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Innovation partnerships for development along green value chains

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Abstract

Growth and development success stories are often linked to new technological waves and innovation success. Green technologies emerge as a new technology category in which innovation quality in Emerging and Developing Economies (EMDE) - even when excluding China - is relatively high when measured via the value of knowledge spillovers they generate. This suggests that further R&D investment in developing country green-tech could be growth-enhancing. How could this be funded? We show that the highest-impact developing-country innovations are produced in collaborations between developing-country innovators and firms or innovators in High-Income Countries (HIC). Indeed, such collaborations, while amounting to only about 2% of HIC innovations, account for nearly half of all EMDE innovations. We also find that more diversified firms, with R&D staff from both HIC and EMDE, generate more knowledge spillovers in both EMDE and HIC. We suggest a model of innovation where the likelihood of a successful innovation is enhanced by more diverse but complementary knowledge stocks. Our results suggest that observed diversification is likely well below optimal levels and could be enhanced by policies such as tax breaks for R&D in EMDE or co-investments by development banks.

Keywords: innovation in developing economies; knowledge spillovers; green technology; HIC–EMDE collaboration; multinational R&D; inverted-U

JEL codes: O31, O33, O38, F23, Q55, O19

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1 Introduction

Innovation is a central driver of long-run productivity growth, but it also entails a classic market failure. Because knowledge generated by R&D can be used by other firms and economies, innovators typically capture only part of the social value of their inventions, creating a wedge between private investment and the socially optimal level of innovation (Jones and Williams, 1998; Bloom et al., 2013). Many studies have also documented that innovation spillovers are shaped by geographic proximity or by proximity in other domains such as, for example, supply-chain relationships, technological similarity, or social networks.¹ These issues are particularly pertinent in emerging and developing economies (EMDE), where innovation can offer an important route to technological catch-up and growth but where linkages that provide access to knowledge spillovers may be weaker.

That said, the recent performance of China provides a striking example of how innovation can support economic development. In recent years, the emergence of green technologies has created opportunities for rapid expansion in industries such as renewable energy, electric vehicles, and modern transport. China has not only captured value in the physical stages of these value chains, but has also developed substantial capabilities in the intangible, knowledge-intensive activities that underpin them — the *knowledge economy value chain*.² More generally, the development experiences of Taiwan, Korea, Japan, and India illustrate how innovation and entry into knowledge-intensive activities can become closely intertwined with economic growth.

This raises the question whether similar latent opportunities exist in other EMDEs.³ A recent IFC report (International Finance Corporation, 2025) finds that green technologies in EMDEs are of relatively high quality, as measured by the knowledge spillovers they generate. This relies on an estimate built from the citation network of patented innovations (Guillard et al., 2021). While this is a welcome result from a development perspective, it also highlights a potential challenge: it suggests that private firms on their own will not invest enough in green R&D in EMDEs, because they do not capture the full social value of their innovations. This provides a rationale for EMDE governments and development banks to support green R&D, but their ability to do so may be constrained by limited financial resources. We document the emergence of another mechanism for increasing the amount of R&D in EMDEs: collaborations between EMDE innovators and firms or innovators in high-income countries (HIC hereafter).

Using global innovation data from patents,⁴ we document that about 48 percent of EMDE green innovations are produced collaboratively with firms or innovators in high income countries.⁵⁶ We also show that these collaborative innovations are precisely the ones that generate the highest spillovers. The average green EMDE collaborative innovation generates about \$9.3 million more in spillovers than a non-collaborative one.⁷ This suggests that an effective way to generate high-quality innovation in EMDE economies is to encourage EMDE-HIC collaborations, a disproportionate share of which involve Multi-National Enterprises (MNEs), mostly based in HICs. However, considering MNEs as potential drivers and funders of green EMDE innovation via collaborations raises at least two questions.

First, to what extent do developing countries benefit from the knowledge generated by these collaborations? We might be concerned that developing countries have limited absorptive capacity for frontier research. Hence, while HIC firms might benefit from the lower wages of EMDE R&D workers, the impact on the host economy could be limited. Indeed, highly skilled EMDE R&D workers might be induced to redirect their focus to research areas that are well suited to HIC firms but further away from where the broader EMDE ecosystem has absorptive capacity.

Second, could the diversification of innovation activities be to the detriment of global spillovers or spillovers to HICs? This could happen even while spillovers to EMDE are increasing. The answer to this will affect the global social optimum, and how HICs are willing to promote these collaborations.

We explore these questions by combining patent data with information on the world’s top R&D investing

¹See Jaffe et al. (1993) and Keller (2002) on geographic localisation, Bloom et al. (2013) on technological proximity, Javorcik (2004) and Isaksson et al. (2016) on supply-chain linkages, and Agrawal et al. (2008) on social networks.

²A series of studies show that owning intangible assets such as patents or brands is key to capture value from value chains (Mudambi, 2008). In value chains, value-added is concentrated at the upstream (R&D, design, patents) and downstream (branding, after-sales) ends of the chain while the middle (fabrication, assembly) is squeezed, forming the so-called *smile curve* of value creation (Baldwin and Ito, 2021; Meng et al., 2020).

³In the remainder of the paper we use the acronym EMDE to refer to Emerging and Developing Economies excluding China for simplicity.

⁴Derived from the 2025 PATSTAT database, filing years 2013–2022.

⁵This is not particular to green technologies: the share of all EMDE innovation that is collaborative with HIC is 47 percent.

⁶Earlier work (Branstetter et al., 2014, 2019) has documented that US multinationals have been shifting R&D activity to EMDEs. By contrast, we focus on the totality of EMDE innovation. We also compute up-to-date numbers for the share of HIC innovations that are collaborative with EMDE innovators (see Figure 2, bottom row).

⁷The gap for all technologies is slightly smaller than for green technologies, with collaborative innovations generating an estimated \$8.7 million additional spillover compared to non-collaborative ones.

companies as collected by the EU Joint Research Centre R&D Scoreboard, comprising 6,300 firms, of which 4,474 have patented innovations in our sample window. We find that most of these are not conducting R&D in EMDE, and those that do, only do so to a small extent. On average across all firms, only about 2 percent of the innovations patented by firms involve EMDE partners. Nevertheless, the Scoreboard firms account for about half of all EMDE-HIC innovations found in the patent data. Further analysis results in two key findings:

First, the relationship between firms' involvement in EMDE collaborations and knowledge spillovers to EMDEs is inverse U-shaped. Firms with a greater share of innovations involving EMDE collaborators generate larger spillovers to EMDEs, but only up to a point. We estimate the spillover-maximising diversification share — the fraction of a firm's innovations involving EMDE collaborators — at around 44 percent.⁸ Firms whose innovations involve *only* EMDE collaborators generate fewer spillovers to EMDEs than more diversified firms, which retain a non-zero share of innovation in HICs. One possible explanation is that HIC innovation tends to be of higher quality, so that even with geographic distance barriers to knowledge diffusion, the greater value of HIC-generated knowledge can result in larger spillovers reaching EMDEs. This result is not entirely surprising: trade linkages, investment linkages, and geographic proximity have previously been identified as important conduits of knowledge spillovers. However, it is not a trivial result. As suggested earlier, a concern is that the impact of EMDE-HIC collaborations could be limited by a lack of absorptive capacity, or could even be counterproductive if research is redirected away from where EMDE absorptive capacity is located. Hence, a robust positive effect on spillovers is a strong indication that EMDEs have absorptive capacity and that any negative effects from a redirection of research focus are more than compensated by quality improvements.

Second, the inverted-U relationship is not specific to spillovers accruing to EMDEs: it also characterises global spillovers and spillovers accruing to HICs. This implies that diversification is beneficial not only for maximising spillovers to EMDEs, but also for maximising the overall global spillover value and the spillovers accruing to HICs.

We develop a simple model to probe the mechanism behind these findings. Individual innovators have specific innovation types. Innovation occurs with a probability that is increasing in the diversity of the knowledge stocks of the innovators involved. Innovators within one country are more similar to each other than innovators in different countries; however, barriers between countries mean that this between-country diversity is not fully exploited. Those barriers are reduced when firms invest in R&D labs in other countries. We suggest that such foreign labs can not only increase the innovation productivity of the firms establishing the labs but also provide a bridge to access more diverse and complementary innovation types for firms and innovators close to a firm with foreign R&D presence. We demonstrate in the appendix that this can generate the empirical pattern found in the data.

What are the potential concerns and implications of these findings? The primary concern is that more diversified firms with the resources to establish R&D labs in multiple countries are larger and also spend more on R&D. Hence, it could be these factors rather than diversity that drive higher spillover outcomes. However, the diversification premium is robust to controlling for firm size, R&D spending, the private value of a firm's innovations and a variety of other characteristics. Moreover, we do not find the inverted-U pattern for the private value of firm-level innovations, suggesting that private incentives do not explain our key results.

We therefore conclude that the higher spillovers associated with more diversification are driven by factors external to firms. This implies that individual firms will not necessarily gain directly by increasing their share of foreign R&D collaborations. However, we suggest that further diversification is likely to lead to higher social returns including within HICs. Hence, our result could provide a rationale for HIC governments to support tax incentives for R&D in EMDEs or for development banks to co-invest in such R&D activities.

The remainder of the paper is organised as follows. Section 2 describes the data. Section 3 gives a broad landscape of spillover quality for HIC vs. EMDE⁹ innovations. Section 4 looks at the composition of EMDE innovations by collaboration type and the returns to each type. Section 5 examines the leading R&D investors and their involvement in developing-country innovation. Section 6 tests the inverted-U relationship between a firm's share of EMDE collaborations and its spillover outcomes. Finally, Section 7 concludes.

⁸We do not see this as a precise estimate of a welfare-optimising equilibrium. Increasing the diversification share from the current, rather low level of about 2 percent would be a large, non-marginal change that would likely trigger many responses beyond the scope of this study. Nevertheless, the figure gives a sense that the effects we identify are potentially economically meaningful.

⁹Unless explicitly stated otherwise, all our results exclude China from the EMDE classification.

2 Data

Our analysis draws on two data sources: the 2025 release of the PATSTAT global patent database,¹⁰ and the EU JRC R&D Scoreboard database tracking the world’s leading R&D investors. We describe each in turn, and close the section with descriptive statistics on the main analysis sample.

Innovations Our innovation universe is the set of patent families filed between 2013 and 2022, extracted from the autumn 2025 release of PATSTAT (the EPO’s worldwide statistical patent database). We use the simple-family (*docdb*) grouping, which collapses all patent documents referring to the same underlying invention across jurisdictions into a single record. We use the word *innovation* throughout this paper to refer to a docdb family. The analysis sample contains approximately 20 million innovations for which it is possible to assign at least one country mapping. We use three sources to do so. Firstly, the person file from PATSTAT, which we further clean and harmonise. Secondly, we rely on the geocoded patent dataset published by de Rassenfosse et al. (2019), which provides cleaned inventor- and applicant-country information for the global patent universe. Thirdly, we use the mappings contained in the ORBIS IP database provided by Bureau van Dijk (whose cleaning conventions we follow Kalemli-Ozcan et al., 2015). We map an innovation to a country if either one of the assignees or one of the named inventors is based in that country, and we treat an innovation as collaborative between countries or country groups (such as HIC vs. EMDE) if at least one inventor or assignee is based in each of the relevant countries.

Knowledge spillover values For each innovation in the analysis sample we follow Guillard et al. (2021) and construct value indicators that aggregate the direct and indirect forward-citation network into an estimate of the social value of the citing chain (*Patent Rank*). The algorithm assigns part of the private value of citing patents across the collection of cited patents through the citation network, with decay factor of 0.5^k , where k is the degree of indirectness. The patent-level private value estimates are based on Kogan et al. (2017), which uses an event study on the stock-market reaction of the patentee in a 3-day window around the patent’s grant date. Because this is only directly estimable for listed firms, we extend it to the full innovation universe via a prediction model based on patent features (narrow technology class, claim count, patent-family size, and filing year). We then compute a measure of the marginal return of further investment in different technology fields and country groups by fitting a simple structural model of the innovation process. The full procedure - including *Patent Rank*, the cost-of-innovation estimates by technology field, and the spillover-flow decomposition - is described in Appendix A; see also Guillard et al. (2021) and Martin and Verhoeven (2023). The version of the spillover calculations we use is the one that powers the database of the Innovation Strategy Explorer (ISEapp) online tool.

Country classification We classify each inventor’s country of residence into one of three groups based on the World Bank income classification at the time of filing. First, *HIC* groups the High Income Countries. Second, the *EMDE excluding China* group covers Emerging and Developing Economies, with China handled separately throughout because of its volume and rapidly evolving classification (throughout the rest of the paper, for brevity, EMDEs refer to EMDEs excluding China unless otherwise specified). Third, *China* forms its own category. An innovation is labelled by inventor-country group when at least one of its inventors resides in that group; innovations can fall into more than one group (e.g. a HIC–EMDE collaboration is labelled both *HIC* and *EMDE*). When we report aggregate statistics by inventor group we use this “any-inventor” classification.

Green technology We label an innovation as a *green technology* if at least one of its patent classifications falls under the EPO Y02 system (climate-change mitigation and adaptation technologies).

R&D firms (Scoreboard) For the firm-level analysis we use the universe of the world’s leading R&D investors compiled in the EU JRC R&D Scoreboard.¹¹ The Scoreboard is published annually by the European Commission’s Joint Research Centre and identifies the firms with the highest disclosed R&D spending worldwide. We use the 2003–2024 panel of Scoreboard editions, which covers 6,300 distinct firms after harmonising company names across editions (6,339 distinct names), 5,937 of them with at least one Scoreboard entry in 2013–2022. We match each Scoreboard firm to its PATSTAT patent portfolio using a name-matching procedure that handles subsidiaries, corporate-group structure, and name variants. The match links 5,460 firms to at least one PATSTAT inventor or applicant record and 4,474 firms to at least one innovation filed in 2013–2022; of

¹⁰PATSTAT (the EPO Worldwide Patent Statistical Database) is compiled and distributed by the European Patent Office. It covers the bibliographic records of patent applications filed with more than 100 patent offices worldwide — applicants, inventors, technology classifications, citations and family links — in a form designed for statistical analysis, and is updated twice a year (a spring and an autumn edition; we use the autumn 2025 edition). It is available by subscription from the EPO at <https://www.epo.org/en/searching-for-patents/business/patstat>.

¹¹<https://iri.jrc.ec.europa.eu/scoreboard/2025-eu-industrial-rd-investment-scoreboard>

these, 4,286 firms have non-missing controls and form the regression sample with information on their innovation activities and other basic characteristics. For each firm we observe annual R&D spending, total innovation count over 2013–2022, the country composition of its inventor pool, and the spillover-value distribution of its innovations.

