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# The Future of Global Technology Cooperation

## Trends and Risks of the EU's Engagement in International R&D Networks

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**The ongoing debate on the EU's economic security nourishes a skeptical attitude towards cooperation with third countries, including joint innovation. Yet, in particular for technologies considered critical, a regular cross-border exchange of knowledge and ideas is indispensable for innovation success. Based on comprehensive patent data, this cepStudy investigates patterns of EU research cooperation for six critical technology fields: advanced materials, AI, biotechnologies, connectivity, energy and semiconductor technologies. The results are translated into recommendations for an EU cooperation strategy.**

**Key results:**

- In terms of the extent of patenting activity, the EU does not possess comparative advantages in any of the technology fields investigated. In particular, it set a much smaller research focus on critical technologies than major competitors like China and Japan.
- In all fields, recent EU patenting activity showed a high intensity of cooperation with third countries. The US were constantly the most important research partner of the EU, but China gained in relevance.
- EU patents resulting from research cooperations with third countries received a significantly higher number of citations than those with purely domestic inventors. Their share among the top 10 % most cited patents was also way more than proportional.
- The average level of intellectual property rights protection was comparatively low among EU partners, largely reflecting the relevance of partners from China and India.
- To optimally exploit the benefits of international research collaboration, the EU should develop a dedicated technology cooperation strategy. It should involve a smart diversification of research partners with focus on Japan and South Korea, the integration of cooperation partners into internal R&D support schemes and the merging of bilateral partnerships to plurilateral technology clubs.
- Cooperation in innovation policy should be extended beyond research collaboration, by jointly addressing existing bottlenecks in the commercialization of inventions.

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## 1 Background

In times of a serious worsening of the geopolitical climate, the prevailing view on international cooperation in the Western world is shifting profoundly. The idea of mutual beneficial exchange under the banner of universal rules is replaced by the notion of a fragmented order in which middle and great powers contest, set and enforce regional rules and norms. Instead of embracing the fruits of an international division of labor, a cautious view on cooperation is spreading, stressing the risks for domestic competitiveness and in parts even national security. The EU is no exception in this regard, as evident in its Economic Security Strategy[1] and the related legislative proposals. It also affects the field of technology cooperation with third countries, as expressed by the new policy paradigm of technology sovereignty. This paradigm sees the ability to exert control on the technological development as a necessary condition for sustaining competitiveness.[2] Consequently, avoiding the risks of knowledge outflows through R&D joint ventures, goods exports or Foreign Direct Investment (FDI) might gain policy priority over exploiting the benefits of knowledge exchange with third countries.

For a region like the EU thriving for global technology leadership, such a risk-focused approach is clearly insufficient. This is most obvious for exactly those technologies that the EU considers critical. Due to the complexity and transversal nature of research fields like biotechnologies, digital connectivity and robotics, major innovation efforts require a diverse portfolio of specialized competencies, a portfolio that no single country or region can maintain at reasonable costs. This does not mean that the EU should take a naïve view on the risks of (intended or unintended) knowledge sharing. Instead, a future-oriented EU technology policy should be based on a sober analysis of the potentials and risks of current cooperation patterns in strategically important technology fields.

This cepStudy aims to fuel the debate on technology cooperation by undertaking a detailed analysis of current global R&D networks for a set of critical technologies, drawing on international patent data. It explains the economic view on technology cooperation as a trade-off between productivity gains in knowledge creation and maintaining control over the use of shared knowledge. It identifies general trends in the strength of cooperation linkages at the global scale and the position of EU inventors in these patent networks. It investigates the quality of patents emerging from cooperation with third countries vis-à-vis purely domestic patents. Moreover, it undertakes a risk assessment of the current EU research partner portfolio in the single technology fields through a set of country risk indicators. Finally, it provides recommendations for the advancement of the existing EU partnership strategies.

[1] European Commission / High Representative of the Union for Foreign Affairs and Security Policy (2023). Joint Communication to the European Parliament, the European Council and the Council on “European Economic Security Strategy”. JOIN(2023) 20 final.

