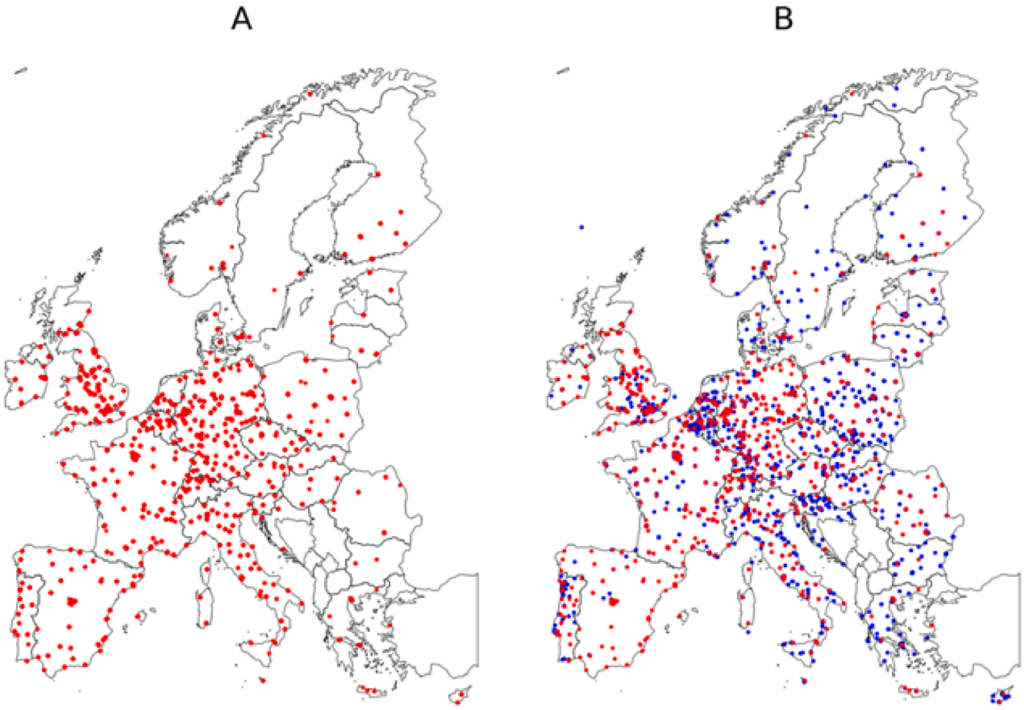

Fig. 2. HEIs in the sample (red – patenting HEIs; blue – non-patenting).
Note: Left map (Fig. 2A) - (- Sample 1: 866 patenting HEIs (1980–2019). Right map (Fig. 2B)-(- Sample 2: 785 patenting and 2101 non-patenting universities (2011–2019). Universities in small islands and overseas territories are not shown. Only direct academic patents. In Sweden, Norway and Finland, the values are likely to be underestimated due to the "professor's privilege" (Caviggioli et al., 2023a,b), so some HEIs in these countries may be in the non-patenting sample even though they have indirect academic patents.
Source: own elaboration using KC-HEI and accompanying datasets.

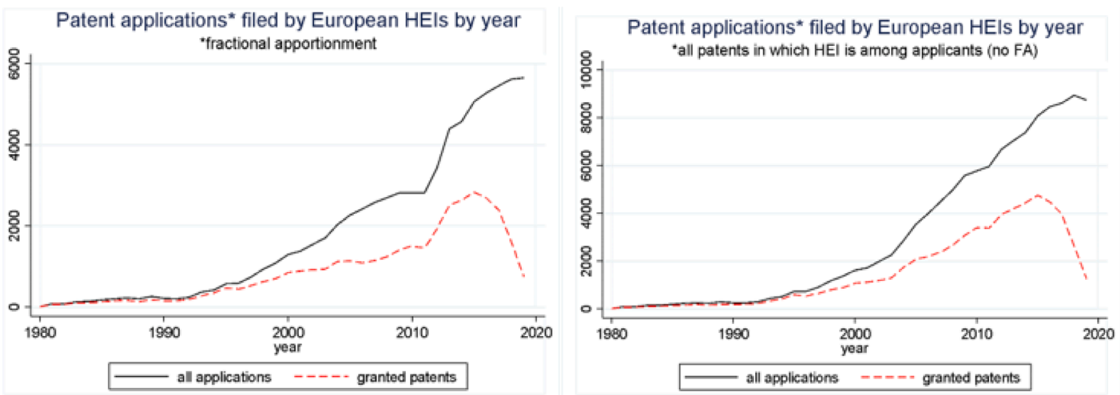

Fig. 3. University patent applications filed by year (1980–2019).
Note: Sample of 866 patenting HEIs in 31 European countries (sample period only to 2019 to avoid end-of-sample truncation bias in PATSTAT). Patent applications filed with IP5. Upper graph: patents allocated to HEIs using fractional apportionment (FA) by applicant share. Lower graph: no FA (patents allocated to HEIs independently of the applicant share). The drop in the number of patents granted in the final years of the analysis is due to the time lag between the application being filed and the patent being granted.
Source: own calculations using KC-HEI database.

granted only. Roughly half the university patents applied for in our dataset are eventually granted (as in Davies et al. (2020)).[22] The patent granting process is long (on average, over five years for final approval), so retaining only patents granted would create a truncation problem at the end of the sample period. We thus use both types of data. That is, every indicator in the KC-HEI database

[22] In Google Patents, the rate is 61% (https://patents.google.com/coverage, date of access: July 30, 2025).

Table 1
Sample composition – number (and share) of universities by country (P – patenting; NP – non-patenting universities).