Descriptive statistics The HIC universe accounts for the largest share of innovations throughout 2013–2022, but China and (to a smaller extent) other EMDEs have both grown noticeably across the decade. The green share of innovation has risen across all groups since 2013; Scoreboard firms maintain a green share at or above the HIC average throughout. The headline composition statistics that motivate the rest of the paper appear in Section 4: about 47 percent of all EMDE innovations involve at least one HIC inventor and about 48 percent for green innovations.

Table 1 reports descriptive statistics for the firm-level regression sample used in Section 6: 4,286 Scoreboard firms with non-missing controls, of which 2,611 are classified as green-innovation firms. The two sub-samples are similar on most dimensions but green-innovation firms have noticeably more international inventor coverage (median 4 vs. 3 inventor countries) and substantially larger innovation portfolios (median 125 vs. 38 innovations).

Table 1: Descriptive statistics for the regression sample

	All firms (n = 4,286)					Green-innovation firms (n = 2,611)				
	Mean	SD	P25	P50	P75	Mean	SD	P25	P50	P75
<i>Headline regressor</i>										
EMDE innovation share	0.022	0.101	0.000	0.000	0.000	0.022	0.098	0.000	0.000	0.002
<i>Spillover outcomes</i>										
Global (USD M / inno)	11.91	18.71	3.98	7.27	13.79	10.65	16.41	4.26	7.00	12.36
to EMDE (USD M / inno)	0.614	1.889	0.011	0.116	0.537	0.440	1.186	0.029	0.124	0.441
to HIC (USD M / inno)	7.38	12.30	1.92	4.29	8.62	6.35	9.89	2.09	4.05	7.48
<i>Private value</i>										
Private value (USD M / inno)	40.58	25.29	24.09	35.09	52.12	38.18	20.89	24.18	33.39	47.25
<i>Firm controls</i>										
Innovation portfolio size (100s)	7.59	35.98	0.08	0.38	2.20	12.30	45.48	0.31	1.25	5.87
Number of inventor countries	5.4	8.0	1.0	3.0	6.0	7.3	9.7	2.0	4.0	8.0
R&D per innovation (USD M)	78.24	530.79	1.57	6.61	25.91	20.32	88.66	0.88	3.48	11.26
R&D missing	0.059	0.236	0.000	0.000	0.000	0.057	0.233	0.000	0.000	0.000
Cost of innovation step (USD M)	11.59	6.33	6.52	10.68	16.05	11.19	5.84	6.60	10.11	15.27

Notes: Firm-level means over 2013–2022. The sample is all Scoreboard firms with non-missing EMDE-innovation share, inventor-country count and private value; the green column restricts to firms with at least one green-tagged innovation. R&D per innovation and cost of the innovation step are shown in levels; they enter the regressions as safe logs (the log where defined, zero otherwise, paired with a missing-value dummy), and are set to zero here on the same convention.

3 The quality of Green EMDE innovation

Innovation is central to long-run productivity growth and technological catch-up, but its role in development extends beyond the adoption of technologies developed at the frontier. Developing-country firms can also generate innovations that adapt technologies to local conditions and create knowledge that can be reused by other firms, making the social value of innovation potentially larger than its private returns (Cirera and Maloney, 2017). This distinction is particularly relevant for green technologies: evidence suggests that clean technologies generate particularly large knowledge spillovers (Dechezleprêtre et al., 2014), and that EMDE countries have strong green-innovation capabilities (International Finance Corporation, 2025).

Green innovation largely closes the quality gap. In Figure 1, we reproduce the findings of International Finance Corporation (2025), with a more recent sample of patent data. In panel (a), we see that the average value of knowledge spillovers generated by green innovations is higher in both HICs and EMDEs. While EMDE innovation remains somewhat less valuable on average, the difference is greatly attenuated for green innovation. Moreover, with \$8.01M, green EMDE innovations exceed the HIC average for all innovations of \$7.68M.

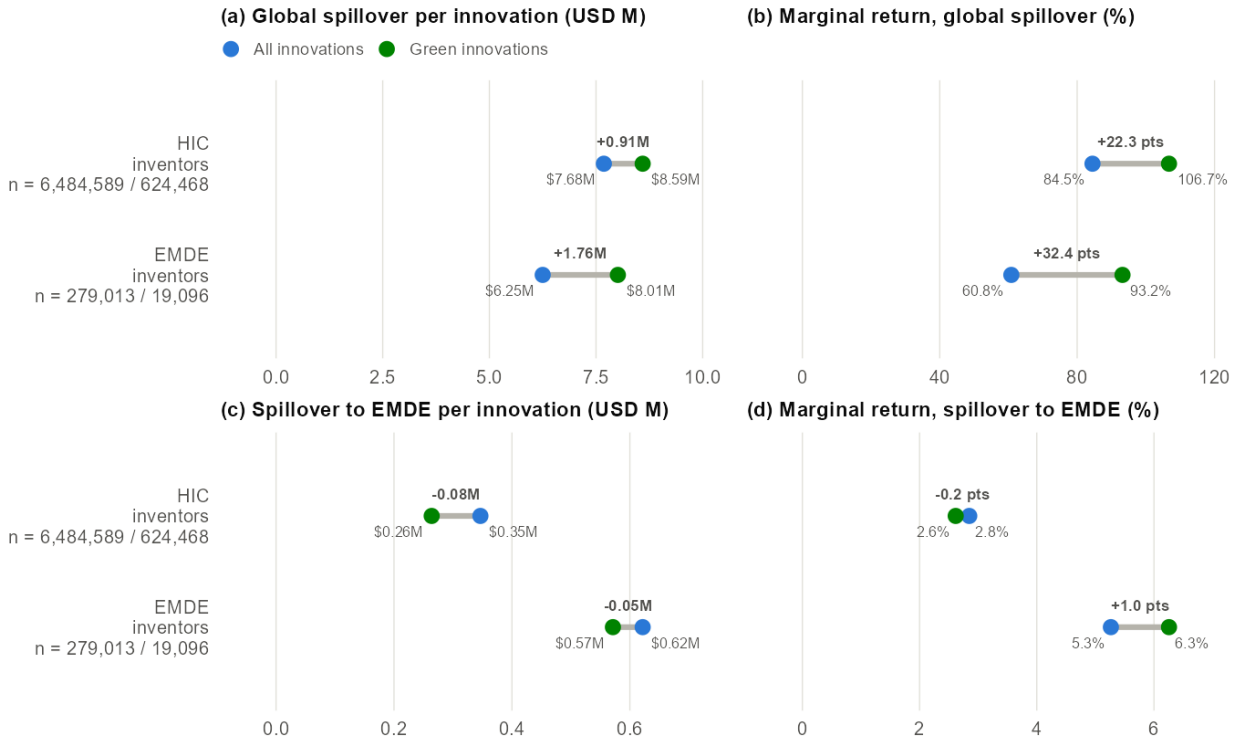
The case for green innovation is stronger once innovation costs are taken into account. Comparing realised spillover values alone does not tell us how attractive additional R&D investment is, because the cost of generating new innovations can differ substantially across technology areas. We therefore turn to the Marginal Return Index developed in Guillard et al. (2021), which combines the expected value of innovation and its knowledge spillovers with the estimated cost of producing additional innovations in a field. As shown in Figure 1,

panel (b), green technologies generate substantially higher marginal returns than non-green technologies, and the difference is particularly large for EMDE innovations. For EMDE innovations, the average marginal return rises from 61 percent across all technologies to 93 percent for green innovations, an increase of 32.4 percentage points. The corresponding figures for HIC innovations are 85 and 107 percent, an increase of 22.3 percentage points. The cost-adjusted evidence therefore strengthens the case for green R&D in EMDEs: the high spillover value of green innovation is not simply the result of a larger stock of realised innovation outcomes, but is accompanied by high estimated returns to further investment.

EMDE innovation generates particularly valuable spillovers within EMDEs. The figures in panels (a) and (b) examine global spillovers. By contrast, panels (c) and (d) focus on spillovers that accrue to inventors in EMDEs. This underlines that knowledge spillovers are geographically localised: the average value of spillovers from HIC innovators to EMDE recipients is, at \$0.35M, substantially lower than the average spillover value from EMDE innovators to other EMDE peers (\$0.62M). There is also a reversal in the relative value of green innovations. A similar pattern emerges when examining marginal returns in panel (d). However, we still find a green premium for within EMDE spillovers: green innovations show a gap in returns of 1 percentage point. Hence, purely from a growth point of view, a focus on green R&D is supported by our results.

Taken together, these results point to a potentially important development opportunity. EMDE innovation is somewhat less valuable than HIC innovation on average, but the gap is substantially smaller for green technologies, while green innovation has particularly high cost-adjusted returns to additional R&D. Moreover, EMDE innovations generate relatively large spillovers within EMDE economies themselves. The next question is therefore not only where the high-value innovation opportunities lie, but who is producing them. In the next section, we examine the composition of EMDE innovation and show that high-value EMDE innovation is disproportionately associated with collaboration with HIC innovators.

Figure 1: Per-innovation knowledge spillover: HIC vs. EMDE



Notes: Dots are cell means. Rows are innovations with at least one HIC inventor and innovations with at least one EMDE inventor; the two are not mutually exclusive, since a collaborative innovation appears in both. China is excluded from the EMDE group throughout the paper. Left column: spillover flows in USD millions per innovation. Right column: the same flows as marginal returns on the innovation's worldwide value. Top row: global flows. Bottom row: flows accruing to EMDE economies. PATSTAT 2025, filing years 2013–2022.

4 Who produces the high-value EMDE innovations?

International co-invention provides one potential mechanism through which developing-country innovators can access knowledge and technological capabilities located at the global frontier. It can also provide finance not

otherwise available. Unlike more indirect forms of international technology diffusion, collaboration among inventors creates opportunities for sustained interaction and exchange of both codified and tacit knowledge (Branstetter et al., 2014; Giuliani et al., 2016).

EMDE innovation is unusually collaborative. EMDE innovation is characterised by a much greater reliance on international collaboration than HIC innovation. 47 percent of EMDE innovations involve at least one HIC inventor, and this share rises to 48 percent among green innovations (Figure 2, panels (c) and (d)). By contrast, around 90 percent of HIC innovations are produced entirely within HIC countries, while only around 2 percent involve an EMDE inventor (Figure 2, panels (a) and (b)). The asymmetry is striking: collaboration with HIC inventors is already an important part of the EMDE innovation system, whereas collaboration with EMDE inventors remains a small (around 2 percent) component of innovation produced in HIC economies. Cross-border collaboration among EMDE countries without HIC participation is also rare, even if we were to include China in the EMDE group. These findings are consistent with the idea that international collaboration can connect innovators operating at different points in the technological landscape, facilitating access to frontier knowledge in emerging economies, particularly in the field of green innovations.

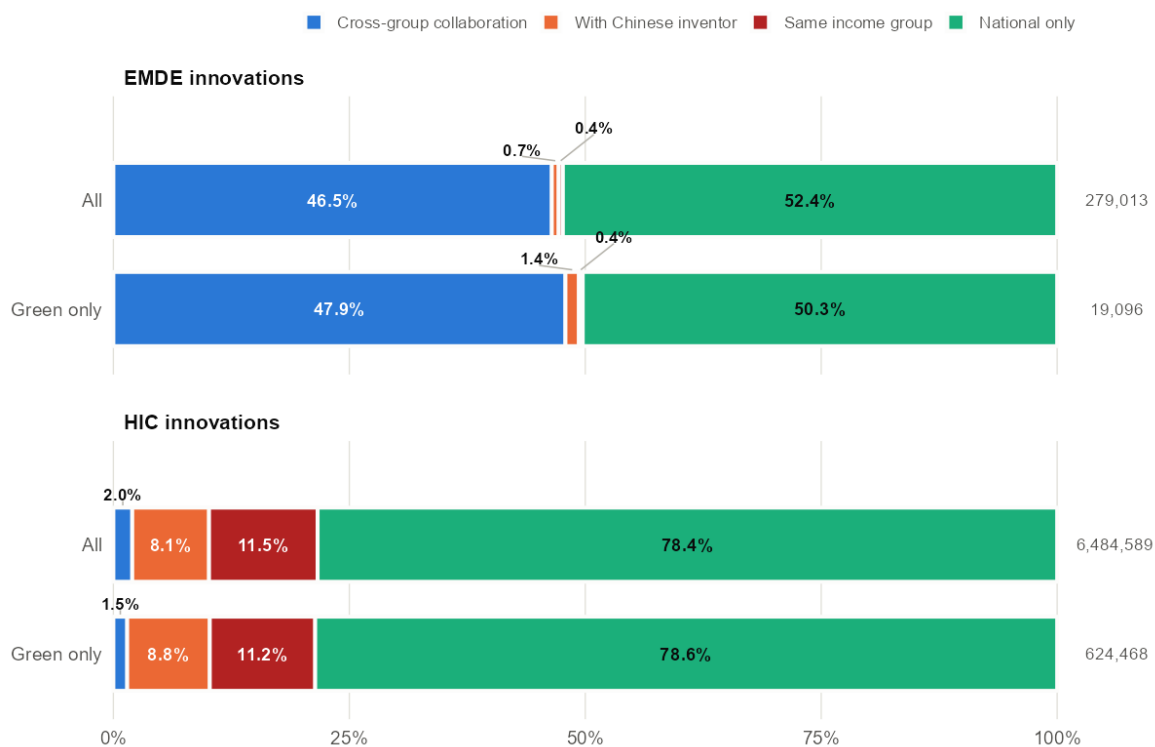
HIC collaboration is strongly associated with high-value EMDE innovation. The innovations involving HIC inventors are not simply a sizeable component of EMDE innovation; they are also the most valuable. Figure 3, panel (a), shows that EMDE innovations involving HIC collaborators generate substantially larger global knowledge spillovers than either innovations produced entirely within EMDE economies or other forms of international collaboration. Across all technologies, average global spillovers reach \$10.75 million per innovation for HIC-involving collaborations, compared with \$2.07 million for innovations without international collaboration. The same pattern is present among green innovations, for which the corresponding figures are \$12.44 million and \$3.18 million. The cost-adjusted measure reinforces this result (Figure 3, panel (b)). HIC-involving collaborations generate a global marginal return of 90.9 percent across all technologies and 121.1 percent for green innovations, compared with 34.6 and 61.3 percent, respectively, for innovations without international collaboration. Thus, the higher global spillover value associated with HIC collaboration is not simply a reflection of realised innovation outcomes: once differences in the cost of generating innovation are taken into account, HIC-involving innovations also exhibit substantially higher estimated marginal returns.