[2] Edler, J., Blind, K., Kroll, H., & Schubert, T. (2023). Technology sovereignty as an emerging frame for innovation policy. Defining rationales, ends and means. Research Policy, 52(6), 104765.

# 2 Forms and effects of international technology cooperation

## 2.1 Joint knowledge creation

International research collaboration has long been proven as indispensable for solving global problems. Most recently, the COVID-19 pandemic has spurred a significant amount of dynamic and successful cross-border research which has made a decisive contribution to ending the pandemic.[3] Such collaborations are not limited to the world of academia. At a smaller scale, cross-border research is also part of the daily operations of companies with knowledge-intensive production. The literature suggests that motivation and prospects for success of such commercial international research and development (R&D) projects can vary by institutional arrangement.

First of all, a distinction can be made whether international research cooperation takes place within or outside the boundaries of a corporation. The first case corresponds to a scenario in which R&D activities are relocated from the headquarters of a multinational enterprise (MNE) to a foreign affiliate. This may be a foreign production site or an affiliate created solely for the purposes of R&D activities. There can be several reasons for outsourcing R&D activities from the company's perspective. One reason may be the high availability of researchers and engineers with adequate skills at the foreign location. In addition to the knowledge embodied in research workers, foreign R&D locations can also serve to gain access to non-codified knowledge at the location through personal exchange with local R&D institutions, i.e. to benefit from spatially bounded knowledge spillovers. In both cases, the decision on the research location is the result of a company-wide optimization of R&D efficiency. However, it can also be of a long-term nature and aimed at conquering the respective foreign markets. Following this idea, the presence of foreign R&D affiliates should also serve to gain information about the foreign markets (e.g. preferences, competitors, specific regulatory conditions) and in this respect represents a lower-risk alternative to the immediate establishment of foreign production sites.

In many cases, international research cooperation reaches beyond the borders of a single corporation. While cooperation between non-profit research institutions such as universities around the world is a long-established phenomenon and generally serves to improve mutual efficiency, the situation is more complex for private companies. Important questions are what rules are established for the use of pre-existing and jointly created knowledge and how these can be enforced. Particular attention has been paid in the literature to the case of independent companies that agree on a clearly defined and time-limited research partnership. Hagedoorn et al. (2000) distinguish between two categories of such formal research partnerships: Research companies and research joint ventures.[4] Research companies are defined as equity joint ventures that focus on R&D activities of two or more independent companies and take the form of joint ownership of a separate company. The establishment of such an institution is accompanied by a high level of commitment (capital, human resources, organizational effort) on the part of the companies involved.

Research joint ventures are defined as non-equity contractual agreements. They offer more flexibility and require less organizational effort, as no new organization is created. However, unlike research

[3] Grammes, N., Millenaar, D., Fehlmann, T., Kern, F., Böhm, M., Mahfoud, F., & Keller, A. (2020). Research output and international cooperation among countries during the COVID-19 pandemic: scientometric analysis. Journal of medical Internet research, 22(12), e24514.

[4] Hagedoorn, J., Link, A. N., & Vonortas, N. S. (2000). Research partnerships. Research policy, 29(4-5), 567-586.

corporations, they do not represent a solution to the problem of incomplete contracts stressed by the Transaction Cost School.[5] Common R&D efforts are governed by high specificity and an incalculably wide spectrum of risks. In this regard, the internalization of relationships within a common organization can represent a reasonable strategy to reduce transaction costs, e.g. by allowing to better specify and monitor the performance of the other party. Research corporations are therefore primarily a solution for long-term and comprehensive research collaborations, while research joint ventures are suitable for clearly narrowed projects.