		Sample 1 (1980–2019) $n = 866$ P		Sample 2 (2011–2019) $n = 785$ P		$n = 2101$ NP	
Code	Country	No.	%	No.	%	No.	%
AUT	Austria	25	2.89	22	2.80	49	2.33
BEL	Belgium	22	2.54	16	2.04	143	6.81
BGR	Bulgaria	2	0.23	2	0.25	49	2.33
CHE	Switzerland	21	2.42	20	2.55	18	0.86
CYP	Cyprus	2	0.23	2	0.25	29	1.38
CZE	Czech Rep.	18	2.08	18	2.29	59	2.81
DEU	Germany	167	19.28	149	18.98	251	11.95
DNK	Denmark	7	0.81	6	0.76	37	1.76
ESP	Spain	64	7.39	62	7.90	17	0.81
EST	Estonia	5	0.58	3	0.38	26	1.24
FIN	Finland	17	1.96	16	2.04	31	1.48
FRA	France	156	18.01	145	18.47	247	11.76
GBR	UK	117	13.51	103	13.12	154	7.33
GRC	Greece	13	1.50	13	1.66	44	2.09
HRV	Croatia	3	0.35	3	0.38	39	1.86
HUN	Hungary	9	1.04	6	0.76	43	2.05
IRL	Ireland	18	2.08	17	2.17	9	0.43
ISL	Iceland	2	0.23	1	0.13	6	0.29
ITA	Italy	63	7.27	61	7.77	156	7.43
LTU	Lithuania	7	0.81	6	0.76	35	1.67
LUX	Luxembourg	1	0.12	1	0.13	2	0.10
LVA	Latvia	5	0.58	4	0.51	44	2.09
MLT	Malta	1	0.12	1	0.13	3	0.14
NLD	Netherlands	13	1.50	12	1.53	49	2.33
NOR	Norway	13	1.50	11	1.40	43	2.05
POL	Poland	50	5.77	42	5.35	242	11.52
PRT	Portugal	19	2.19	19	2.42	95	4.52
ROU	Romania	10	1.15	10	1.27	76	3.62
SVK	Slovakia	6	0.69	6	0.76	25	1.19
SVN	Slovenia	3	0.35	3	0.38	48	2.28
SWE	Sweden	7	0.81	5	0.64	32	1.52
Total	31 countries	**866**	**100**	**785**	**100**	**2101**	**100**

Note: countries listed in alphabetical order. P – all university units that were among assignees in at least one patent application in PATSTAT Global (Autumn 2022) in 2011–2019; NP – universities present in ETER (Lepori et al., 2023) but having no patent application filed in any of the three databases (KC-HEI, OrgReg, RISIS Patent) in 2011–2019. Only direct academic patents. In Sweden, Norway and Finland values are likely to be underestimated due to ‘professor’s privilege’ (Caviggioli et al., 2023a,b).
Source: own calculations.

is gauged both for all patent applications and for granted patents only. See Supplementary materials, Appendix A for the description of all the variables in KC-HEI.

As to the sample period, in line with (Davies et al., 2023), who use the same edition of PATSTAT, we consider patent applications filed since 1980. We observe a significant decline in patent applications from 2020 onwards, so we retain only the records from 1980 to 2019 in our dataset.

2.3. The identification of HEIs in the patent data: The PATSTAT–ETER crosswalk

The identification of university-based patents is a complex task (Dornbusch et al., 2013). In line with (Caviggioli et al., 2023b), we classify an application as a direct “university patent” if there is at least one HEI among the assignees. We take the data on patents of applicants, not inventors, because a university, as an institution, may appear among the patent contributors only as an applicant (while only a natural person can be an inventor). In allocating patents to university units, we rely on fractional apportionment based on applicant shares within the patent application.

The IDs of assignees are specific to the PATSTAT database (variable *psn_id*), making it impossible to analyse university-level factors related to knowledge creation, which would require merger with external datasets (e.g. ETER) that use different identifiers (codes). In PATSTAT, 80 or even more different *psn_id* codes could actually refer to one and the same university. We solve this problem by

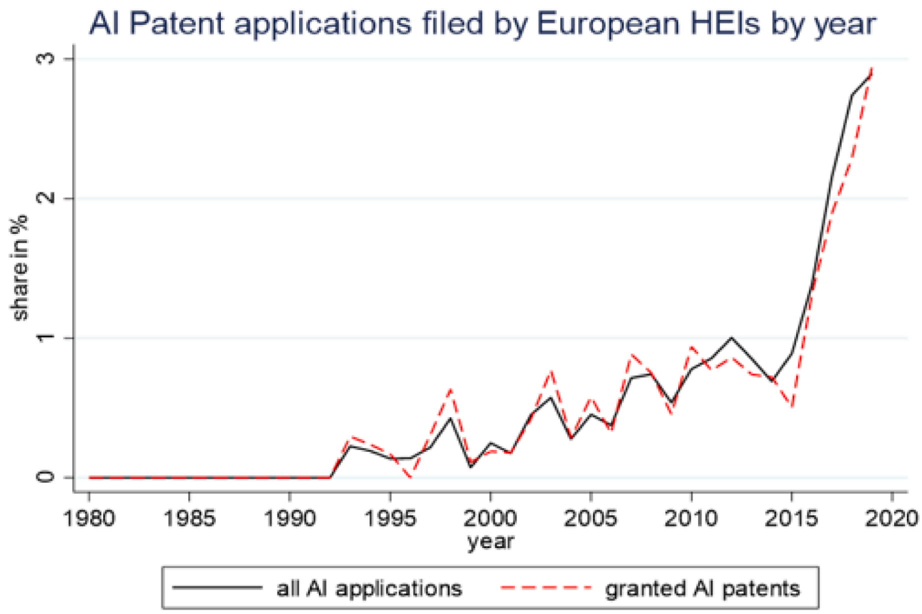

Fig. 4. AI Patent applications filed by European HEIs (1980–2019) – share in all direct university patents.
Note: Sample of 866 patenting HEIs in 31 European countries. AI patents identified by AI CPC codes from WIPO (https://www.wipo.int/tech_trends/en/artificial_intelligence/patentscope.html).
Source: own elaboration using KC-HEI database.

creating a crosswalk[23] that provides unique correspondence between *psn_id* in PATSTAT and *eter_id* for 1068 universities. A detailed crosswalk description is provided in Supplementary materials, Appendix B.