The benefits of HIC collaboration are also visible in spillovers accruing to EMDE economies themselves. Average EMDE-directed spillovers are \$1.09 million per innovation for HIC-involving collaborations, compared with \$0.21 million for innovations without collaboration (Figure 3, panel (c)). Among green innovations, the corresponding values are \$0.87 million and \$0.28 million. The marginal return to spillovers accruing to EMDEs is 8.0 percent for all HIC-involving innovations, compared with 3.1 percent for innovations without collaboration (Figure 3, panel (d)). For green innovations, the corresponding figures are 7.8 percent and 4.8 percent. Taken together, these results show that HIC collaboration does not appear simply to redirect the value of EMDE innovation towards the global or HIC innovation system. Rather, EMDE innovations involving HIC collaborators are also associated with substantially greater spillovers reaching EMDE innovators themselves. We also interpret these results as signaling that EMDE have sufficient absorptive capacity to benefit from HIC collaboration. Indeed, we argue that our measure of knowledge spillovers gives a conservative estimate of absorptive capacity. EMDEs may have other channels through which to absorb frontier research output, that are not captured by our measure: a local firm might simply adopt a new technology or develop a new product based on the collaborative research, rather than develop further frontier innovation building on it.

Taken together, Figures 2 and 3 show that international collaboration with HIC innovators is already a major component of EMDE innovation, and that these collaborations are disproportionately represented among the highest-value innovations. This pattern is consistent with the literature’s emphasis on co-invention as a channel through which developing-country firms can access frontier knowledge and build technological capabilities (Giuliani et al., 2016). At the same time, our evidence goes beyond the question of technology transfer: the higher value of these collaborations is visible not only in global spillovers, but also in the spillovers accruing to EMDE economies themselves.

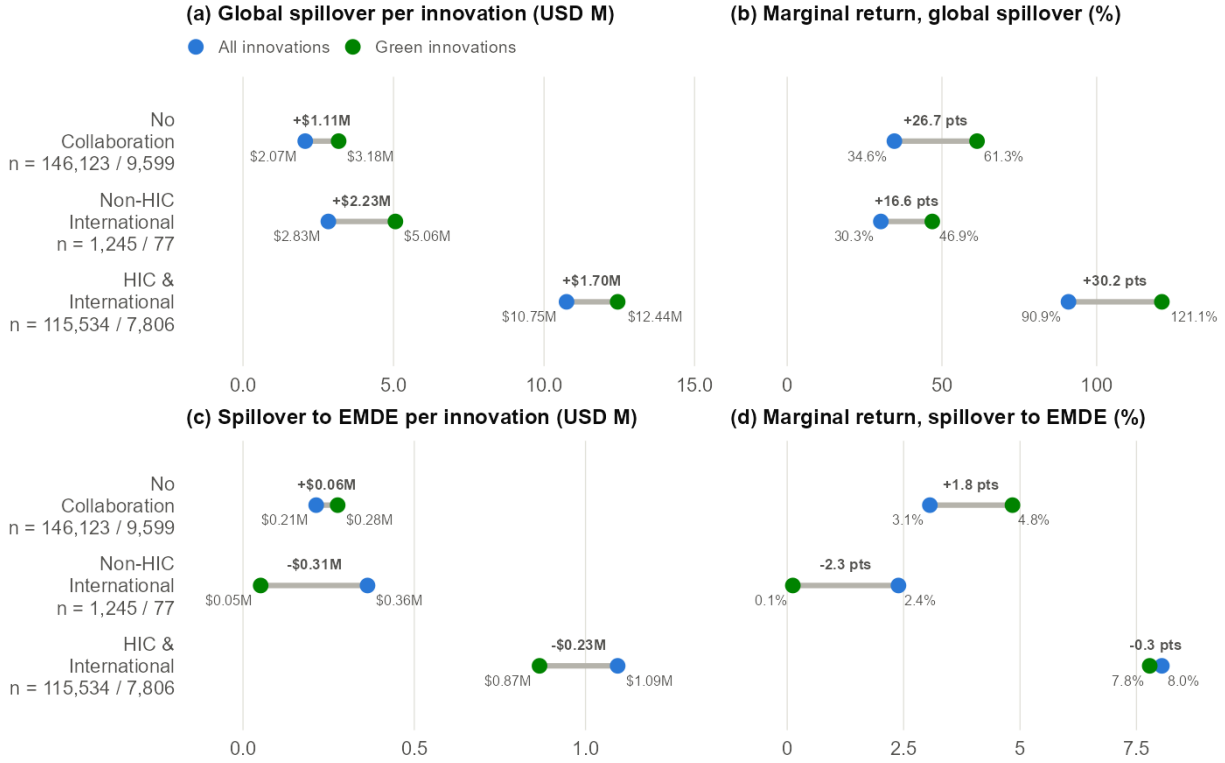
This raises a natural next question. If HIC collaboration is so important for producing high-value innovation in EMDEs, *which HIC firms are providing these collaborations?* In the next section, we turn to the world’s leading R&D investors and examine their contribution to HIC–EMDE innovation.

Figure 2: Composition of EMDE and HIC innovations by inventor-team type.



Notes: Each bar is the full set of innovations in that panel, divided into four mutually exclusive inventor-team types. Assignment is by priority: an innovation with both a HIC and an EMDE inventor is a HIC–EMDE collaboration; otherwise one with a Chinese inventor is counted under China; otherwise one with inventors in more than one country is international within its own income group; the remainder are single-country. Top panel: EMDE innovations. Lower panel: HIC innovations. Sample: PATSTAT 2025, filing years 2013–2022

Figure 3: Knowledge spillovers per innovation by inventor-team type.



Notes: Dots are cell means. Rows are mutually exclusive inventor-team types: a single inventor country (no collaboration), more than one country with none high income (non-HIC international), and more than one country with at least one high income (HIC & international). Innovation counts below each row label are all innovations and green innovations respectively. Left column: spillover flows in USD millions per innovation. Right column: the same flows as marginal returns on the innovation's worldwide value. Top row: global flows. Bottom row: flows accruing to EMDE economies. The green non-HIC-international cell contains only 77 innovations and its estimates in the bottom row should be read with that in mind. Sample: PATSTAT 2025 innovations with at least one EMDE inventor and no Chinese inventor, filing years 2013-2022.

5 Leading R&D firms and developing-country innovation

A natural place to look for innovation partners is the world's largest R&D investors. We examine the universe of the highest reported R&D spenders globally captured by the EU JRC R&D Scoreboard database. This database covers the 2,000 largest R&D investors annually, comprising 6,300 distinct firms across the 2003–2024 editions. Linking these companies to the PATSTAT patent database allows us to understand their innovation quality, the geography of their innovation activities, and the associated returns.

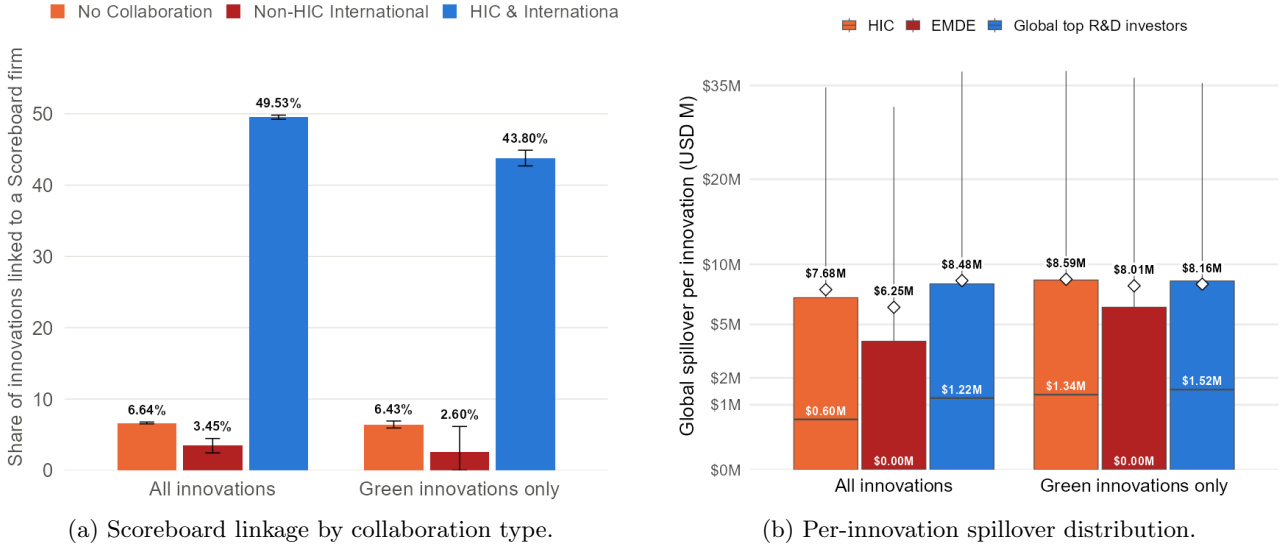
First, Scoreboard firms account for a disproportionate share of collaborative innovations between HICs and EMDEs. Strikingly, just 4,474 firms produce nearly half of all HIC collaborations in EMDEs (Figure 4, panel (a)).¹² This result is similar to and an extension of earlier findings such as Branstetter et al. (2014) showing that the rapid growth in high quality patents (US patents) awarded to inventors based in India and China is driven significantly by MNEs from advanced industrial economies.

Second, Scoreboard firms' innovations have substantially higher spillover values than those of other innovators. Figure 4, panel (b) compares the global spillover value of Scoreboard firms' patents to all patents from HIC countries and EMDEs. Scoreboard firms generate on average about 10% higher global spillover values than other HIC innovators and about a third higher values than their EMDE counterparts. The differences in the typical innovation value are even starker: the median Scoreboard firm's innovation is more than twice as valuable as that of all HIC innovators. For green innovations, the gap is somewhat smaller, but the spillover value of the median Scoreboard firm's green patent is still more than 13% higher than that of the median HIC innovation.¹³

¹²We showcase some of these firms along with their collaborative innovations in Appendix D and in an online gallery.

¹³Appendix D highlights some concrete examples of the Scoreboard firms with the highest marginal return of spillovers to EMDE in green innovations, as well as some of the high value innovations that are HIC-EMDE collaborations.

Figure 4: Leading R&D firms: EMDE collaborations and spillover values.



Notes: Panel (a): share of EMDE innovations linked to a Scoreboard firm, by inventor-team type (no collaboration, non-HIC international, HIC & international), for all innovations and green innovations only; error bars are 95% confidence intervals. Panel (b): boxplots of global spillover per innovation (USD M) for innovations with at least one HIC inventor, at least one EMDE inventor, and innovations linked to a Scoreboard firm; left group all innovations, right group green innovations only. Diamond symbols indicate sample means. Y-axis is in square root scale to improve readability. Sample: PATSTAT 2025, filing years 2013–2022.

Yet, despite being a major contributor to innovation collaborations with EMDEs globally, the Scoreboard firms still do very little of their R&D *in* EMDE economies: the median Scoreboard firm has no patented innovation involving an EMDE inventor, and the mean is only about 2% of the firm’s innovations (Table 1). The natural next question is, what is different about the firms that collaborate more with EMDE inventors?

Table 2 reports differences between non-collaborative firms, firms with any HIC-EMDE collaborations, and firms that are highly collaborative (those with EMDE collaboration share above the sample mean of 2.2%). The results suggest three notable patterns. First, collaborating firms are an order of magnitude larger, with an innovation portfolio of 2,466 innovations against 251, and far more globally diversified, 13.6 inventor countries against 3. These differences are consistent with larger and better-resourced firms being more likely to engage in global R&D operations. Note that their R&D per innovation is lower, 22 against 102 USD M, which may also be driven in part by the size difference. However, one characteristic that is notably similar across the two groups is their average private innovation value at around 40 USD M per innovation. Interestingly, firms with above-average EMDE collaboration (share above 2.2%) look significantly different from the average collaborator. Their innovation portfolios are smaller at 1,107 innovations, and they are slightly less diverse in inventor countries. However, their average private innovation value is slightly higher than the non-collaborators and the average collaborator. We return to these differences in the next section. Because collaboration is strongly correlated with firm characteristics in a non-linear manner, the analysis in the next section is reported throughout with multiple controls for these characteristics.

6 Should top R&D firms do more R&D in developing countries?

Section 5 established that Scoreboard firms account for a sizeable share of the high-value HIC–EMDE collaborations but at the same time do very little of their R&D *in* EMDEs. Should they do more?

We examine this by exploring how the amount of spillover generated varies with a firm’s share of EMDE innovations. Figure 5, panels (a) and (b) show the unconditional relationship which reveals an inverted U-shaped relationship between EMDE collaboration share and spillover values. In other words, firms with a very low share of EMDE innovations (like the current Scoreboard average) generate relatively low spillover value, and so do firms with a very high share of EMDE innovations. The maximum spillover value occurs among firms with a diversified inventor pool that includes a substantial share of EMDE innovators and innovations undertaken by those inventors. Importantly, we find the same inverted U-shaped relationship between spillover values and EMDE collaboration share for *global* spillovers, spillovers to *EMDEs*, as well as spillovers to *HICs*. For spillovers to EMDEs, the initial increase may reflect the greater relevance of innovations developed with

Table 2: Firm characteristics by EMDE-collaboration group

	Group means		
	No collaboration (1) n = 3,303	Any collaboration (2) n = 983	Share > 2.20% (3) n = 486
EMDE innovation share	0.000	0.096***	0.186***
HQ in a high-income country	0.861	0.927***	0.886
Innovation portfolio size (100s)	2.51	24.66***	11.07***
Number of inventor countries	3.0	13.6***	11.8***
R&D per innovation (USD M)	102.04	21.94***	35.80***
R&D missing	0.067	0.034***	0.039***
Cost of innovation step (USD M)	11.45	12.03***	13.18***
Private value (USD M / inno)	40.82	39.78	42.04