Apart from these discrepancies, both forms can be the result of similar motivations. In the case of partnerships between independent companies from different countries, these include the reasons mentioned for firm-internal cross-border research (access to foreign skills, information and markets). In addition, there are the advantages resulting from the joint pooling of capital. These include cost advantages from the sharing of fixed costs for R&D facilities and efficiency gains through the common exploitation of economies of scale and scope. Furthermore, in a long-term perspective, the sharing of the manifold risks (e.g. development of technologies and markets) involved in R&D activities contribute to a reduction in the financing costs of the participating companies.[6] An important aspect that can increase the mutual gains from partnerships is the complementarity of the partners' knowledge profiles. Companies with expertise and experience in different knowledge segments can complement each other well in joint R&D activities, provided that the knowledge involved can be combined. This enables synergies and provides room for mutual learning.[7] In the case of cross-border cooperation, this represents a special case of international division of labor. Finally, another reason may be the desire for improved internalization of the knowledge generated in the context of R&D, i.e. the avoidance of knowledge spillovers. Collaboration thus also serves to better monitor and limit the handling of the knowledge generated by the collaboration partners.

One obstacle to the conclusion of research partnerships is the risk that the limitation of knowledge use fails due to insufficient monitoring or enforceability. This applies, for example, to cases in which a partner uses jointly created knowledge for its own follow-up innovations improving its market position, especially if the collaborators compete in the same markets. Institutional mismatch between the partners can also hinder collaborations, e.g. in the case of major organizational and cultural differences.[8] The latter factor is of particular relevance for international research collaborations, as in this case they could emerge from general national differences in corporate cultures.

R&D cooperations between firms and public research institutions (universities, public research institutes) represent a special case. In this type of cooperation, a possible institutional mismatch relates not only to the form, but also to the objectives of the organizations. Institutions primarily aiming at the long-term accumulation of knowledge and expertise are at odds with the desire of companies to commercialize created knowledge and amortize R&D investments. Therefore, collaborations often focus on the passive support of research institutions in basic research activities.[9] This enables companies to outsource basic research activities and thus specialize in later stages in the innovation process. In

5 Williamson, O. E. (1996). The mechanisms of governance. Oxford university press.

6 Vonortas, N. S. (2012). Cooperation in research and development (Vol. 11). Springer Science & Business Media.

7 Harrison, J. S., Hitt, M. A., Hoskisson, R. E., & Ireland, R. D. (2001). Resource complementarity in business combinations: Extending the logic to organizational alliances. Journal of management, 27(6), 679-690.

8 Georghiou, L. (1998). Global cooperation in research. Research policy, 27(6), 611-626.

9 Mascarenhas, C., Ferreira, J. J., & Marques, C. (2018). University–industry cooperation: A systematic literature review and research agenda. Science and Public Policy, 45(5), 708-718.

line with this idea, Hall et al. (2003) show that research partnerships with university involvement are specializing on new groundbreaking research areas. On the one hand, they are reported to be associated with more difficulty and delay. On the other hand, they are less likely to be stopped prematurely, stressing the long-term continuous engagement characterizing these partnerships.[10]

From a societal perspective, research partnerships promise a (partial) solution to the problem of socially insufficient R&D activities by private firms caused by the presence of positive externalities (knowledge spillovers). Even with strict patent and copyright laws in place, such spillovers can in many cases not be fully avoided, as any protection of intellectual property is limited in time, restricted to codifiable knowledge and subject to enforcement costs. By contrast, formalized research cooperation allows partners to exert more control on the outflow of information, while at least allowing for some sharing of non-rival knowledge within the partnership. This contributes to more overall R&D activity, while not fully suppressing the welfare-enhancing channel of knowledge spillovers.[11] In contrast to general R&D subsidies, the specific promotion of research partnerships also helps to reduce adoption costs through joint involvement in the creation of the technology. Hence, policies providing fiscal incentives (e.g. tax breaks on R&D joint ventures, R&D vouchers) and/or collaborative infrastructure to research partnerships have the potential to be welfare-improving.

However, this needs to be weighed against the risk that common product innovation might become the starting point of a production joint venture or collusion, potentially evoking monopoly situations on future markets. Moreover, from a national perspective, cross-border knowledge spillovers caused by research cooperation can be harmful in cases where they significantly strengthen the competitiveness of foreign firms. This holds in particular when those firms are competing in specialization areas of the domestic economy. Any targeted cooperation support policy thus requires careful conditioning and must be complemented by firm rules on knowledge appropriation and collusion prevention.