2.4. Sample composition and the share of patenting HEIs by country

The final KC-HEI database contains records on 866 HEIs in 31 European countries (listed in Table 1)[24] for the period 1980–2019 (unbalanced panel). The overlap between KC-HEI and ETER can be observed for the years 2011–2019. HEIs from Sample 1 account for almost 78% of all IP5 patent applications by universities present in PATSTAT Global (Autumn 2022) in the sample period and the sample countries.

We analyse universities throughout Europe (Fig. 2); the number naturally varies from country to country. Table 1 reports the number of HEIs by country in the two sample periods, longer and shorter. In Sample 1 (only patenting HEIs, 1980–2019), most are located in Germany (167 universities, 19% of the entire sample), France (156, 18%) and the UK (117, 13%). In Sample 2 as well, which includes non-patenting institutions (a total of 2886 HEIs but a shorter period: 2011–2019; Fig. 2B), most are located in these same three countries. For the 31 countries in our sample, ETER contains information on 3070 HEIs (which can be taken as the most complete set of European HEIs on which institutional-level data can be gathered), so Sample 2 covers 94% of all European universities in the 31 countries.

3. Stylised facts on European university patenting using KC-HEI

3.1. Trends over time

Globally, the share of university patents in total PCT applications has risen slowly but steadily – from nearly zero in 1980 to almost 4.5% in 2000 and 6% in 2011 (Source: (WIPO, 2011)). In our sample, the number of university patents has increased over the years (Fig. 3) - (- in keeping with the general upward trend in patent applications as recorded in PATSTAT (see (Davies et al., 2023)). A drop in the number of patents granted after 2015 mirrors the lag between application and patent granting while university patents before 1990 were limited.

There is no great difference between the series generated with and those without fractional apportionment of patents (simple patent counts) – Fig. 3. What strikes the eye, however, is the difference between IP5 applications and patents granted. The latter

[23] File `crosswalk_PSNid_to_ETERid.csv` is openly available at: https://doi.org/10.34808/h4h3-2k20.
[24] AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GR, HR, HU, IE, IS, IT, LT, LU, LV, MT, NL, NO, PL, PT, RO, SE, SI, SK, UK.

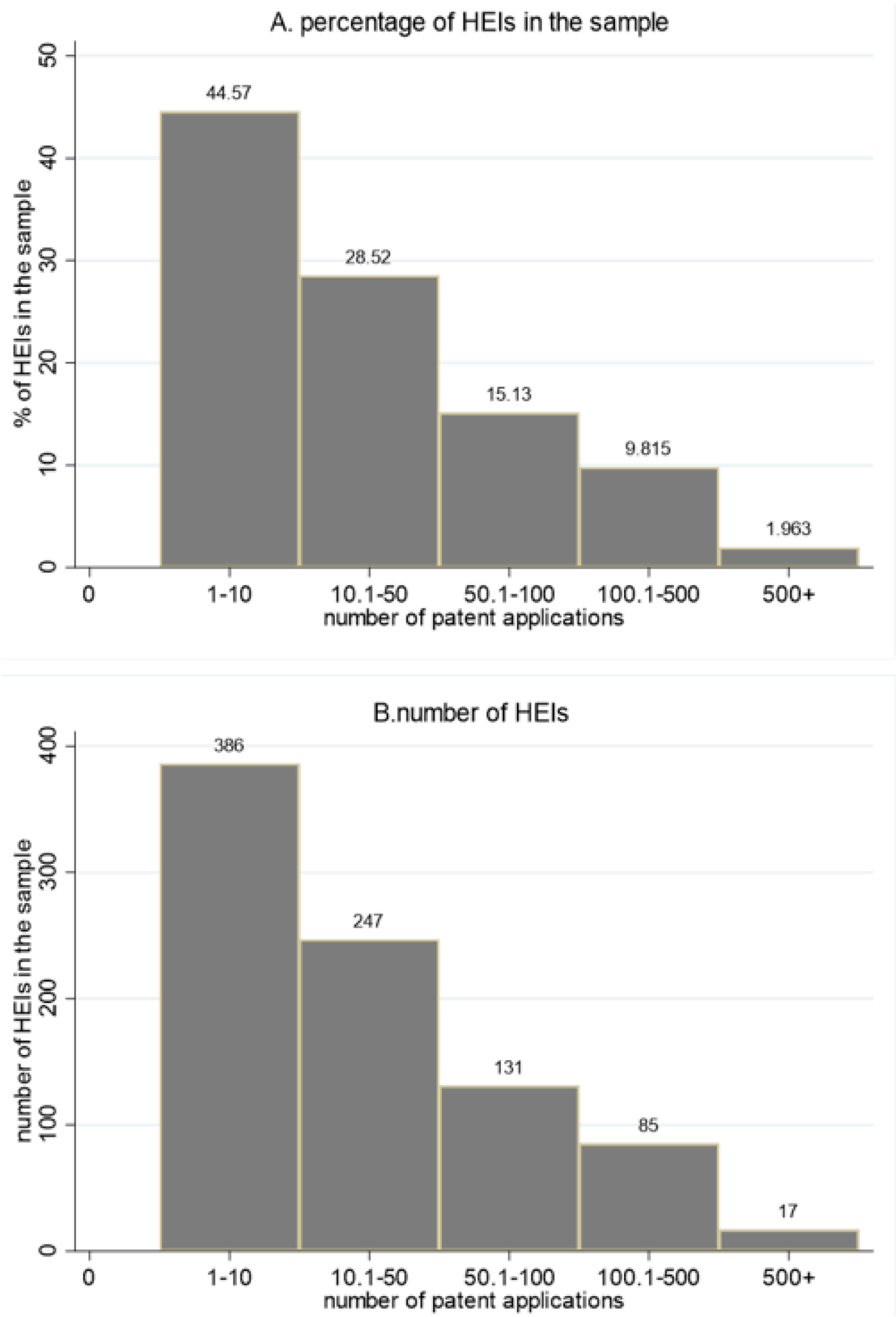

Fig. 5. Distribution of patents among patenting HEIs (1980–2019).
Note: Sample of 866 patenting HEIs in 31 European countries. All patent applications filed with IP5. Patents allocated to HEIs using fractional apportionment (FA) by applicant share. Graph A – bins by percentage of HEIs in the sample. Graph B – bins by number of HEIs.In Sweden, Norway and Finland, the values are likely to be underestimated due to “professor’s privilege” (Caviggioli et al., 2023a, 2023b).
Source: own calculations using PATSTAT and KC-HEI database.