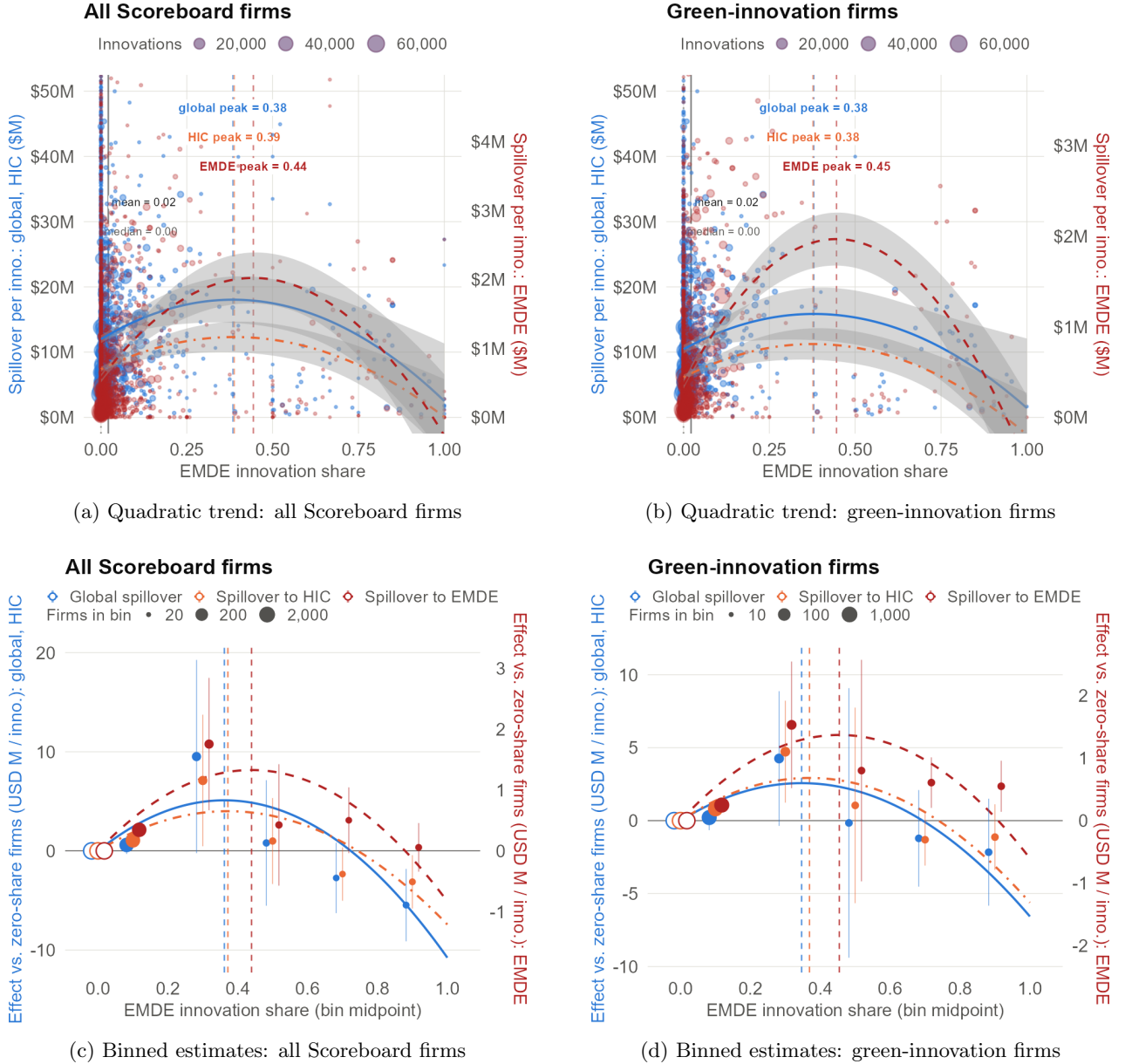
Notes: Firm-level means over 2013–2022, for the firms entering Table 3. Column (1) is firms with no EMDE collaboration, column (2) firms with a positive EMDE-innovation share, and column (3) firms whose share exceeds 2.20%. For reference the mean share is 2.19% across all firms and 9.55% across the firms with a positive share. Column (3) is a subset of column (2), so the two are not independent samples. All variables are in levels. R&D per innovation and the cost of the innovation step are averaged over the firms for which they are defined; the share of firms without R&D data is reported in its own row. These two enter the regressions as safe logs. Stars mark Welch *t*-tests of columns (2) and (3) against column (1): * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The headquarters indicator is the country declared on the firm’s JRC R&D Scoreboard record.

EMDE participation to the needs and production conditions of other EMDEs, consistent with the literature on appropriate technology (Acemoglu and Zilibotti, 2001; Moscona and Sastry, 2025) and previous empirical findings that spillovers are often localised (Jaffe et al., 1993; Lychagin et al., 2016). However, as the EMDE collaboration share increases further, reduced participation by HIC inventors may limit access to complementary knowledge and technological capabilities, potentially explaining the subsequent decline in spillovers. Consistent with this interpretation, spillovers to EMDEs peak at an estimated EMDE share of 0.44, indicating a slight bias towards HIC inventors. Nevertheless, the decline is estimated from relatively few firms with small innovation portfolios and should be interpreted with caution.

That the inverted-U pattern also applies to HIC and global spillovers speaks to a diversification benefit. By bringing together innovators with what are likely more diverse backgrounds, knowledge spillover becomes higher also in HICs and globally. Appendix C sets out a simple simulation model in which this pattern arises from knowledge diversity alone: a firm whose people combine both types of countries’ knowledge reaches more complementary partners, innovates more, and therefore feeds into more innovations outside the firm in both countries.¹⁴ Rather intuitively, the optimal diversification point is further biased towards HIC (0.39) when it comes to HIC spillovers. In Figure 5, panel (b) we restrict the sample to firms with at least one green innovation and find very similar patterns.

¹⁴An interactive version of the model, in which every parameter can be changed and the simulated economy replayed cycle by cycle, will be available at <https://mondpanther.github.io/amodel/>.

Figure 5: Firm-level inverted-U: EMDE-innovation share and knowledge spillover.



Notes: **Panels (a) and (b):** Horizontal axis shows the share of the firm's innovations involving at least one EMDE inventor. Left axis (blue, solid fit): firm-mean global spillover per innovation. Right axis (red, dashed fit): firm-mean spillover to EMDE per innovation. Orange (dotdash) overlays the same outcome for spillover to HIC. Bubble size is proportional to the firm's innovation count. Panel (a): full Scoreboard sample. Panel (b): firms with at least one green innovation in 2013–2022. **Panels (c) and (d):** Horizontal axis shows share of the firm's innovations involving at least one EMDE inventor in 5 equal-width bins. Left axis (blue, solid fit): conditional mean of global and HIC spillover per innovation relative to the zero-share firms. Right axis (red, dashed fit): conditional mean of EMDE spillover per innovation relative to the zero-share firms. Controls include all variables as in Table 3. Orange (dotdash) overlays the same outcome for spillover to HIC. Bubble size is proportional to the bin's sample size. Panel (c): full Scoreboard sample. Panel (d): firms with at least one green innovation in 2013–2022. The coefficient estimates are reported in Appendix B, Table 4. For a full set of robustness checks with additional functional forms and flexible controls, see link

As discussed above, collaborative firms look distinct from non-collaborative ones. Table 2 illustrates that larger and better resourced firms both operate more globally and produce higher quality innovations, so the unconditional relationship may reflect scale rather than diversification. The relationship between higher quality and more diversified innovation teams could also be one of reverse causality. Table 3 therefore conditions on the number of countries in which the firm is R&D active, its total innovation count, its total R&D, cost of innovation, and the average private value of its innovations. The inverted U pattern still holds.

The high share of firms with no collaborations, as well as the non-linearities in firm characteristics associated with their collaboration share, further motivates a more flexible functional form. Figure 5, panels (c) and (d) plot the results from binned estimates using 5 equal-width bins, taking firms with no EMDE collaboration as the

Table 3: Spillover outcomes and firm EMDE-innovation share

Per innovation (USD M) Sample	to EMDE All (1)	Global All (2)	to HIC All (3)	to EMDE Green (4)	Global Green (5)	to HIC Green (6)
EMDE innovation share	6.0439*** (0.8646)	28.2053*** (8.4947)	21.5379*** (5.5651)	6.0366*** (0.7346)	14.8265 (10.2122)	15.8479*** (6.1025)
(EMDE innovation share) ²	-6.8748*** (1.1013)	-38.9818*** (10.8198)	-28.9643*** (7.0883)	-6.6403*** (0.9736)	-21.3908 (13.5354)	-21.4646*** (8.0883)
Number of Inventor Countries	0.0089* (0.0046)	0.0857* (0.0449)	0.1018*** (0.0294)	0.0062** (0.0030)	0.0979** (0.0422)	0.1066*** (0.0252)
log(Number of Innovations, 100s)	-0.0887*** (0.0204)	-0.9108*** (0.2006)	-0.7707*** (0.1314)	-0.0399** (0.0168)	-1.0547*** (0.2329)	-0.7759*** (0.1392)
log(R&D per innovation)	0.0303 (0.0198)	0.7464*** (0.1946)	0.2579** (0.1275)	0.0497*** (0.0165)	0.8988*** (0.2296)	0.3447** (0.1372)
R&D missing	-0.0031 (0.1278)	-0.7713 (1.2553)	-0.6552 (0.8224)	-0.0821 (0.0989)	-1.6157 (1.3747)	-0.7679 (0.8215)
log(Cost of innovation step)	0.4324*** (0.0501)	5.3938*** (0.4920)	3.2416*** (0.3223)	0.3527*** (0.0474)	5.5585*** (0.6592)	2.6886*** (0.3939)
Private value (USD M / inno)	0.0037*** (0.0013)	0.0269** (0.0123)	0.0421*** (0.0081)	0.0021* (0.0013)	0.0161 (0.0177)	0.0480*** (0.0106)
Observations	4,286	4,286	4,286	2,611	2,611	2,611
R ²	0.05824	0.07305	0.08032	0.09518	0.08716	0.10267

Notes: Each column regresses one firm-level knowledge-spillover outcome on the firm’s EMDE-innovation share (the share of its innovations involving at least one EMDE inventor) and its square, plus controls. Columns 1–3: all Scoreboard firms; columns 4–6: restricted to green-innovation firms (firms with at least one green-tagged innovation in 2013–2022). Controls include the number of distinct inventor countries, the log of the firm’s portfolio size in 100s of innovations, safe-log R&D per innovation (log of total firm R&D over 2013–2022 divided by total innovation count, when defined, else 0), safe-log mean innovation cost (log of mean per-innovation cost when defined, else 0), and the firm’s mean private value per innovation (USD M). The R&D control is paired with a missing-value dummy that flags firms where the log is undefined (variable missing or ≤ 0). Portfolio size enters in logs rather than the levels of the published specification: in levels the control is insignificant in every column, because a linear slope is flattened by the long right tail of firm size. The robustness check restricting the sample to firms with more than 10 innovations is reported in Appendix B, Table 5.

omitted group. The picture is consistent with the quadratic over the range where most firms are concentrated. HIC spillover per innovation is already about \$1.1 million higher than for non-collaborating firms in the 0–0.2 bin, a difference that is statistically significant, rises to a peak of about \$7 million in the 0.2–0.4 bin, and falls back thereafter. Spillover to EMDEs similarly follows an inverted U-shaped pattern and peaks in the 0.2–0.4 share range. Results are qualitatively similar for green innovations. In summary, in all of the specifications above, our results suggest that the current average rate of HIC-EMDE collaboration among the Scoreboard firms looks suboptimal socially. Further diversifying their innovation portfolio to EMDEs can increase spillover values to not only EMDEs but also HICs.¹⁵

To illustrate the economic values involved, consider an increase in a firm’s EMDE innovation share from the sample mean of 2.2 percent to 12.3 percent, equivalent to one sample standard deviation. Holding the other covariates fixed, the estimates in Table 3 imply an increase in predicted spillover value of approximately \$1.8 million per innovation accruing to HICs and \$0.5 million accruing to EMDEs (\$2.3 million globally). The positive gains arise well below the estimated peak of the inverted-U relationship. These numbers have to be taken with some caution. But at face value they imply that there is a rationale for HIC countries to subsidise the diversification efforts by large R&D firms by up to several million dollars in a self-interested way while also providing for substantial spillover value flows to EMDE countries.¹⁶

While our results so far are fully based on spillover and thus external returns, we might also wonder if there is any evidence that firms ‘leave money on the table’ - not maximising their private returns - by not sufficiently diversifying. Hence, we examine whether we find the same inverted U pattern for the private values achieved by the firms in Figure 6.¹⁷ There is no trace of the pattern for all innovations. There is a hint of the inverted U pattern for green innovations but there is no significant positive slope in the relationship between diversification

¹⁵We conduct further robustness tests in Appendix B (Sections B.2–B.7) where we show that results are robust to various alternative specifications: restricting the sample to firms that have at least one innovation in collaboration with EMDE inventors and firms with at least one green innovation in collaboration with EMDE inventors, firms that are headquartered in HICs, firms with a portfolio of more than 10 innovations, specification controlling for sector fixed effects, specifications using EMDE inventor share instead of innovation share, and results restricting the sample to pre-2019 data only to address potential issues due to forward-citation truncation bias.

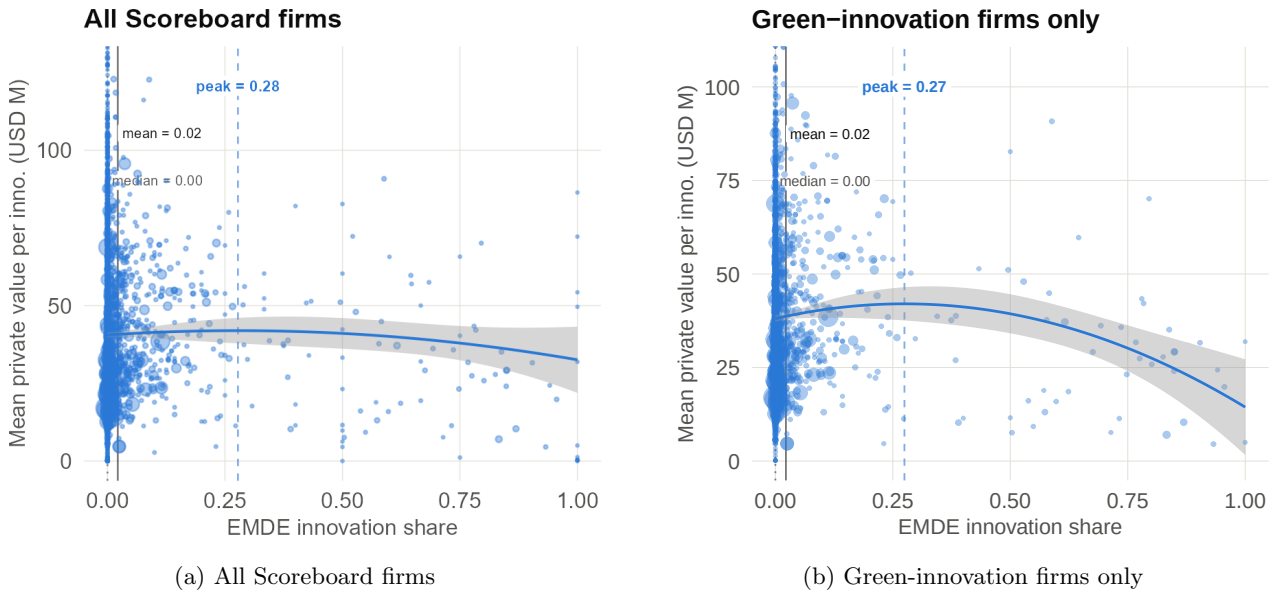
¹⁶This could come in the form of a tax credit along similar lines as a recent proposal by Isaac and Attridge (2025).

¹⁷Appendix B.8, Table 9 shows results with additional controls.

and private values. Hence, it would seem the patterns derive primarily from effects that are *external* to a given innovating firm, and not driven by endogenous behaviour of the firm undertaking R&D investments. In other words, from an individual firm’s point of view, our evidence looks like they are already maximising their private returns at the current degree of diversification. It could be the case that further diversification entails additional costs that we are not fully capturing with the R&D controls included in Table 3.