Empirically, the evidence on the success of private research partnerships is fairly mixed and points to several conditionalities. By drawing on subjective assessments by participating firms, Caloghirou et al. (2003) identify three main success factors: the closeness of the common research activity to the regular in-house research of firms, the institutional learning efforts undertaken by firms related to the partnership and the existence of clear rules on knowledge appropriation.[12] More recently, Noseleit & de Faria (2013) investigated the side effects of partnerships on the efficiency of firm-internal R&D. They found a positive side effect in cases of collaboration with partners from related industries and a negative effect with partners from unrelated industries.[13] This stresses the fact that any positive impact of knowledge complementarities is lowered with increased knowledge distance between partners.

## 2.2 Knowledge sharing and transfers

Another important form of international technology cooperation is the (intended or unintended) transfer of knowledge created in one country to persons/institutions located in another country. The

10 Katz, M. L. (1986). An analysis of cooperative research and development. The RAND Journal of Economics, 527-543.

11 Hall, B. H., Link, A. N., & Scott, J. T. (2003). Universities as research partners. Review of Economics and Statistics, 85(2), 485-491.

12 Caloghirou, Y., Hondroyiannis, G., & Vonortas, N. S. (2003). The performance of research partnerships. Managerial and Decision economics, 24(2-3), 85-99.

13 Noseleit, F., & de Faria, P. (2013). Complementarities of internal R&D and alliances with different partner types. Journal of Business Research, 66(10), 2000-2006.

root of the channel is the partly public, partly private nature of the returns to technological investments (see previous Subsection). Often only parts of the knowledge created through research and development can be kept internal by the innovating party. And legal protection of generated knowledge is often subject to time limits. In societal perspective, the occurrence of knowledge spillovers is welfare-enhancing due to their nature as positive externalities.[14]

The causes and effects of cross-border knowledge spillovers have for a long time caught the attention of development and growth economists. Developing economies are typically characterized by low R&D intensities, due to insufficient resources for the buildup of a domestic research infrastructure. Therefore, the inflow of knowledge from technologically advanced economies represents an important source of technological upgrading and, as a consequence, productivity improvements over time. This has given rise to the concept of leader-lagger models, where macroeconomic growth of technologically inferior lagging countries is crucially driven by the continuous inflow of new knowledge from leader countries heavily investing in R&D.[15] This inflow is usually subject to some delay compared to the creation of the knowledge, implying a persistent technology gap between leader and lagger countries.

Following the common view that the cost of innovation is decreasing in the stock of existing knowledge[16], such a form of international division of labor can be considered welfare-optimal in global perspective. To what extent it contributes to a gradual convergence or divergence in international income levels depends on a set of specific parameters. These include the speed of cross-border knowledge transfers, the time pattern of technology diffusion among lagging countries, the costs of technology adoption and the absorptive capacity.

Benhabib & Spiegel (2005) illustrate the important role of the nature of technology diffusion by distinguishing between an exponential and a logistic process of technology uptake by lagging countries over time.[17] Under the premises of exponential technology diffusion, leader and lagger countries are shown to converge to the same long-term GDP growth rates. This corresponds to an arrangement where the leading countries play the role of "growth locomotives" for the rest of the world, with lagging countries catching up in terms of growth dynamics, but not in terms of absolute income levels. Under the premises of a logistic diffusion path, the technology uptake is heavily delayed for lagging countries far away from the technology frontier. This reflects the particular difficulty the most technologically inferior economies face in adopting advanced technology. Benhabib & Spiegel (2005) show that this can under some constellations give rise to international income divergence. At the same time, clubs of conditional growth convergence among countries with similar technology level can emerge.[18] Breaking out of these clubs requires heavy investment in the domestic absorptive capacity.

Regarding the domestic conditions for technology uptake, the literature stresses the role of absorption costs as a crucial parameter for the stability of a leader-lagger structure. The facts that imitation tends to be cheaper than innovation and innovation productivity increases in the stock of knowledge

14 Keller, W. (2004). International technology diffusion. Journal of economic literature, 42(3), 752-782.

15 Nelson, R. R., & Phelps, E. S. (1966). Investment in humans, technological diffusion, and economic growth. The American economic review, 56(1/2), 69-75.