Table 2
Ranking of countries in KC-HEI by number of IP5 patent applications and patents. Top 5 countries shaded.

Ranking by patent applications			Ranking by patents granted		
Pos.	Country	No. applications	Pos.	Country	No. patents
1	United Kingdom	14931.59	1	United Kingdom	7310.85
2	Germany	10495.73	2	Germany	4900.74
3	France	7564.01	3	France	4018.86
4	Switzerland	4384.33	4	Switzerland	1949.85
5	Belgium	3543.73	5	Belgium	1658.59
6	Netherlands	3063.62	6	Netherlands	1343.52
7	Italy	2416.07	7	Italy	1243.44
8	Spain	2245.52	8	Spain	986.70
9	Denmark	1678.51	9	Ireland	641.34
10	Ireland	1596.92	10	Denmark	637.33
11	Austria	1040.56	11	Poland	469.65
12	Poland	858.84	12	Austria	403.23
13	Portugal	525.06	13	Czech Rep.	288.63
14	Norway	491.35	14	Norway	209.76
15	Czech Rep.	474.22	15	Finland	195.31
16	Finland	414.52	16	Portugal	191.00
17	Hungary	164.79	17	Hungary	92.31
18	Lithuania	108.06	18	Slovenia	55.88
19	Slovenia	102.46	19	Lithuania	52.56
20	Estonia	92.23	20	Estonia	45.59
21	Latvia	81.17	21	Latvia	36.33
22	Sweden	76.95	22	Sweden	23.34
23	Luxembourg	58.48	23	Greece	17.29
24	Greece	43.31	24	Luxembourg	15.77
25	Romania	22.85	25	Croatia	7.91
26	Slovakia	20.92	26	Malta	7.50
27	Cyprus	17.87	27	Romania	7.45
28	Croatia	14.66	28	Cyprus	7.37
29	Malta	12.75	29	Iceland	6.53
30	Iceland	10.37	30	Slovakia	6.33
31	Bulgaria	2.42	31	Bulgaria	0.75

Notes: Sample 1 – patenting HEIs in 31 countries, 1980–2019. Patents allocated to HEIs using fractional apportionment by applicant share. Only direct academic patents. In Sweden, Norway and Finland, the values are likely to be underestimated due to 'professor's privilege' (Caviggioli et al., 2023a,b).
Source: own calculations using KC-HEI database.

number is some 50% lower than that of the former in 1980–2019[25] – that is, roughly half of the university patent applications are successful.[26]

KC-HEI can also help document patterns of knowledge creation by universities in a field that has attracted a great deal of attention in recent years: artificial intelligence. AI patenting by universities is limited, but it should be borne in mind that the boom in AI occurred in the years beyond our sample period. Only a very small proportion of European university patents from 1980 to 2019 can be classified as AI-related, although this share increased from zero in the 1980s to almost 3% of university patents in 2019 (Fig. 4). Some 75% of the HEIs in our sample were not active in AI patenting at all; only 25% (206 of 868 HEIs in Sample 1) applied for at least one AI-related patent during the period. Only 15% of the HEIs in the KC-HEI database were granted AI patents up to 2019.

3.2. Distribution of university patents by country and by university units

Using KC-HEI, we find an extremely strong concentration of university patenting in Europe: just five countries account for over 70% of university patents. We arrive at this striking number by ranking the countries according to overall university patenting (Table 2). The unquestionable leaders are the UK, Germany, France, Switzerland, and Belgium – whose universities produced 72% of all university patent applications and 74% of patents granted to the 866 HEIs in our sample, 1980–2019. Universities in the leading country – the UK – account for a fourth of applications and patents (26% and 27%, respectively). The second-leading country (Germany) is responsible for 19% of applications and 18% of patents. Breakthrough inventions (i.e. the top 1% patents by number of

[25] Supplementary materials, Appendix C shows the graph for the entire period up to 2022. It is clear that the apparent decrease in patent applications in 2020–2022 is an artificial result of the end-of-sample truncation in PATSTAT, which is why we end our analysis at 2019 (as in (Davies et al., 2023)).

[26] Precisely, the proportion of grants to applications in Sample 1 is 47% in the series with fractional apportionment (FA) and 50% without it (simple patent counts).

Table 3
Percentage of patenting and non-patenting universities (all and STEM only), by country.

		All HEIs		STEM only	
Code	Country	No. in sample	% patenting	No. STEM	% STEM patenting
AUT	Austria	71	30.99	39	51.28
BEL	Belgium	159	10.06	47	21.28
BGR	Bulgaria	51	3.92	34	5.88
CHE	Switzerland	38	52.63	18	94.44
CYP	Cyprus	31	6.45	22	9.09
CZE	Czech Republic	77	23.38	33	51.52
DEU	Germany	400	37.25	237	62.03
DNK	Denmark	43	13.95	29	20.69
ESP	Spain	79	78.48	76	81.58
EST	Estonia	29	10.34	12	16.67
FIN	Finland	47	34.04	38	42.11
FRA	France	392	36.99	203	66.01
GBR	United Kingdom	257	40.08	158	62.66
GRC	Greece	57	22.81	46	28.26
HRV	Croatia	42	7.14	27	11.11
HUN	Hungary	49	12.24	28	21.43
IRL	Ireland	26	65.38	22	68.18
ISL	Iceland	7	14.29	6	16.67
ITA	Italy	217	28.11	80	73.75
LTU	Lithuania	41	14.63	28	21.43
LUX	Luxembourg	3	33.33	1	100.00
LVA	Latvia	48	8.33	25	16.00
MLT	Malta	4	25.00	2	50.00
NLD	Netherlands	61	19.67	38	31.58
NOR	Norway	54	20.37	36	30.56
POL	Poland	284	14.79	221	19.00
PRT	Portugal	114	16.67	64	29.69
ROU	Romania	86	11.63	9	33.33
SVK	Slovakia	31	19.35	18	33.33
SVN	Slovenia	51	5.88	12	25.00
SWE	Sweden	37	13.51	28	17.86
TOTAL		**2886**	**27.21 (mean)**	**1637**	**45.45 (mean)**