This wedge between private and social returns is similar to the mechanism in Chikis et al. (2025). A firm that adds an R&D location creates knowledge spillovers for other firms there but incurs additional labour costs and captures only its own return, so it opens too few locations whenever a small presence already generates most of the spillover. Chikis et al. (2025) show this condition determines the direction of the distortion and estimate that it holds for US firms such that they operate in too few markets. Our estimates give a global counterpart to their result, measured on values rather than inferred from citation counts. They also find that policies encouraging wider geographic reach deliver larger welfare gains than conventional R&D subsidies. As we have seen, the benefits to HIC-based inventors of further diversification are likely to be substantial and indeed exceed the benefits to EMDE - and could justify substantial subsidies by HIC governments for firms to diversify to help firms overcome such additional costs.

Figure 6: Firm-mean private value per innovation and EMDE-innovation share.



Notes: Single quadratic fit per panel (95% CI shaded). Bubble size proportional to innovation count. Left: all Scoreboard firms. Right: green-innovation firms only.

7 Conclusion

In this study we provide evidence that the quality of innovation in developing countries other than China can be of similar quality to HIC innovation, and particularly so for green technologies. We further document systematically for the first time from an EMDE country perspective the importance of innovation collaboration between HIC and EMDE innovators. Almost half of EMDE patented innovation derives from such collaborations. More importantly, this type of innovation is the prime driver of high value innovation in EMDE, where value is defined by innovation spillovers. Despite this apparent benefit, we also document for the first time that among the global top R&D firms only very few engage in innovation efforts in EMDEs. We therefore ask if it would be desirable that such firms engage in more R&D. We answer this question by exploring how the value of knowledge spillovers - measured via an indicator derived from direct and indirect patent citations - varies with the degree of R&D diversification, the share of a firm’s innovations that are undertaken with EMDE innovation partners. The results reveal an inverted U-shaped relationship not only for spillover flows towards EMDE but also to HIC spillover recipients. This result suggests room for a Pareto improvement, with potentially more economic growth for both HIC and EMDE via increased knowledge spillovers, as diversification increases from the current very low levels of around 2%.

Our results suggest an optimal diversification ratio well above the current average diversification rate. Given that increased diversification benefits both HICs and EMDEs, there is a potential case for diversification subsidies by HIC governments to overcome fiscal constraints that may be present in many EMDEs. This could

come in a variety of forms, for instance via tax credits for HIC firms when they undertake R&D investments in EMDEs or via co-investments by development banks.

A variety of HICs have in recent years severely cut back their development assistance to EMDEs. The motivation for this has been a mixture of public financial constraints and political movements fuelled by xenophobia. Overcoming these trends will be a challenge for years to come. However, this study points to a mechanism through which policy makers can appeal to the self-interest of voters in efforts to increase financial support to EMDEs. Unlike in other cases where such appeals are made, our study points to a more easily measurable diagnostic for the actual occurrence of such effects, namely exploring innovation data and studying citation networks as we have done here. Moreover, it might be an area where any aid given could be particularly potent in leveraging additional private finance.¹⁸

¹⁸See the related recent proposal by Isaac and Attridge (2025).

A Patent Rank and the construction of innovation returns

This appendix sketches the methodology that produces the patent-level value and spillover indicators on which the main-text analysis is built. The procedure is from Guillard et al. (2021) and applied to the 2025 PATSTAT universe. Two parts mirror the corresponding sections of the IFC report (International Finance Corporation, 2025): the structural cost-of-innovation model (Box 3.1 in the report) and the Patent-Rank-based construction of returns and spillover flows (Appendix 2 in the report). Full derivations are in Guillard et al. (2021); the green-tech application is documented in Martin and Verhoeven (2023).

The starting point throughout is the patent-level private value of Kogan et al. (2017). For each patent issued to a publicly listed firm, the abnormal stock-market return of the patentee in a narrow window around the grant date delivers a market-based estimate of the present value v_i (in USD millions) of the cash flows attributable to that single patent, purged of the firm-level common factor. Because the procedure requires a listed patentee, v_i is directly observed only for the subset of patents granted to publicly traded firms. For all remaining patents we impute v_i via a within-class prediction model using observable patent features (4-digit CPC class, claim count, patent-family size, and other characteristics correlated with v_i among the listed-firm subset). This delivers a v_i for every patent in the universe.

Part 1: Inferring the cost of innovation

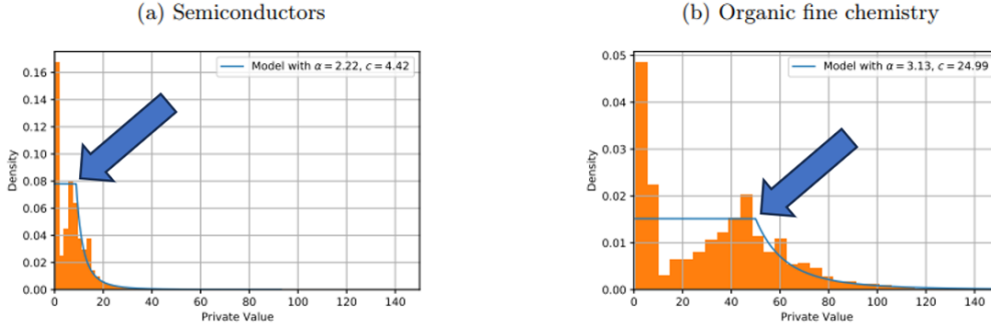
Patent-level private values vary not only because some innovations are more valuable than others, but also because different technology fields differ in how expensive it is to generate a patentable innovation and how skewed the underlying distribution of idea quality is. We disentangle the two using a simple structural model fit at the 4-digit CPC technology level.

Model. In each technology field c , ideas are drawn from an underlying skewed quality distribution, modelled as Pareto with shape parameter α_c — a larger α_c means more mass near zero (fewer “superstar” ideas, a thinner right tail). Turning an idea into a patentable innovation requires a sunk R&D cost K_c that has to be paid *before* the realised value is known.

Decision rule and kink. If realised values were perfectly known in advance, only ideas with realised value above K_c would ever be developed, and we would see a strict truncation of the observed value distribution at K_c . Because realised outcomes are uncertain, some ex-post low-value innovations are still developed (and observed). The combination of (i) idea-generation skewness and (ii) the sunk-cost cutoff produces a characteristic *kink* in the empirical patent-value distribution.

Identification. Fitting the model to the Kogan-based v_i distribution within each 4-digit CPC field recovers the two parameters from two distinct features of the data: the *location* of the kink identifies K_c (the right-shifted the kink, the higher the cost), and the *curvature* of the distribution to the right of the kink identifies α_c (a steeper right-tail drop indicates more mass-at-zero idea generation). Field-level point estimates differ markedly: organic fine chemistry has $K_c \approx \$25\text{M}$ per innovation and a relatively thick right tail; semiconductors have $K_c \approx \$4.4\text{M}$ and very few innovations valued above $\$60\text{M}$. Figure 7 illustrates the fit visually: the orange bars are the empirical patent-value distribution and the blue curve is the fitted model, with arrows pointing to the kink that identifies K_c . Across all fields, green-technology K_c values are about 3% lower on average than non-green, and the green–non-green R&D-cost gap accounts for more than 20% of the cross-country variation in green revealed technological advantage in Martin and Verhoeven (2023).

Figure 7: Inferring the cost of innovation from the empirical patent-value distribution.



Notes: The Figure illustrates how Guillard et al (2021) derive estimates of R&D costs across different technology areas by a modeled distribution function (Model) to the actual distribution of (private) innovation values derived using the Kogan et al (2017) [approach](#); i.e. by examining the shock on share prices of stock listed innovators.

Notes: Reproduced from Guillard et al. (2021) (Figure illustrated in Box 3.1 of International Finance Corporation (2025)). The panels show the empirical patent-value distribution (orange bars) and the fitted structural model (blue line) for two illustrative 4-digit CPC technology fields. Panel (a): semiconductors, with fitted $\alpha_c = 2.22$ and $K_c = \$4.42\text{M}$. Panel (b): organic fine chemistry, with fitted $\alpha_c = 3.13$ and $K_c = \$24.99\text{M}$. Blue arrows mark the kink in each distribution whose location identifies the sunk R&D cost K_c . The two fields illustrate the cross-field range of innovation-cost estimates.

Part 2: Computing returns and spillover flows from innovation

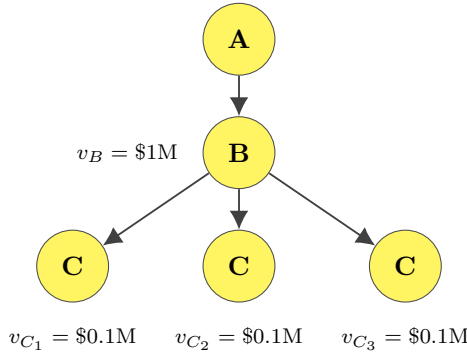
The Part 1 estimates of (K_c, α_c) are inputs to a patent-network construction that propagates the private values v_i along the forward-citation network and decomposes the resulting flows by country group.

Patent Rank. Raw forward-citation counts treat a citation from a low-value patent the same as one from a high-value patent and ignore chains of citations through many generations. *Patent Rank* corrects both issues by adapting the PageRank algorithm to the patent citation network. Concretely, the Patent Rank PR_i of patent i solves the linear system

$$PR_i = v_i + d \sum_{j \in F(i)} w_{ji} PR_j,$$

where $F(i)$ is the set of patents that directly cite i ; $w_{ji} = 1/n_j$ with n_j the number of backward citations of citing patent j (so each citer distributes its rank uniformly over what it builds on); and $d \in (0, 1)$ is a damping factor, set to $d = 0.5$ following Guillard et al. (2021). The fixed point is computed iteratively in standard PageRank fashion across the millions of patents in the network. The intuition: PR_i is the inventor's own private value v_i plus a discounted share of the private values of every downstream patent that builds on i directly or indirectly — i.e. the *total social value* that patent i ultimately creates by seeding the subsequent innovation chain. Figure 8 illustrates this on a toy three-generation chain.

Figure 8: Patent Rank intuition on a three-generation citation chain.



Notes: Schematic of the Patent Rank construction based on Guillard et al. (2021). Innovation A is cited by B , which is in turn cited by three downstream innovations C_1, C_2, C_3 . Private values v_i (Kogan-et-al., 2017) sit at each node. With damping d and uniform inward weights $w_{ji} = 1/n_j$, Patent Rank propagates the downstream private values back along the arrows so that PR_B includes v_B plus a share of $v_{C_1}, v_{C_2}, v_{C_3}$, and PR_A in turn includes v_A plus a (more heavily discounted) share of PR_B . Group-restricted spillover flows zero out the v 's of nodes outside the group of interest before solving.

Spillover-flow decomposition by group. To recover the slice of social value that flows to a given inventor-country group G , we re-solve the same linear system with $v_j = 0$ for every patent j whose inventors are outside G . The resulting group-restricted Patent Rank PR_i^G measures only the spillovers from i that land on group- G inventors. The firm-level outcomes used throughout the paper are the per-innovation averages of these group-restricted ranks: ev_{global} keeps every downstream patent, ev_{HIC} keeps only the HIC-inventor downstream patents, and ev_{EMDE} keeps only the EMDE downstream patents. Cross-group flows are equally supported (e.g. the spillover from EMDE inventors to HIC inventors).

Marginal social return (ISTRAX). Combining Part 1 with the Patent-Rank construction yields a marginal-social-return indicator at the technology-field level:

$$\text{ISTRAX}_c = \frac{\alpha_c}{K_c} \cdot \overline{SR}_c,$$

where $\overline{SR}_c$ is the average *social* component of Patent Rank — $PR_i - v_i$, the spillover portion left over once the inventor’s own appropriation is netted out — across innovations i in field c . The two field-level parameters multiply this average in intuitive directions: a smaller K_c means each marginal R&D dollar buys more projects, and a larger α_c means more idea mass is ready to be developed at the margin — so both raise the marginal return.

Replacing the unrestricted PR_i with the group-restricted PR_i^G in $\overline{SR}_c$ yields a group-specific ISTRAX, which is how we compute “national” (within-country), “regional”, and “global” returns. The gap between the global and the national ISTRAX is the cross-border spillover that motivates the main-text counterfactual.

B Robustness

This appendix collects the robustness checks supporting the main-text results. Each subsection re-runs the headline inverted-U regression of Table 3 on a different sub-sample, with an alternative classification, or with additional controls.

B.1 Binned regression results

Table 4: Binned estimates: spillover outcomes and firm EMDE-innovation share

Bin	All innovations				Green innovations			
	Firms (1)	to EMDE (2)	Global (3)	to HIC (4)	Firms (5)	to EMDE (6)	Global (7)	to HIC (8)
0 (reference)	3,303				1,808			
1	866	0.3458*** (0.0523)	0.5994 (0.4643)	1.0637*** (0.3356)	733	0.2489*** (0.0442)	0.2109 (0.4407)	0.8081*** (0.3090)
2	44	1.7536*** (0.5544)	9.5160* (4.9736)	7.1035** (3.3861)	28	1.5307*** (0.5162)	4.2582* (2.3542)	4.7253*** (1.7823)
3	26	0.4258 (0.5088)	0.7994 (3.2317)	0.9929 (2.2122)	14	0.8000 (0.9030)	-0.1574 (4.7117)	1.0450 (3.4189)
4	23	0.5027* (0.2756)	-2.7318 (1.8122)	-2.3407* (1.3732)	14	0.6077*** (0.2061)	-1.2140 (1.6883)	-1.3075 (0.9049)
5	24	0.0572 (0.2036)	-5.4698*** (1.8629)	-3.1247** (1.3732)	14	0.5492*** (0.2081)	-2.1634 (1.8707)	-1.1294 (1.1471)
Observations	4,286				2,611			

Notes: Each spillover column regresses one firm-level knowledge-spillover outcome (USD M per innovation) on dummies for five equal-width bins of the firm’s EMDE-innovation share (the share of its innovations involving at least one EMDE inventor): bin 1 is (0, 0.2], bin 2 (0.2, 0.4], bin 3 (0.4, 0.6], bin 4 (0.6, 0.8] and bin 5 (0.8, 1]. Firms with a share of exactly zero (bin 0) are the omitted reference group, so each coefficient is the difference in spillover per innovation relative to firms with no EMDE collaboration. The Firms columns report the number of firms in each bin. Controls are as in Table 3. Columns 1–4: all Scoreboard firms; columns 5–8: green-innovation firms (firms with at least one green-tagged innovation in 2013–2022). HC1-robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The estimates are plotted in Figure 5, panels (c) and (d).