16 Porter, M. E., & Stern, S. (2000). Measuring the" Ideas" Production Function: Evidence from International Patent Output (No. 7891). National Bureau of Economic Research, Inc.

17 Benhabib, J., & Spiegel, M. M. (2005). Human capital and technology diffusion. Handbook of economic growth, 1, 935-966.

18 Durlauf, S. N., & Johnson, P. A. (1995). Multiple regimes and cross-country growth behaviour. Journal of applied econometrics, 10(4), 365-384.

together imply that such an arrangement can be stable. There is also consensus that the costs of technology adoption decline with the age of the technology.[19] This implies that a focus on implementing less recent technologies can represent an efficient strategy for lagging countries.

The level of domestic human capital is seen as a crucial factor for the overall capacity for technology adoption of a country, first propagated by the seminal model of Nelson & Phelps (1966).[20] Through a strategy of investing in higher education, countries could succeed in escaping growth traps by improving their ability for a fast uptake of the latest technology. However, recent research points to the conditionality of a such a human capital-centered growth model. Comin & Hobijm (2010) demonstrate that the relevance of human capital is technology-specific. It is most effective in reducing the adoption lag for technologies which are heavily dependent on specialized high-tech skills like PC's, robots and electricity.[21] Moreover, Asif & Lahiri (2021) point to the need of distinguishing between different forms of human capital. They ascertain that learning-by-doing is a more important factor for the absorptive capacity than cognitive skills or years of schooling.[22]

Regarding the specific ways of transferring technological knowledge across borders, the literature identifies four main channels: merchandise trade, Foreign Direct Investments (FDI), personal communication and dedicated technical cooperation aid. These channels are not mutually exclusive, but overlap and reinforce each other. Through participating in cross-border merchandise trade, technological laggers have the possibility to access foreign knowledge through learning-by-importing. The knowledge from foreign blueprints is embodied in the imported products. Through methods like reverse engineering, lagging countries can access this knowledge and convert it to own competitive products. As long as the intermediate good is cheaper than its opportunity costs, involving the R&D costs of own product development, this channel is beneficial for the importing country.[23]

In this way, learning-by-importing is a potentially successful strategy for developing economies to escape growth restrictions from unfortunate trade specialization. or at least to mitigate its consequences. Using the import side for continuous technological upgrading promises a way out of the resource trap these economies are facing on the export side. This is an additional argument for positive long-term growth effects of free trade, complementing the static productivity gains from specialization by the perspective of dynamic productivity gains through spillovers. In such a trade order, inequality between countries might be maintained, as certain countries possess the critical technological edge that lets them remain innovation leader. Yet, all trading countries might end up being better-off, as this arrangement maximizes overall R&D productivity and distributes the innovation outcomes through trade.

At the same time, the intensity of such an effect can be expected to depend on the composition of traded goods. Imports from high-tech sectors offer more potential for knowledge spillovers. As a consequence, trade and industrial policies of developing economies could focus on enhancing import demand for high-tech goods (e.g. through targeted tariff reduction and promotion of domestic downstream capacities) as a means to boost general productivity. The empirical literature provides at least

[19] Keller, W. (1996). Absorptive capacity: On the creation and acquisition of technology in development. Journal of development economics, 49(1), 199-227.

[20] See Nelson and Phelps (1966).

[21] Comin, D., & Hobijn, B. (2010). An exploration of technology diffusion. American economic review, 100(5), 2031-2059.

[22] Asif, Z., & Lahiri, R. (2021). Dimensions of human capital and technological diffusion. Empirical Economics, 60(2), 941-967.

[23] Keller, W. (2021). Knowledge Spillovers, Trade, and FDI (No. 28739). National Bureau of Economic Research, Inc.

for some product groups evidence on such a linkage between import composition and productivity growth. For instance, Xu & Wang (1999) show a robust composition effect for capital goods.[24] This hints at the conditionality of any learning-by-importing strategy. It presupposes the existence of a sufficient industrial base providing both the demand impulses for high-tech imports and the skills necessary for extracting and applying the embodied knowledge.