Note: Values based on Sample 2 (2011–2019). Patenting HEI – at least one IP5 patent application in 1980–2019; STEM institutions identified in line with ETER (Lepori et al., 2023, p. 119) as HEIs with positive shares of students and graduates in fields 05, 06 and 07. Only direct academic patents. In Sweden, Norway and Finland, the values are likely to be underestimated due to ‘professor’s privilege’ (Caviggioli et al., 2023a,b).
Source: own calculations using KC-HEI database

Table 4
Characteristics of patenting and non-patenting universities – mean values.

	All sample		STEM	
	Patenting ($n = 785$)	Non-patenting ($n = 2101$)	Patenting ($n = 744$)	Non-patenting ($n = 893$)
Foundation year	1864	1971	1864	1977
Academic staff (FTE)	1547.8	167.8	1567.2	237.4
Total students	19590.0	2940.5	19784.4	4773.0
Students per academic staff	15.04	21.12	14.97	25.35
Graduates per academic staff	3.69	5.26	3.68	6.32
Publications per academic staff	0.281	0.086	0.278	0.083
Total revenues (€ PPP)	255.4M	30.5M	257.7M	43.7M
Revenues per academic staff (€ PPP)	174,031	150,916	172,156	147,452
Third-party revenues (share 0–1)	0.182	0.079	0.181	0.083

Note: Values based on Sample 2 (2011–2019). Only direct academic patents. FTE – full time equivalent. In Sweden, Norway and Finland, the values are likely to be underestimated due to “professor’s privilege” (Caviggioli et al., 2023a, 2023b).
Source: own calculations using KC-HEI and accompanying datasets and ETER data.