B.2 Sample of firms with existing presence in EMDE

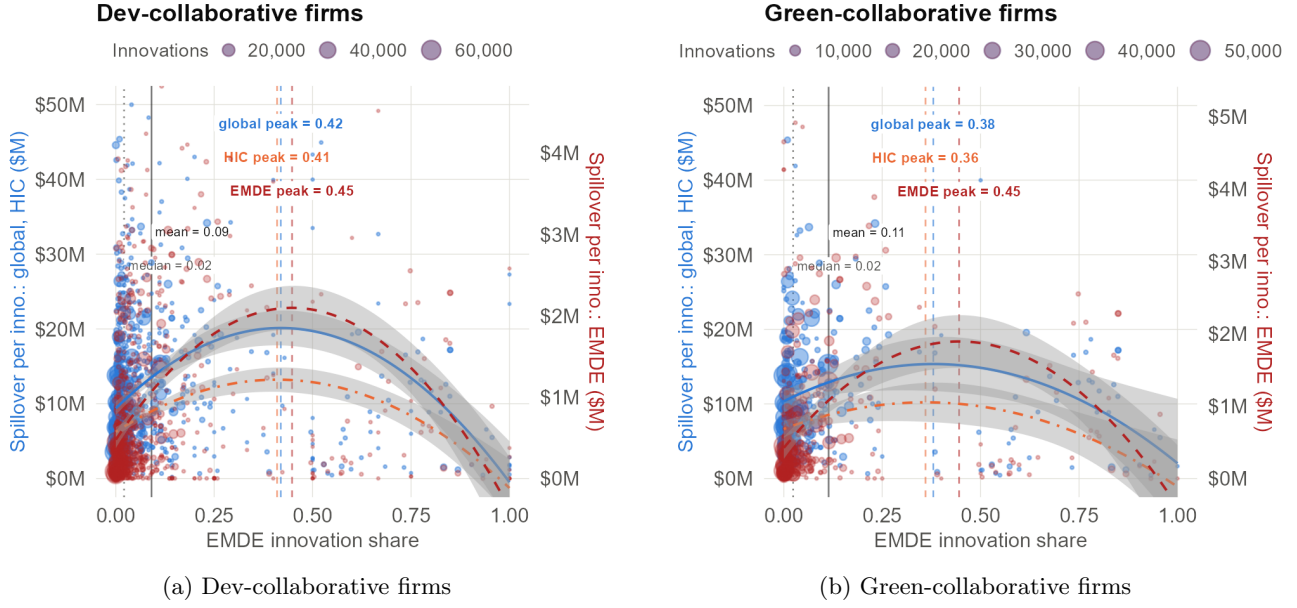
The main text classifies a firm as a *green-innovation firm* if it has at least one innovation in 2013–2022 tagged as a green technology (EPO Y02 codes; see Section 2). That definition is permissive: a single solo-HIC green innovation is enough to qualify. The green-innovation-firm subsample therefore mixes firms whose green innovations *do* involve a developing-country collaborator with firms whose green innovations are produced entirely by HIC inventor teams.

This appendix re-runs the headline analysis on two progressively tighter sub-samples:

- *Dev-collaborative firms* — those with at least one innovation in 2013–2022 involving an EMDE inventor (any technology). This is the subset of Scoreboard firms with non-zero EMDE-innovation share (1,453 firms in the regression sample).
- *Green-collaborative firms* — those with at least one green-tagged innovation that also involves an EMDE inventor (606 firms). A strict subset of the dev-collaborative sample, and a strict subset of the green-innovation-firm sample used in the main text.

Figure 9 plots the inverted-U scatter for both sub-samples. The inverted-U pattern survives the restrictions; the spillover-maximising EMDE innovation share is in the 30–40% range on the global-spillover axis for both samples.

Figure 9: Inverted-U scatter on the dev-collaborative and green-collaborative sub-samples.

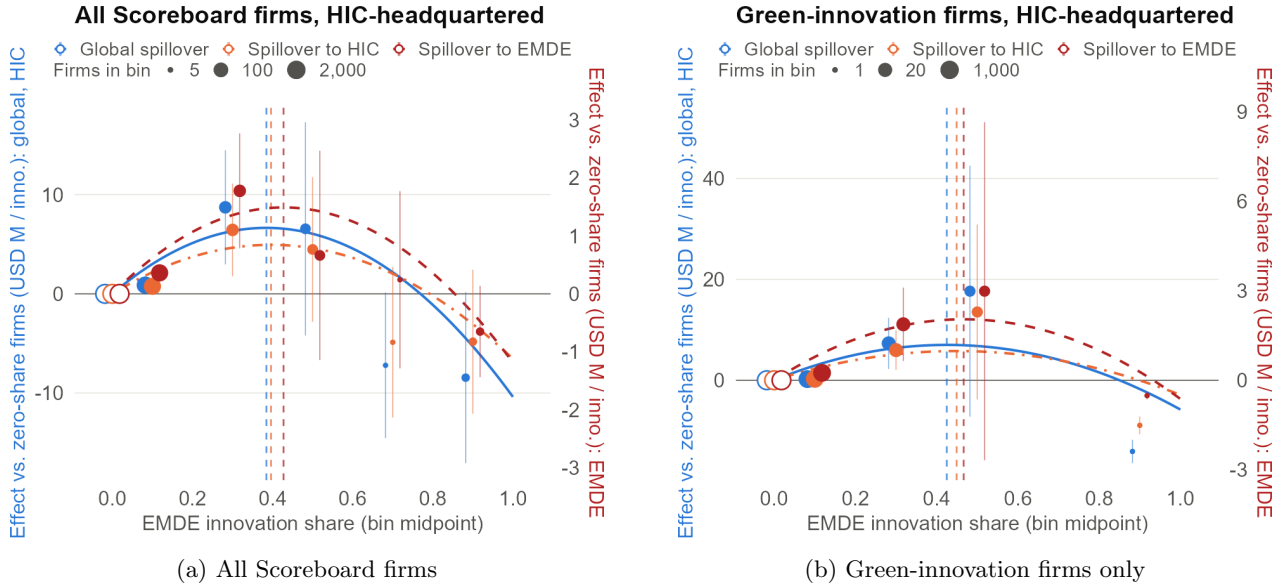


Notes: Panel (a): firms with at least one EMDE-tagged innovation (any technology). Panel (b): firms with at least one green-tagged innovation that also involves an EMDE inventor. Same dual-axis layout, quadratic fit, and \$50M y-axis cap as Figure 5b, which uses the broader green-innovation-firm subsample.

The inverted-U pattern on these sub-samples is sharper than on the full-sample headline regression — restricting to firms with non-zero EMDE engagement drops the mass of zero-share firms that contribute nothing to the share quadratic.

B.3 Sample of firms that are HIC-headquartered

Figure 10: Firm-level inverted-U: EMDE-innovation share and knowledge spillover (HIC-headquartered).



Notes: Horizontal axis: share of the firm's innovations involving at least one EMDE inventor. Left axis (blue, solid fit): firm-mean global spillover per innovation. Right axis (red, dashed fit): firm-mean spillover to EMDE per innovation. Orange (dotdash) overlays the same outcome for spillover to HIC. Bubble size is proportional to the firm's innovation count. Panel (a): Scoreboard firms headquartered in HICs. Panel (b): Scoreboard firms headquartered in HICs with at least one green innovation in 2013–2022.

B.4 Innovation-share specification, $n_{innovations} > 10$ subsample

Table 5 reproduces Table 3 on the $n_{innovations} > 10$ subsample. Columns 1–3 restrict to all Scoreboard firms with more than 10 PATSTAT innovations over 2013–2022; columns 4–6 further intersect with the green-firm subset. This drops the long left tail of near-singleton firms (roughly the bottom 30% of the $n_{innovations}$ distribution) to confirm that the inverted-U pattern is not driven by them. The inverted-U signs and the firm-R&D / mean-cost controls behave the same as in the headline specification.

Table 5: Robustness: $n_{innovations} > 10$ subsample

Per innovation (USD M) Sample	to EMDE	Global All, $n > 10$	to HIC	to EMDE	Global Green, $n > 10$	to HIC
	(1)	(2)	(3)	(4)	(5)	(6)
EMDE innovation share	7.9293*** (0.6911)	32.5594*** (7.1746)	26.1231*** (5.1149)	7.2655*** (0.5760)	21.7422*** (7.3510)	19.1150*** (5.2614)
(EMDE innovation share) ²	-8.9024*** (0.9449)	-41.7597*** (9.8097)	-33.9609*** (6.9936)	-8.0018*** (0.7775)	-27.5556*** (9.9224)	-24.8203*** (7.1019)
Number of Inventor Countries	-0.0034 (0.0028)	-0.0269 (0.0287)	0.0106 (0.0205)	0.0019 (0.0020)	0.0040 (0.0260)	0.0402** (0.0186)
Number of Innovations (100s)	0.0000 (0.0006)	-0.0021 (0.0061)	-0.0045 (0.0043)	-0.0003 (0.0004)	-0.0034 (0.0053)	-0.0058 (0.0038)
log(R&D per innovation)	0.0850*** (0.0136)	1.0639*** (0.1409)	0.7080*** (0.1005)	0.0582*** (0.0109)	0.9596*** (0.1393)	0.5834*** (0.0997)
R&D missing	-0.0298 (0.0967)	-0.9264 (1.0040)	-0.1698 (0.7158)	-0.0645 (0.0752)	-1.2027 (0.9599)	-0.2550 (0.6870)
log(Cost of innovation step)	0.3951*** (0.0420)	5.2968*** (0.4361)	2.9113*** (0.3109)	0.3004*** (0.0372)	4.7401*** (0.4750)	2.3217*** (0.3400)
Private value (USD M / inno)	0.0061*** (0.0012)	0.0621*** (0.0128)	0.0691*** (0.0092)	0.0048*** (0.0011)	0.0669*** (0.0137)	0.0695*** (0.0098)
Observations	3,080	3,080	3,080	2,346	2,346	2,346
R ²	0.15001	0.14801	0.14474	0.18596	0.14912	0.13611

Notes: Robustness check for Table 3: the entire six-column structure of Table 1 is re-estimated on the $n_{innovations} > 10$ subsample. Columns 1–3 restrict to all Scoreboard firms with more than 10 innovations over 2013–2022; columns 4–6 further intersect with the green-innovation-firm subset. Same RHS as Table 1.

B.5 Specification with sector fixed-effects

Table 6 replicates the main-text Table 3 but absorbs JRC R&D Scoreboard industry-sector fixed effects (roughly 36 sectors, one per firm). The sample drops firms without a Scoreboard sector tag. The inverted-U coefficients on the EMDE-innovation-share margin survive the sector demeaning – the within-sector association between EMDE engagement and spillovers retains the same sign pattern as the pooled specification – so the headline result is not a composition artefact of which industries the EMDE-active firms cluster in.

Table 6: Robustness: sector fixed effects

Per innovation (USD M) Sample	to EMDE All (1)	Global All (2)	to HIC All (3)	to EMDE Green (4)	Global Green (5)	to HIC Green (6)
EMDE innovation share	5.2639*** (0.8655)	24.0056*** (8.5896)	18.0357*** (5.5949)	5.2906*** (0.7411)	12.3840 (10.2573)	15.0218** (6.0442)
(EMDE innovation share) ²	-5.9354*** (1.1026)	-33.5203*** (10.9418)	-24.4016*** (7.1269)	-5.6697*** (0.9812)	-18.0843 (13.5807)	-20.1372** (8.0025)
Number of Inventor Countries	0.0095** (0.0046)	0.0720 (0.0455)	0.0915*** (0.0296)	0.0057* (0.0031)	0.0773* (0.0426)	0.0935*** (0.0251)
log(Number of Innovations, 100s)	-0.0830*** (0.0214)	-0.7444*** (0.2128)	-0.6136*** (0.1386)	-0.0393** (0.0177)	-0.8835*** (0.2447)	-0.6578*** (0.1442)
log(R&D per innovation)	0.0167 (0.0203)	0.7498*** (0.2017)	0.2278* (0.1314)	0.0472*** (0.0171)	0.9500*** (0.2370)	0.3233** (0.1397)
R&D missing	0.0078 (0.1279)	-0.6255 (1.2688)	-0.5167 (0.8265)	-0.0586 (0.0991)	-1.3534 (1.3721)	-0.5768 (0.8085)
log(Cost of innovation step)	0.3033*** (0.0583)	4.2406*** (0.5782)	2.2854*** (0.3766)	0.2613*** (0.0572)	4.5866*** (0.7919)	1.9500*** (0.4666)
Private value (USD M / inno)	0.0051*** (0.0013)	0.0308** (0.0132)	0.0412*** (0.0086)	0.0028** (0.0014)	0.0072 (0.0189)	0.0404*** (0.0111)
Observations	4,277	4,277	4,277	2,605	2,605	2,605
R ²	0.09328	0.08936	0.10684	0.12832	0.12827	0.16666
Fixed effects						
Sector fixed effects	✓	✓	✓	✓	✓	✓

Notes: Robustness check for Table 3: absorbing JRC R&D Scoreboard sector fixed effects, one sector per firm. The sample drops firms with no Scoreboard sector tag, which is why it is smaller than in Table 3. Right-hand side and column structure are otherwise identical (columns 1–3 all Scoreboard firms, columns 4–6 green-innovation firms). Standard errors are clustered on the absorbed sector. The share coefficients are identified only off within-sector variation, so the inverted-U surviving here means it is not an artefact of which industries the EMDE-active firms cluster in. R² is the within-sector figure.

B.6 Specification with inventor-share

The main text fits the inverted-U on the firm-level share of *innovations* involving an EMDE inventor (Figure 5 and Table 3). For completeness, the table below gives the parallel single-margin specification for the *inventor*-share margin – the firm-level share of distinct inventors based in EMDE (a per-person count), as opposed to the share of innovations *involving* such an inventor (a per-innovation count, used in the main-text figure). The inverted-U is visible on this margin in isolation as well.

Table 7: Single-margin inventor-share specification

Per innovation (USD M) Sample	to EMDE All (1)	Global All (2)	to HIC All (3)	to EMDE Green (4)	Global Green (5)	to HIC Green (6)
EMDE inventor share	4.8625*** (0.8991)	13.9790 (8.8212)	13.3194** (5.7795)	5.8384*** (0.7408)	9.8851 (10.2777)	12.9546** (6.1425)
(EMDE inventor share) ²	-4.9166*** (1.0154)	-19.5692** (9.9630)	-17.3991*** (6.5275)	-5.8091*** (0.8216)	-14.1944 (11.3994)	-16.2697** (6.8128)
Number of Inventor Countries	0.0093** (0.0046)	0.0958** (0.0453)	0.1066*** (0.0297)	0.0058* (0.0031)	0.1013** (0.0426)	0.1077*** (0.0255)
log(Number of Innovations, 100s)	-0.0885*** (0.0205)	-0.9074*** (0.2008)	-0.7672*** (0.1315)	-0.0417** (0.0168)	-1.0635*** (0.2328)	-0.7824*** (0.1391)
log(R&D per innovation)	0.0300 (0.0199)	0.7373*** (0.1948)	0.2517** (0.1276)	0.0493*** (0.0166)	0.8927*** (0.2296)	0.3402** (0.1372)
R&D missing	-0.0105 (0.1281)	-0.8419 (1.2570)	-0.7115 (0.8236)	-0.0920 (0.0991)	-1.6608 (1.3750)	-0.8091 (0.8218)
log(Cost of innovation step)	0.4441*** (0.0501)	5.4854*** (0.4919)	3.3039*** (0.3222)	0.3686*** (0.0474)	5.6324*** (0.6575)	2.7508*** (0.3930)
Private value (USD M / inno)	0.0035*** (0.0013)	0.0252** (0.0123)	0.0409*** (0.0081)	0.0019 (0.0013)	0.0149 (0.0176)	0.0471*** (0.0105)
Observations	4,286	4,286	4,286	2,611	2,611	2,611
R ²	0.05398	0.07131	0.07844	0.09158	0.08715	0.10242

Notes: Right-hand side mirrors Table 3 with the firm's EMDE-inventor share (the share of its distinct inventors based in EMDE, a per-person count) and its square replacing the EMDE-innovation share (a per-innovation count) and its square. Every other control is identical, including the safe-log R&D and mean-innovation-cost terms. Columns 1–3: all Scoreboard firms; columns 4–6: restricted to green-innovation firms. Note that the published version of this table prints a different control set from the one its note describes – portfolio size and R&D in levels, and no cost control. This table follows the stated specification, so it differs from the published one by more than the share variable.