Another channel for cross-border knowledge flows is the operation of foreign firms in a country, i.e. a form of FDI. In particular, knowledge transfer can arise if these firms open manufacturing sites or research centers in the country. In this way, domestic production and R&D workers gain knowledge and experience in handling foreign technologies. Again, the intensity of such effects can be expected to be product-specific. To reduce the technology gap, technologically lagging countries have a specific incentive to attract high-quality FDI, i.e. firms producing close to the technology frontier.

Producers from the source countries can benefit from resulting knowledge transfers as well. A smaller technology gap allows them to produce less costly in host countries and thus benefit more from an international division of labor.[25] However, from the perspective of the single investor, these benefits are largely external, while he is immediately confronted with the costs of knowledge outflows (competition by domestic firms in host countries). Therefore, host countries will need to put additional measures in place to gain access to critical firm knowledge. One prominent example is China's policy of joint venture obligations.[26] Overall, the empirical evidence on the role of FDI for knowledge diffusion is fairly mixed, partly because FDI in countries with the biggest need for catching-up is still mostly low-skill activity.[27]

The importance of personal communication for knowledge diffusion is due to the fact that not all knowledge is codifiable. A part of it is tacit and can be best transferred through personal face-to-face or digital communication. Yet, due to the difficulty of observing and measuring these types of knowledge flows, empirical evidence on its relevance is scare. Finally, a vehicle for fully intended technology diffusion is technical cooperation aid to developing economies. This can involve specific development projects or regular forms of exchange through scholarships, seminars and workshops. Compared to other diffusion channels, it depends less on the absorptive capacity of recipient countries, but instead contributes to a strengthening of this capacity. In fact, Sawada et al. (2012) show that technical cooperation aid is able to compensate for the adverse effects of a lack of human capital in the catch-up process of a developing economy.[28]

Finally, the literature points to the importance of certain framework conditions for successful knowledge diffusion. To these belong the existence of competitive markets and the absence of major distortions to international trade and investment.[29] The development level of the financial sector plays

24 Xu, B., & Wang, J. (1999). Capital goods trade and R&D spillovers in the OECD. Canadian Journal of Economics, 1258-1274.
25 Glass, A. J., & Saggi, K. (1998). International technology transfer and the technology gap. Journal of development economics, 55(2), 369-398.
26 Jiang, K., Keller, W., Qiu, L., & Ridley, W. (2019). China's Joint venture Policy and the International Transfer of Technology. VoxChina.
27 Keller, W. (2004). International technology diffusion. Journal of Economic Literature, 42(3), 752-782.
28 Sawada, Y., Matsuda, A., & Kimura, H. (2012). On the role of technical cooperation in international technology transfers. Journal of International Development, 24(3), 316-340.
29 See Keller (2004).

a prominent role as well. Comin & Nanda (2019) show that a greater depth in financial markets increases the speed of technology diffusion for capital-intensive technologies.[30]

# 3 EU policies on critical technologies

## 3.1 Research support and cooperation initiatives

The will to promote cross-country research cooperation in key technologies has been an integral part of the European idea right from the start. As a first major manifestation, in 1971 the European Economic Community (EEC) plus 19 further European countries established the Cooperation in Science and Technology (COST) program,[31] an initiative promoting the building of international research networks in Europe. In 1983, the first community-financed research framework program was approved.[32] Subsequently, the multi-annual framework program was included in the EEC treaty. From then on, the programs have been gradually expanded with each programing period. Horizon Europe, the current framework program for the period 2021-2027, comprises a budget for research and innovation strategy of 95.5 billion EUR.[33] Further means for research funding are allocated through the EU's European Structural and Investment Funds. In its technology-specific development strategies, the funding aspect is complemented by support policies for overcoming bottlenecks in the implementation of innovation in business models. Most recent examples for such a holistic approach are the initiative on biotechnology and biomanufacturing[34] and the strategy on advanced materials.[35]