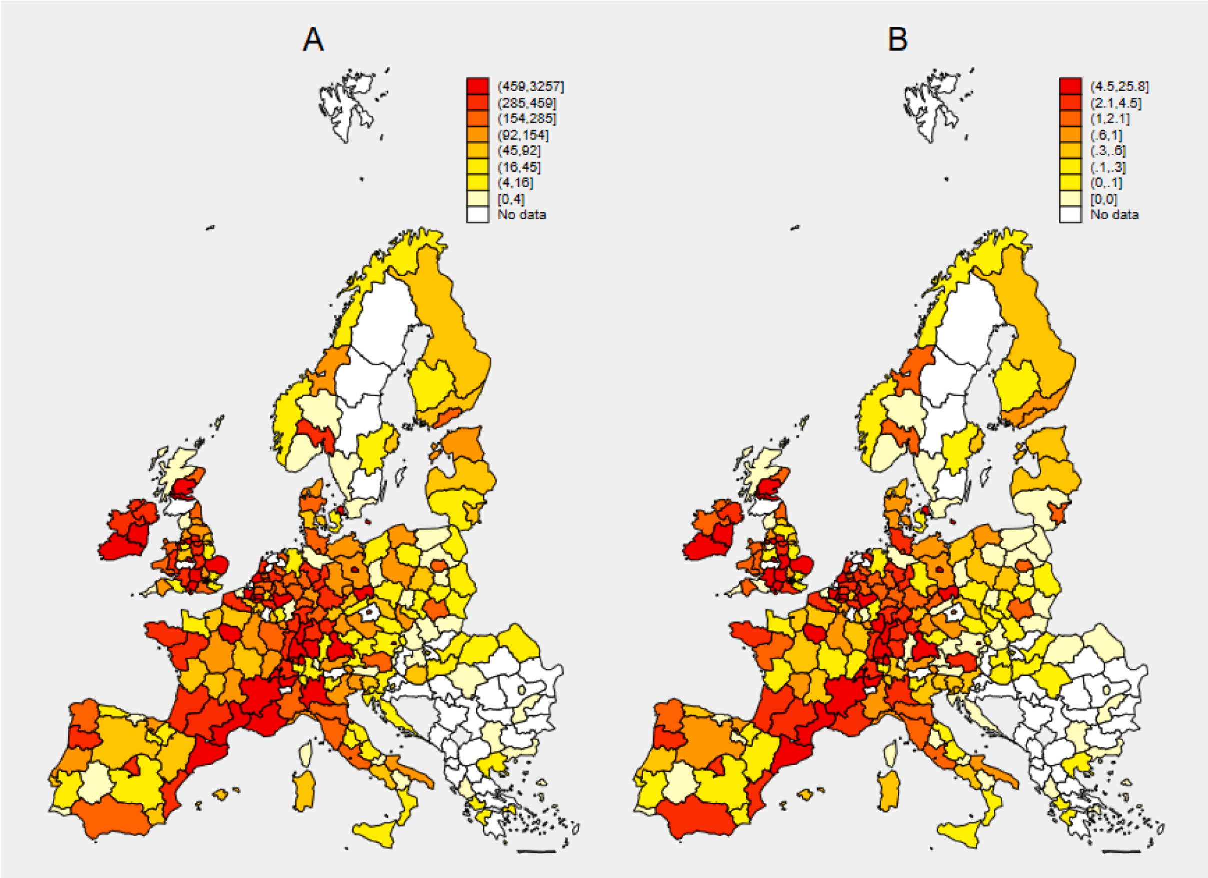

Fig. 6. Regional distribution of university patents and citations, NUTS2 regions (1980–2019). Fig. 6A – patent applications; Fig. 6B – patent citations (top regions in red).
Note: Sample of 866 patenting HEIs from 31 European countries. Only direct academic patents. In Sweden, Norway and Finland, the values are likely to be underestimated due to 'professor's privilege' (Caviggioli et al., 2023a,b). Iceland, Cyprus and overseas regions are not shown. Fig. 6A: patent applications filed with IP5. Patents allocated to HEIs using fractional apportionment (FA) by applicant share. Fig. 6B: patent citations measured by the number of forward citations of EPO patents in 5 years, normalised by the maximum number of citations in the corresponding technological field. *Legend:* regions divided into 8 categories according to percentiles. Dark red indicates the top 12.5% regions. Categories 1 and 2 – top 25%; categories 7 and 8 – bottom 25%. No data – regions without any HEIs or where HEIs have no patent activity.
Source: own elaboration using KC-HEI database.

citations) come mainly from HEIs in Britain, Switzerland and Germany. Of course, country size matters (some countries have many university units, others just a few – Table 1), so it is useful to recalculate to gauge the number of patents per university (Table 7A in Supplementary materials, Appendix A). In this case, the small Benelux countries move up in the ranking.

The concentration of university patenting can also be observed at the micro level. KC-HEI shows that very few university units stand out as crucial nodes in the European innovation system (see Fig. 1), while the bulk are absent from market-oriented innovation. The distribution of patenting activity across European universities is highly uneven: in KC-HEI Sample 1 of 866 patenting universities (thus excluding universities with no patents), the number of applications filed in 1980–2019 ranged from just 1 to over 2000 (Table 2A in Supplementary materials, Appendix A presents pairwise correlations between alternative indicators of university patenting activity in KC-HEI; summary statistics are reported in Table 3A in Appendix A). Fig. 5 shows that 45% of the patenting universities have filed fewer than 10 applications to IP5 since 1980. At the other extreme, just 17 universities,[27] or 2% of the sample units, were among the assignees in more than 500 applications.

Sample 2, which contains data on both patenting and non-patenting universities (2011–2019), shows that a full 73% of European universities (2101 HEIs) were inactive (see Figure C2 in Supplementary materials, Appendix C). In many countries, the majority

[27] University of Oxford, University College London, Federal Institute of Technology Lausanne, Federal Institute of Technology Zurich, Imperial College London, KU Leuven, University of Cambridge, Technical University of Denmark, Ghent University, University of Zurich, ULB, Karlsruhe Institute of Technology, Technical University of Munich, University of Manchester, University of Freiburg, Leiden University, Delft University of Technology.

Table 5
Factors related to patenting by HEIs in Europe. *Dependent variable: annual number of patent applications to IP5 patent offices*.

	(1)	(2)	(3)	(4)	(5)	(6)
Age_i	0.021***	0.020***	0.012***	0.010***	0.014***	0.012***
	[0.000]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
$STEM_{it}$		6.110***	4.868***	6.044***	8.378***	6.211***
		[0.235]	[0.229]	[0.277]	[0.394]	[0.412]
$Stud_{it}$			0.235***	0.230***	0.278***	0.248***
			[0.006]	[0.007]	[0.010]	[0.010]
$Stud\_acad_{it}$				- 0.055***	- 0.101***	- 0.075***
				[0.004]	[0.008]	[0.008]
Rev_acad_{it}					5.667***	1.302
					[1.246]	[1.260]
$Publ\_acad_{it}$						10.668***
						[0.672]
N	18,263	16,976	16,920	14,833	9639	9639
R^2	0.25	0.28	0.34	0.37	0.40	0.42
Countries	31	31	31	31	26	26

Notes: All specifications include region, country and time-fixed effects. $^{*}p < .10$, $^{**}p < .05$, $^{***}p < .01$ *Source:* authors' calculations using PATSTAT Global (Autumn 2022), OrgReg and ETER.

Table 6
Factors related to HEIs' patent quality in Europe. *Dependent variable: forward citations of EPO patents*.

	(1)	(2)	(3)	(4)	(5)	(6)
Age_i	0.016***	0.015***	0.009***	0.008***	0.012***	0.011***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
$STEM_{it}$		5.684***	4.890***	6.095***	8.404***	6.899***
		[0.256]	[0.257]	[0.316]	[0.455]	[0.480]
$Stud_{it}$			0.153***	0.151***	0.183***	0.163***
			[0.007]	[0.008]	[0.011]	[0.011]
$Stud\_acad_{it}$				- 0.040***	- 0.071***	- 0.054***
				[0.005]	[0.009]	[0.009]
Rev_acad_{it}					3.026**	- 0.005
					[1.439]	[1.468]
$Publ\_acad_{it}$						7.409***
						[0.783]
N	18,263	16,976	16,920	14,833	9639	9639
R^2	0.17	0.20	0.22	0.24	0.26	0.27
Countries	31	31	31	31	26	26

Notes: All specifications include region, country and time-fixed effects. $^{*}p < .10$, $^{**}p < .05$, $^{***}p < .01$ *Source:* authors' calculations using PATSTAT Global (Autumn 2022), OrgReg and ETER.

of HEIs never filed even a single patent application. Table 3 reports the percentage of patenting HEIs by country (Sample 2). For instance, in 2011–2019, half of Swiss universities filed at least one application, 40% of British, and a third of German universities, while in Bulgaria and Slovenia, the figure was under 10%. These numbers should be treated with caution, however, because both the number of HEIs and their typology (technical universities tend to patent more) vary greatly between countries.