B.7 Specification with innovations filed 2013-2019 only

A concern with the main sample is that patents filed towards the end of the sample have had less time to accumulate citations, so their estimated spillover values are underestimated. The main result on the U-shaped pattern is potentially biased if firms with more diverse innovation portfolios also file patents systematically more or less over time. Table 8 repeats the Table 3 regressions on filings through 2019 and finds the inverted U unchanged in sign, significance and approximate location.

Table 8: Spillover outcomes and firm EMDE-innovation share, innovations filed 2013–2019

Per innovation (USD M) Sample	to EMDE All (1)	Global All (2)	to HIC All (3)	to EMDE Green (4)	Global Green (5)	to HIC Green (6)
EMDE innovation share	6.6552*** (0.9914)	26.3409*** (9.9024)	23.6362*** (6.4905)	7.5302*** (0.8726)	16.4991 (11.1126)	20.0605*** (6.7683)
(EMDE innovation share) ²	-6.6391*** (1.0677)	-33.4689*** (10.6646)	-28.9015*** (6.9900)	-7.3367*** (0.9248)	-22.0136* (11.7772)	-24.6199*** (7.1731)
Number of Inventor Countries	0.0148** (0.0070)	0.0906 (0.0697)	0.1432*** (0.0457)	0.0094* (0.0050)	0.1120* (0.0632)	0.1515*** (0.0385)
log(Number of Innovations, 100s)	-0.0944*** (0.0272)	-0.5949** (0.2720)	-0.6846*** (0.1783)	-0.0544** (0.0235)	-1.0274*** (0.2995)	-0.8437*** (0.1824)
log(R&D per innovation)	0.0442* (0.0249)	1.0268*** (0.2490)	0.3687** (0.1632)	0.0536** (0.0227)	1.2425*** (0.2892)	0.4840*** (0.1762)
R&D missing	-0.0210 (0.1557)	-1.4464 (1.5555)	-1.0329 (1.0196)	-0.1218 (0.1273)	-2.4636 (1.6213)	-1.1386 (0.9875)
log(Cost of innovation step)	0.6609*** (0.0655)	8.4943*** (0.6542)	5.0588*** (0.4288)	0.5354*** (0.0624)	8.9721*** (0.7949)	4.7317*** (0.4841)
Private value (USD M / inno)	0.0035*** (0.0014)	0.0391*** (0.0135)	0.0540*** (0.0089)	0.0020 (0.0014)	0.0206 (0.0174)	0.0516*** (0.0106)
Observations	4,232	4,232	4,232	2,414	2,414	2,414
R ²	0.06993	0.08853	0.09855	0.11693	0.12799	0.14799

Notes: Robustness check for Table 3: the entire six-column structure is re-estimated on subsample of innovations over 2013–2019. Columns 1–3 restrict to all Scoreboard firms; columns 4–6 further intersect with the green-innovation-firm subset.

B.8 Specification with private values as outcome

Table 9: Mean private value per innovation and firm EMDE-innovation share

Private value (USD M / inno) Sample	Private value (USD M / inno) All (1)	Private value (USD M / inno) Green (2)
EMDE innovation share	9.6586 (11.7412)	17.0592 (13.0782)
(EMDE innovation share) ²	-19.2189 (14.9695)	-38.6970** (17.3552)
Number of Inventor Countries	0.2845*** (0.0600)	0.3601*** (0.0515)
log(Number of Innovations, 100s)	-1.9860*** (0.2067)	-2.7873*** (0.2397)
R&D per innovation (USD M)	-0.0009 (0.0007)	0.0046 (0.0047)
R&D missing	-6.2229*** (1.6235)	-7.4216*** (1.7116)
Observations	4,286	2,611
R ²	0.02467	0.06694

Notes: Both columns regress the firm’s mean private value per innovation on its EMDE-innovation share and its square. Column 1: all Scoreboard firms; column 2: restricted to green-innovation firms. The specification mirrors Table 3 with two changes: private value becomes the dependent variable rather than a control, the mean-innovation-cost control is dropped, and R&D per innovation enters in levels (USD M, set to 0 where undefined) rather than as a safe log, paired with the same missing-value dummy.

C A simple model of knowledge diversity, foreign R&D labs and spillovers

This appendix sets out a deliberately minimal simulation model in which the inverted-U relationship of Section 6 arises from three ingredients: innovation happens when inventors with *different* knowledge meet; firms form from repeated collaboration; and a foreign R&D lab connects a firm’s people to the inventors of the other country. The model is not calibrated to the data. Its purpose is to show that the pattern in Figure 5 is what one should expect from knowledge diversity alone, and to make explicit what a spillover is in such a world.¹⁹

Set-up

There are N_1 inventors in country 1 and $N_2 < N_1$ in country 2. Inventor i has a type of knowledge $\alpha_i \in [0, 1]$. Country 1 draws its knowledge from the left end of the interval and country 2 from the right end,

$$\alpha_i = \begin{cases} d_i & \text{country 1} \\ 1 - d_i & \text{country 2} \end{cases}, \quad d_i \sim \text{Beta}(1, s),$$

so that with $s > 1$ each country’s knowledge is concentrated at its own end of the line and the two overlap only in the tails.

Time runs in cycles. In each cycle every inventor i , in random order, attempts to innovate with one partner j : with probability λ a past successful partner, otherwise an inventor drawn uniformly from i ’s own country—or, once i belongs to or is connected to a firm with a foreign lab, from both countries, with the draw landing abroad with probability π . The attempt succeeds when a uniform draw u exceeds a threshold that falls with the knowledge distance between the two sides and with belonging to the same firm,

$$u > \tau_0 - \beta |\alpha_i - \alpha_j| - \gamma \mathbb{I}[\text{same firm}],$$

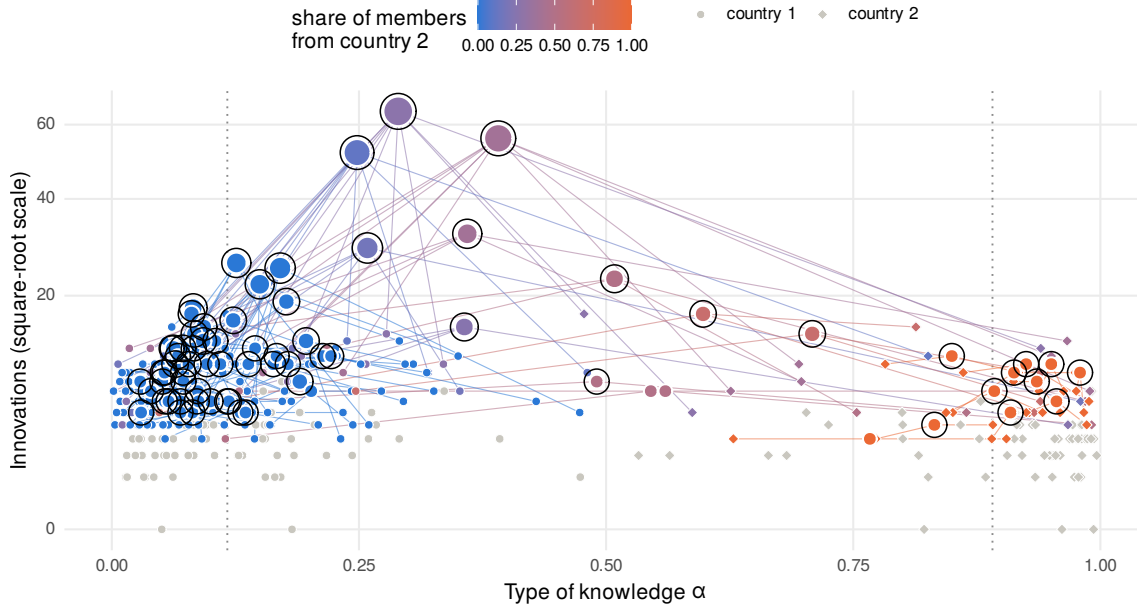
so that partners with complementary knowledge are the better partners. A member of a firm brings the firm’s whole knowledge range to a collaboration, so $|\alpha_i - \alpha_j|$ is the widest gap between the two sides’ ranges. Country 2 inventors are less productive: the success probability is multiplied by $q_2 < 1$ for each country-2 participant, a stand-in for thinner research infrastructure.

A *firm* forms when two inventors reach κ joint innovations; an inventor who reaches κ joint innovations with a member joins the firm, and two firms whose members do so merge. An inventor is *connected* to a firm after one joint innovation with a member. For the first n cycles the two countries are closed. From cycle $n + 1$ on, a firm without a lab opens one abroad when a Cobb–Douglas score of its knowledge distance from the other country, $d = |\bar{\alpha}_{\text{firm}} - \bar{\alpha}_{\text{other}}|$, its size, $s_f = m_f / (m_f + 2)$ with m_f members, and a luck draw $u_f \sim U(0, 1)$ clears a threshold, $d^a s_f^b u_f^c > \kappa_{RD}$. A lab is irreversible, and from then on the firm’s members and everyone connected to them draw partners from both countries.

The default parameters are $N_1 = 240$, $N_2 = 100$, $s = 7.5$, $q_2 = 0.8$, $\tau_0 = 0.8$, $\beta = 0.5$, $\gamma = 0.25$, $\lambda = 0.75$, $\kappa = 3$, $\kappa_{RD} = 0.12$, $(a, b, c) = (0.25, 1, 0.5)$, $\pi = 0.75$, $n = 3$ cycles before labs may open and $m = 7$ after. Figure 11 shows one simulated economy at the end of its tenth cycle.

¹⁹An interactive version of the model, in which every parameter below can be changed and the economy replayed cycle by cycle, will be available at <https://mondpanther.github.io/amodel/>. The figures in this appendix are produced by the R implementation in the same repository.

Figure 11: One simulated economy on the knowledge line (default parameters, seed 1).



Notes: Horizontal axis: type of knowledge α ; country 1 draws from the left, country 2 from the right (dotted lines: each country's mean). Vertical axis: innovations after ten cycles. Small dots are inventors (circles: country 1, diamonds: country 2; grey: in no firm); large dots are firms at their mean knowledge, linked to their members; a black ring marks a firm with a foreign lab. Firms and their members are coloured by the firm's share of country-2 members, from the country-1 colour (blue) to the country-2 colour (orange).

What a spillover is in the model

Every successful attempt is a joint innovation of i and j , and it is counted as an innovation for both. The model's counterpart of the spillover measure of Section 6 is defined at the level of the firm: a *spillover from firm f* is a joint innovation in which a member of f collaborates with an inventor who is *not* a member of f —that is, an innovation to which the firm's knowledge contributed but which the firm does not own outright. It is a spillover *to country 1* when the outside partner is a country-1 inventor and *to country 2* when the partner is from country 2. Innovations between two members of the same firm stay inside the firm and are not spillovers. This is the model analogue of a citation to the firm's patents by an inventor outside the firm: in the data, the spillover value of a firm's innovation is the value of the later innovations that build on it; in the model, where a joint innovation is the only channel through which knowledge moves between people, it is the count of the outside innovations a firm's people fed into.²⁰ The firm's *EMDE share* has the same two readings as in the paper: the share of its members from country 2 or the share of its innovations that involve a country-2 inventor; the figures below use the first.

Results

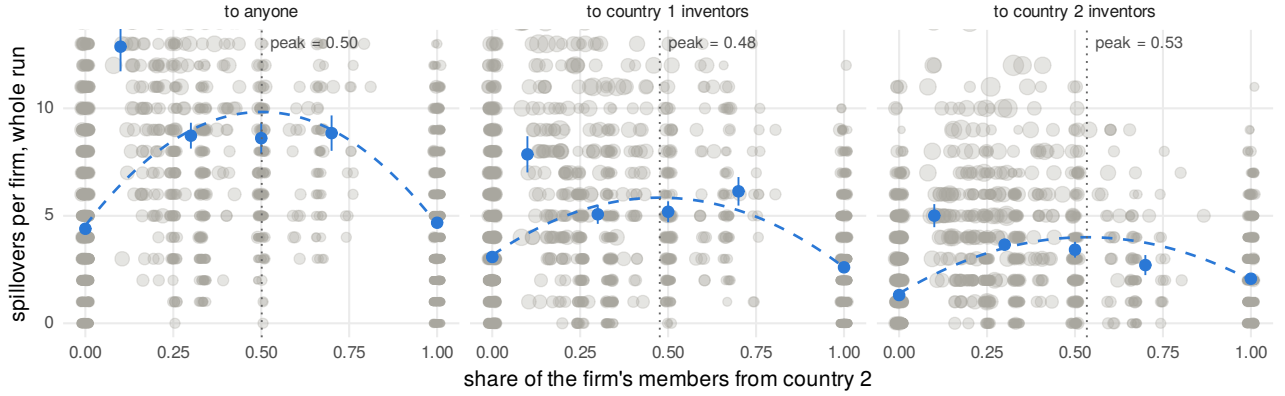
One economy ends with a few dozen firms, so Figure 12 pools the firms of 60 simulated economies and plots each firm's spillovers over the whole run against its share of country-2 members, with bin means and a quadratic fit, as in Figure 5.

²⁰The interactive version also offers a value-weighted variant, in which each such innovation is weighted by the knowledge distance between the two sides, as a crude analogue of the private value of a patent.

Figure 12: Firm-level spillovers and the firm's country-2 share in the model.

Firm-level spillovers and the firm's country-2 share, default parameters

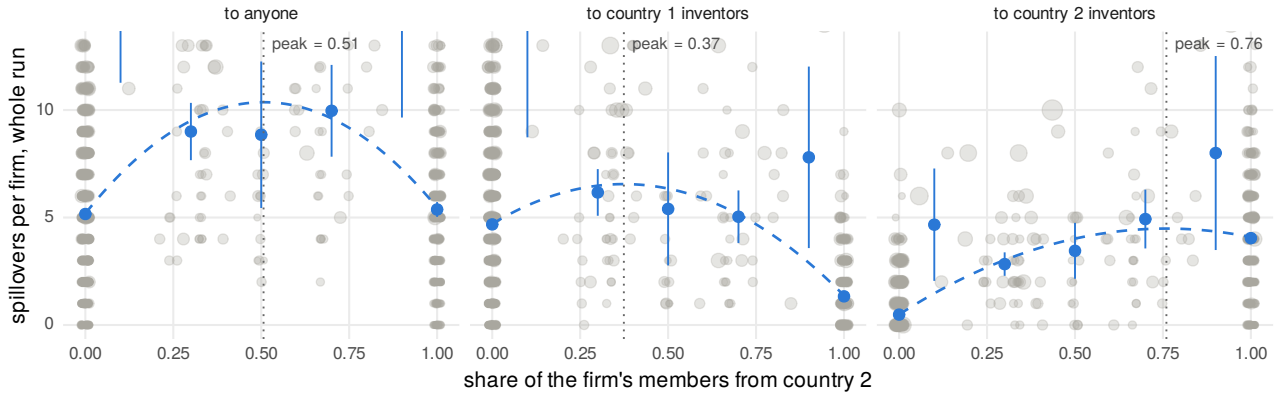
4,438 firms from 60 economies; dots are firms (size = members), blue: bin means with 95% CI and a quadratic fit



(a) Default parameters

The same figure for the symmetric baseline

1,616 firms from 40 economies; $q_2 = 1$, labs by distance only, uniform worldwide draws, individual knowledge



(b) Symmetric baseline: $q_2 = 1$, labs by knowledge distance only, uniform worldwide draws, individual knowledge

Notes: Each grey dot is a firm at the end of a simulated economy (size: members); panel (a) pools 60 economies, panel (b) 40. Vertical axis: the firm's spillovers over the whole run, i.e. the number of innovations in which a member collaborated with an inventor outside the firm, to anyone (left), to country-1 inventors (middle) and to country-2 inventors (right). Horizontal axis: share of the firm's members from country 2. Blue dots: bin means with 95% confidence intervals; dashed line: quadratic fit, with its peak marked when it lies inside the interval. Panel (b) uses 120 and 40 inventors with $s = 3$, $\kappa_{RD} = 0.5$ and $(a, b, c) = (1, 0, 0)$.

With the default parameters the profile is the paper's: spillovers rise from the single-country firms on the left, peak among mixed firms (the fitted peak is at a country-2 share of 0.50 for spillovers to anyone), and fall towards the country-2-only firms on the right. Spillovers to country 1 and to country 2 are both hump-shaped as well, so a mixed firm feeds more into innovation in both countries than a firm drawn from either one alone—the diversification benefit that Section 6 finds for HIC and global spillovers. Table 10 reports the bin means with three normalisations. Mixed firms are larger than single-country firms, so part of the per-firm hump is size; per member the profile is flatter, and the far-right end stays below the middle because country-2 inventors are less productive.

Table 10: Spillovers to anyone by the firm’s share of country-2 members, with three normalisations.

Share of members from country 2	Firms	Members	Spillovers per firm	per member	per firm innovation
0	2957	2.6	4.4	1.74	0.37
0-0.2	129	7.1	12.9	1.80	0.32
0.2-0.4	328	4.8	8.7	1.86	0.34
0.4-0.6	201	4.0	8.6	2.37	0.46
0.6-0.8	72	3.9	8.8	2.35	0.44
0.8-1	1	7.0	21.0	3.00	0.49
1	750	2.2	4.7	2.14	0.47

The mechanism is the one the paper argues for. A firm whose people reach distant, complementary partners innovates more: after labs may open, firms with a lab make 0.52 innovations per member per cycle against 0.39 for firms without one. Since every innovation with an outsider is a spillover, the firms that combine both countries’ knowledge also generate the most spillovers. The right-hand arm turns down for a substantive reason rather than a specification choice: country-2-only firms collaborate, through their labs, with country-1 inventors half a knowledge line away, and would do very well in a symmetric world; the productivity gap $q_2 < 1$ is what keeps them below the mixed firms, as the EMDE-heavy firms in the data are. Panel (b) shows the model without the productivity gap, with labs opened by knowledge distance alone, worldwide draws uniform over everyone and individual rather than pooled knowledge: the profile is flat or rising, the middle of the axis is nearly empty because almost no firm has a mixed workforce, and the country-2-only firms are as productive as any. Each of the four ingredients removes one reason for that picture; the productivity gap is the one that turns the right arm down.

D Concrete examples of EMDE-linked innovation by leading R&D firms

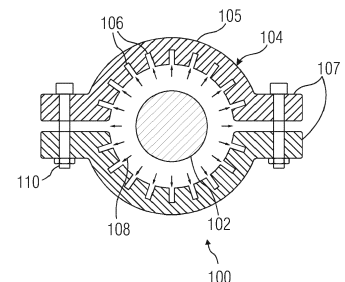
This appendix puts faces to the aggregate results. The firms below are a selection from the 20 Scoreboard firms with the highest average marginal return of spillovers to EMDE inventors across their green innovations that can be tied to a verified research lab in an EMDE (labs from the EMDE R&D Lab Tracker, EMDE-RLT; firms with at least 30 such innovations). For each firm we show one of those innovations, invented with the firm’s EMDE-based inventors, together with its spillover values and marginal returns as used in the paper. The full ranking, and the top twenty innovations and firms on every measure and sample, can be browsed in the interactive companion to this paper at mondpanther.github.io/kevceinsights/emde-inno-examples.html, which also carries the patent drawing and a non-technical summary of every listed innovation; the links next to each heading open the firm’s and the innovation’s card there. Summaries are paraphrases of the patent abstracts; values are from the paper’s data (spillover values in USD million per innovation, marginal returns in percent).

Siemens (Germany; Electronic & Electrical Equipment)

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Quicker, gentler start-up for steam turbines. Steam turbines must be warmed slowly before full operation, because heating the heavy casing unevenly can damage it, and this delays power generation. Here the casing contains built-in channels that are filled with a hot medium during start-up, so the casing absorbs heat directly and warms more quickly. (*Steam turbine with means for warming the casing*, EP2937523, filed 2014; verified lab: Siemens Gamesa R&D India (Bangalore).) Inventor countries on the record: IN, DE. Spillover value per innovation: USD 6.2M globally, 0.7M to HIC and 3.73M to EMDE inventors; marginal return to EMDE 237.6% against 5.9% for the average green lab-linked innovation. It counts as green because the EPO files it under its climate-change-mitigation classes (Green Energy; Y02E20/00 — Combustion technologies with mitigation potential; Y02E20/16 — Combined cycle power plant [CCPP], or combined cycle gas turbine [CCGT]).

FIG 1A



The firm: 21,289 innovations in 2013–2022, of which 1.6% with an EMDE inventor (inventor countries, innovation-weighted: Germany 67%, United States 11%, China 5%, Austria 3%); 42 green innovations tied to a verified EMDE lab, with an average marginal return to EMDE of 12.0% and an average global spillover value of USD 5.1M per innovation.

Honeywell (United States; General Industrials)

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Upgrading factory control systems without stopping. Updating software in industrial control systems usually means halting production. New software is installed on a virtual machine server, which temporarily takes over from an existing control device; the virtual machine is then converted back onto physical hardware, either the original or a new device. (*Method and apparatus for an on-process migration in a virtual environment within an industrial process control and automation system*, EP3271891, filed 2015; verified lab: Honeywell Technology Solutions India (Bengaluru) (Bangalore).) Inventor countries on the record: IN, US. Spillover value per innovation: USD 13.3M globally, 12.0M to HIC and 7.28M to EMDE inventors; marginal return to EMDE 185.7% against 5.9% for the average green lab-linked innovation.

The firm: 7,119 innovations in 2013–2022, of which 14.7% with an EMDE inventor (inventor countries, innovation-weighted: United States 60%, India 14%, China 8%, Czechia 4%); 119 green innovations tied to a verified EMDE lab, with an average marginal return to EMDE of 7.3% and an average global spillover value of USD 10.7M per innovation.

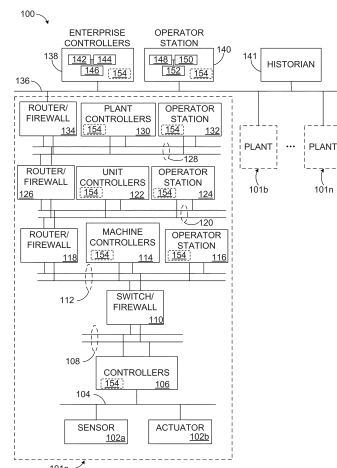
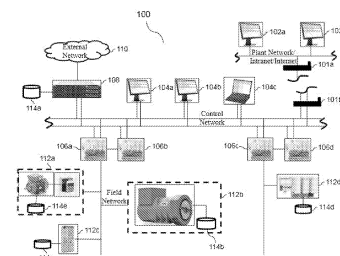


ABB (Switzerland; Industrial Engineering)

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Answering operators' questions about plant equipment. Large process plants run on distributed control systems with information scattered across many databases. This method lets an operator pose a standard type of query about a subsystem's operation or health at the control screen; a server identifies which database holds the relevant information, processes the query, and the system then adjusts the subsystem's process settings. (*A method for managing subsystems of a process plant using a distributed control system*, EP3207432, filed 2014; verified lab: ABB Innovation Center / Corporate Research Bangalore (Bangalore).) Inventor countries on the record: IN, CN, CH. Spillover value per innovation: USD 9.9M globally, 5.0M to HIC and 1.86M to EMDE inventors; marginal return to EMDE 85.7% against 5.9% for the average green lab-linked innovation.

The firm: 5,582 innovations in 2013–2022, of which 5.0% with an EMDE inventor (inventor countries, innovation-weighted: Germany 16%, Sweden 15%, Switzerland 15%, United States 14%); 50 green innovations tied to a verified EMDE lab, with an average marginal return to EMDE of 4.9% and an average global spillover value of USD 13.5M per innovation.



Braskem (Brazil; Chemicals)

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Ceramic tiles made with chemical-industry sludge. Brine sludge is a solid waste from chemical production that is costly to dispose of. Mixing a few per cent of it into ceramic raw materials, then pressing and firing the mass, produces coatings and panels for construction, turning a waste stream into building material. (*Ceramic coating composition, method for obtaining a ceramic coating base mass, use of the ceramic coating composition and ceramic panel*, WO2020069590, filed 2018; verified lab: Braskem Technology & Innovation Center (Triunfo) (Triunfo).) Inventor countries on the record: BR. Spillover value per innovation: USD 3.3M globally, 3.3M to HIC and 3.26M to EMDE inventors; marginal return to EMDE 95.9% against 5.9% for the

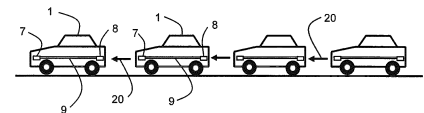
average green lab-linked innovation. It counts as green because the EPO files it under its climate-change-mitigation classes (Green Manufacturing; Y02P40/00 — Technologies relating to the processing of minerals; Y02P40/60 — Production of ceramic materials or ceramic elements, e.g. substitution of clay or shale by alternative raw materials, e.g. ashes).

The firm: 224 innovations in 2013–2022, of which 49.6% with an EMDE inventor (inventor countries, innovation-weighted: Brazil 63%, United States 29%, Germany 2%, France 2%); 32 green innovations tied to a verified EMDERLT lab, with an average marginal return to EMDE of 3.4% and an average global spillover value of USD 12.0M per innovation.

Vestel Elektronik (Turkey; Electronic & Electrical Equipment)

Online: firm card · innovation card

Electric cars charging each other in convoys. Electric vehicles fitted with wireless power transfer units at front and rear can link up into a chain. Each vehicle can act as a power source, a receiver or a relay passing power along the line, letting vehicles share charge between them, for instance while travelling together. (*Electric vehicle and method of forming a charging chain of electric vehicles*, EP3880506, filed 2018; verified lab: Vestel City R&D Centre (Manisa).) Inventor countries on the record: TR, KR. Spillover value per innovation: USD 6.8M globally, 6.8M to HIC and 2.74M to EMDE inventors; marginal return to EMDE 96.1% against 5.9% for the average green lab-linked innovation. It counts as green because the EPO files it under its climate-change-mitigation classes (Green Transport, Electric Vehicles & Mobility, Any battery technology; Y02T10/00 — Road transport of goods or passengers; Y02T10/60 — Other road transportation technologies with climate change mitigation effect; Y02T10/7072 — Electromobility specific charging systems or methods for batteries, ultracapacitors, supercapacitors or double-layer capacitors; Y02T10/72 — Electric energy management in electromobility; Y02T90/00 — Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation).

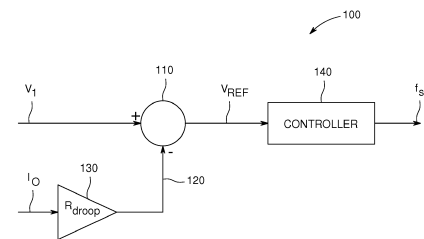


The firm: 1,391 innovations in 2013–2022, of which 86.9% with an EMDE inventor (inventor countries, innovation-weighted: Turkey 99%, Germany 1%, United States 0%, United Kingdom 0%); 66 green innovations tied to a verified EMDERLT lab, with an average marginal return to EMDE of 2.8% and an average global spillover value of USD 2.8M per innovation.

General Electric (United States; General Industrials)

Online: firm card · innovation card

More efficient converters for direct-current power. Many power systems, such as data centres and renewable installations, need to change one direct-current voltage into another. A converter using a resonant circuit and transformer, with its switches run at the circuit's natural frequency, achieves this with low losses while a controller holds the output voltage at the desired level. (*Dc converters with modified droop control and method of use*, EP3300238, filed 2016; verified lab: John F. Welch Technology Centre (JFWTC) (Bangalore).) Inventor countries on the record: IN, CN, JP, US. Spillover value per innovation: USD 30.5M globally, 19.2M to HIC and 5.20M to EMDE inventors; marginal return to EMDE 237.2% against 5.9% for the average green lab-linked innovation. It counts as green because the EPO files it under its climate-change-mitigation classes (Green Housing; Y02B70/00 — Technologies for an efficient end-user side electric power management and consumption; Y02B70/10 — Technologies improving the efficiency by using switched-mode power supplies [SMPS], i.e. efficient power electronics conversion e.g. power factor correction or reduction of losses in power supplies or efficient standby modes).



The firm: 15,127 innovations in 2013–2022, of which 11.5% with an EMDE inventor (inventor countries, innovation-weighted: United States 64%, India 9%, China 8%, Germany 4%); 634 green innovations tied to a verified EMDERLT lab, with an average marginal return to EMDE of 2.5% and an average global spillover value of USD 10.4M per innovation.

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