3.3. Distribution of university patents and patent citations by region

University patenting in Europe displays a strong core-periphery pattern, matching regional/local economic divergences. The maps in Fig. 6 show eight different categories of European NUTS2[28] regions – divided into groups according to university patenting percentiles (the top two classes, in red, correspond to the top 25% NUTS2 regions in number of patent applications – Fig. 6A, left). The university innovation core is composed of university units from regions in the UK, southwestern Germany, Benelux, France, northern Italy and the regions where national capitals are located. The top 10 regions are: UKI3 (Inner London – West), FR10 (Île-

[28] KC-HEI allows for a similar analysis at the more detailed NUTS3 level. The concentration is very granular and often good performances by NUTS2 regions, in terms of university patenting, are actually driven by just a handful of HEIs (and thus more readily observable at NUTS3 level). Results available upon request.

de-France), UKJ1 (Berkshire, Buckinghamshire and Oxfordshire), CH04 (Zürich), CH01 (Région lémanique), NL33 (Zuid-Holland), FRK2 (Rhône-Alpes), DK01 (Hovedstaden), DE12 (Karlsruhe), UKM7 (Eastern Scotland).

Considering only patents granted, the picture does not change much.[29] For comparison, we show a similar map (Fig. 6B, right) generated using patent citations (here: forward citations in a 5-year period, normalised by the maximum number of citations for each technological code and then summed at the level of HEIs and regions). This indicator can proxy for the real 'quality' of patents (Squicciarini et al., 2013) and their effective impact in knowledge flows (Davies et al., 2023). Mostly, cited patents come from HEIs in just a few top regions in Britain, Switzerland, France, Germany, Belgium and Denmark.

4. Patenting by European universities – key factors and correlation analysis

Our data highlights the key differences between higher education institutions (HEIs) that patent and those that do not in Europe (see Table 4). Patenting universities tend to be older and much larger (i.e. with more students). They have lower student-to-teacher ratios and are more active in terms of scientific publishing. They also have more funds per academic staff member and a higher proportion of third-party funding (i.e. contracts and grants). A similar pattern emerges among HEIs classified as technically oriented (i.e. STEM institutions).

To show the potential of KC-HEI in establishing factors correlated with universities' patenting success, we employ simple econometric modelling and regress the following model:

$$Pat_{irct} = \alpha + \beta_1 Age_i + \beta_2 STEM_{it} + \beta_3 Stud_{it} + \beta_4 Stud\_acad_{it} + \beta_5 Rev\_acad_{it} + \beta_6 Publ\_acad_{it} + D_r + D_c + D_t + \varepsilon_{irct} \quad (1)$$

where i refers to a university located in region r (NUTS2) and country c, and t denotes time (year). The dependent variable, Pat, is either the total number of university patent applications (IP5, FA) or patent applications in a specific technological field that has recently received a lot of attention (AI), or an indicator of patent quality (forward citations). The set of explanatory variables includes: the university's age (Age) proxying for experience/tradition and calculated as 2020 minus the foundation year; the proportion of students in STEM disciplines ($STEM$) proxying for technical orientation; the number of students as proxy for institution size ($Stud$); student/academic staff ratio ($Stud\_acad$) as an indicator of teaching load; universities' wealth, i.e. revenues per academic staff (Rev_acad); and scientific publications per academic staff ($Publ\_acad$), reflecting universities' research orientation.[30] In all specifications, we incorporate region (D_r), country (D_c) and time (D_t) specific effects to control for local innovation systems/development levels, national rules (e.g. professors' privileges) and time trends. The results confirm that the quantity and quality of university patents in Europe are related to institutions' structural and financial characteristics. There is a positive relationship of patents' counts (all – Table 5, and AI – Table 10A in Supplementary materials) and patents' quality and impact (Table 6) with universities' tradition, size, technical and research orientation, and financial wealth, and a negative relationship with the average teaching load. However, these results are illustrative of the potential of KC-HEI only and should not be interpreted as identifying causal factorss of patenting activity.

5. Conclusions and policy recommendations

5.1. Findings

In this paper, we offer a unique, large-scale perspective on patenting activity within the European higher education sector. This was made possible by developing a new micro-level dataset (KC-HEI), which covers almost 900 patenting universities in 31 European countries and over 2100 non-patenting higher education institutions. To construct the KC-HEI dataset, we *(i)* examined all patent applications in PATSTAT that could be identified as direct university patents (i.e. applications with at least one higher education institution (HEI) among the applicants) since 1980, and *(ii)* created a unique crosswalk to match university applicants in PATSTAT with other datasets containing university-level characteristics, such as ETER data. Consequently, we have provided an exceptional empirical framework for analysing the innovation, technology transfer efficiency and factors related to patenting of European universities, thereby enabling evidence-based policy decisions that are crucial for strengthening European competitiveness (Draghi, 2024).

Whilst our aim was not to provide a detailed explanation of university-level patenting behaviour (a topic to be explored by researchers using KC-HEI and our PATSTAT-ETER crosswalk[31]), we have provided substantial descriptive evidence and identified the key factors behind universities' patenting success. Using the KC-HEI index, we demonstrate that university patenting is extremely concentrated in Europe. Five countries account for over 70% of all patent applications by European universities. Of the universities that have filed at least one patent application with one of the top five global patent offices (IP5) since 1980, only 17 (2% of the institutions in our sample) were involved in more than 500 applications, while nearly half had no more than 10 IP5 patent applications on record. Comparing patenting and non-patenting universities, we found that three-quarters of European universities do not patent at all. Some do not need to patent due to their academic focus on the humanities and social sciences. However, even among European STEM institutions, which should theoretically be involved in applied innovation, approximately half have not filed a single IP5 patent application since 1980. Within countries, there are strong core-periphery patterns of university patenting at the NUTS 2 and NUTS 3

[29] The additional maps/figures are available upon request.

[30] For instance, (Wang & Guan, 2010) found that while patenting activity does not harm overall research output, it negatively affects both the quantity and quality of publications by university researchers when the patents are assigned to corporations or the scientists themselves.

[31] Available at: https://doi.org/10.34808/h4h3-2k20.

levels, which match the regional distribution of per capita income in Europe. Apart from region- and country-specific factors, the key institution-level features that are related to European universities' patenting include their experience (tradition), size, wealth, technical and research orientation, and teaching load. This example demonstrates how the KC-HEI can be used; in reality it has much greater potential for studies on knowledge creation and patenting in the higher education sector (see Section 5.3 below).

5.2. Policy recommendations

The concentration of university patenting documented with KC-HEI suggests the need for tailored support – actions further enhancing patenting in top HEIs (as key players building European research competitiveness) matched with actions strengthening technology transfer capacity in less active universities.

Although the patenting activity is significantly higher in STEM institutions then in all HEIs, still - on average - half of them show no direct IP5 patenting in the analysed period of time. Besides stronger technology transfer support (TTOs), enhancing patenting in STEM institutions may also require clearer incentives and greater awareness among researchers of the commercial and intellectual property value of their findings. Shared or regional TTOs could be a solution for smaller institutions. Since patenting is expensive and time-consuming, IP literacy programs for STEM faculty as well as clear IP ownership/revenue-sharing rules could reduce researchers' hesitation towards patenting.

The pronounced core-periphery structure of university patenting in Europe suggests that place-based innovation policies may be necessary to reduce territorial disparities in academic patenting and to strengthen the innovation capacity of weaker regions. Support measures should prioritise capacity building, particularly through stronger technology transfer offices, improved intellectual property management, and incentives for collaboration with firms and other research organisations.[32] In HEIs that already demonstrate substantial patenting activity, policy should focus on improving patent quality and impact.

KC-HEI can also be used in the context of EU AI strategic documents, such as the EU's AI Strategy (Commission, 2018), the Apply AI Strategy (European Commission, 2025), and the AI Continent Action Plan (European Commission, 2025b) by identifying where university-based AI knowledge creation is concentrated and which institutional conditions support AI patenting. Our database shows that AI patenting by European universities was still rare in the 1980–2019 period, but is more likely in larger, technically oriented, research-intensive, and better-resourced institutions with lower teaching loads. These patterns are directly relevant for EU policy because the EU's AI agenda includes the build-up of AI infrastructure, access to data and computing, AI skills and talent, and the diffusion of AI across strategic sectors. KC-HEI can therefore help policymakers identify territorial and institutional gaps in AI-related knowledge production and support HEIs that are most likely to contribute to the EU's AI ambitions (the role of universities in this regard is underlined by European University Association (2025)).

5.3. Limitations and future work

Regarding possible limitations of our work, we openly admit that KC-HEI covers direct university patents, which constitute one segment of all academic patents that also include university-generated patents filed by individual inventors (indirect university patents). The exclusion of indirect patents may underestimate total academic patenting, particularly in Nordic countries such as Finland, Sweden and Norway, where the 'professor's privilege' was in place (European Patent Office, 2024, p. 55). Identifying indirect university patents requires additional data sources, such as bibliometric records or person-level data (see (Dornbusch et al., 2013; European Patent Office, 2024; Geuna & Nesta, 2006; Neuhäusler & Frietsch, 2024)). Since a university name appears in patent records only as an applicant, our analysis is limited to applicant-based data. Insights from inventor-based and applicant-based data may differ (Maraut et al., 2008); for instance, the location of the inventor (laboratory, research unit, or place of residence) may not always match that of the corresponding patent applicant (headquarters of the university or technology transfer office).

Moreover, patents represent only one possible outcome of knowledge production. Since HEIs are driven by different objectives than firms in choosing their knowledge transfer strategy, a broader perspective could incorporate publications, licensing, spin-offs, researcher mobility, and industry collaboration (Aghion et al., 2008; Janger, 2019; Perkmann et al., 2013), enabling comparisons of knowledge transfer strategies across institutions and regions.

The KC-HEI contains a wide range of patent-based variables that can be used in further research to investigate various aspects, such as the role of HEIs from different countries in the European innovation system since 1980, their activity in different patent offices (IP5, EPO and USPTO), the quality of patents produced by universities, and their actual impact (e.g. patent citations and breakthrough innovations). It can also be used to analyse differences across technological fields and university patenting in the AI domain. The micro-level structure of the dataset enables the identification of leading universities in direct patenting and the analysis of the differences between them and universities that do not patent their research. The PATSTAT-ETER crosswalk that we developed enables detailed research into the factors related to innovation in HEIs, taking into account characteristics such as size, funding, employment structure, cooperation with firms and/or other universities, and location. Finally, KC-HEI can be used to analyse the patenting performance of a given university in relation to a broad European sample of university units, and in response to changes in country-specific intellectual property law or institution-specific reforms.

Future work can also extend the analysed sample of patenting units by examining patenting activity by other public research organisations beyond universities. Future research using KC-HEI could also broaden the university sample to include HEIs from the US

[32] Wolszczak-Derlacz (2025) shows that only 7% of university patents in European countries are joint company-university patents, with significant variation between countries (the maximum in Netherlands – 16%, the minimum in Latvia and Poland – around 2%).

and/or China, enabling comparison of patenting trends between the European universities and their key global competitors. Finally, researchers could exploit the full potential of the KC-HEI dataset through rigorous causal analysis (count-data models, endogeneity-robust specifications) and/or explainable machine learning approaches to identify the determinants of university-level patenting behaviour, incorporating a broader set of influencing factors. Finally, our dataset ends in 2019 and therefore does not capture the recent surge in generative AI and deep learning patents. Follow-up research is needed to properly capture the current role of European universities in rapid AI development.

CRediT authorship contribution statement

Aleksandra Parteka: Writing – original draft, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization; **Piotr Płatkowski:** Visualization, Software, Resources, Data curation; **Sabina Szymczak:** Writing – original draft, Investigation, Formal analysis, Data curation; **Joanna Wolszczak-Derlacz:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation.

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Supplementary material

Supplementary material associated with this article can be found in the online version at 10.1016/j.joi.2026.101874.

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