In recent years, the attempts to spur R&D cooperation inside the EU have been coupled with an intensified outreach to third countries. With Japan, the EU has signed a first Science and Technology Cooperation Agreement in 2009 foreseeing exchange of R&D resources and a reciprocal opening of own funding programs.[36] It has set the stage for the comprehensive **EU-Japan Strategic Partnership Agreement (SPS)** signed in 2019.[37] As a complement to the trade-liberalizing Economic Partnership Agreement (EPA)[38], it aims to deepen bilateral research and regulatory cooperation in areas like connectivity, digital and energy technologies with the overarching goal of promoting a rules-based global order.[39] As a governance mechanism, a joint science and technology committee supervising progress in

[30] Comin, D., & Nanda, R. (2019). Financial development and technology diffusion. IMF Economic Review, 67, 395-419.
[31] COST (2024). Growing ideas through networks. European Cooperation in Science and Technology.
[32] European Council (1983). Council resolution of 25 July 1983 on framework programmes for Community research, development and demonstration activities and a first framework programme 1984 to 1987. Document 31983Y0804(01)
[33] European Commission (2024a). Horizon Europe. Research and Innovation.
[34] European Commission (2024b). Building the future with nature – Boosting Biotechnology and Biomanufacturing in the EU. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2024) 137 final.
[35] European Commission (2024c). Advanced materials for industrial leadership. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2024) 98 final. See Wolf, A. (2024). Advanced materials for the green and digital age. cepInput No. 8/2024.
[36] European Union (2011). Agreement between the European Community and the Government of Japan on cooperation in science and technology.
[37] European Union / Japan (2018a). Strategic Partnership Agreement between the European Union and its Member States, of the one part, and Japan, of the other part. OJ L 216, 24.8.2018, pp. 4-22.
[38] European Union / Japan (2018b). Agreement between the European Union and Japan for an Economic Partnership. OJ L 330, 27.12.2018, pp. 3-899.
[39] EEAS (2020). EU-Japan Strategic Partnership. Factsheet. European External Action Service.

research cooperation has been established.[40] Moreover, a first partnership specifically dedicated to safety and security in digital technologies was concluded in May 2022.[41]

With South Korea, the EU entered a **EU-Republic of Korea Digital Partnership** in 2022.[42] It is supposed to stimulate joint work in key digital technology areas like quantum computing and Artificial Intelligence (AI) and efforts to make digital innovation compatible with common social values. To date, concrete outcomes of the partnership include a joint call for research proposals on the topic of 6G technologies,[43] the opening of a collaborative semiconductor research forum[44] and South Korea's joining of the EU's Horizon Europe program as an associate member.[45]

With Australia, research cooperation dates back to a first Agreement on Science and Technology Cooperation in 1994.[46]Promoting joint research is also an integral part of the **EU-Australia Framework Agreement** from 2017 strengthening the bilateral partnership to tackle global challenges.[47] With Canada, the framework for research cooperation is set by the **EU-Canada Strategic Partnership Agreement** from 2016.[48] On 3 July 2024, Canada became associated to the industrial research pillar of Horizon Europe.[49]

The most heavy-weighted form of cooperation in terms of market size has so far been established with the US. On June 15th 2021, the **EU-US Trade and Technology Council (TTC)** was put to life.[50] Its main objective is to maintain the industrial and technological leadership of the partners in areas of key strategic concern by working together on common rules for international trade and investment. Its approach is to put research and technology policies in the wider context of global markets and competition. By reducing technology-related market barriers (e.g. lack of interoperability) and managing the diverse risks related to technology implementation (e.g. security of intellectual property, basic human rights, public infrastructure), it aims to define and enforce a safe and fair market environment for advanced technologies. It is organized in working groups covering five key areas of cooperation: export controls, foreign direct investment screening, secure supply chains, technology standards and global trade challenges. Outcomes of the so far six ministerial meetings include agreements on common standards in recharging infrastructure, common principles for the further development of AI and a roadmap for the deployment of 6G technologies.[51] Moreover, the TTC has been complemented by a

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40 European Commission (2023a). The 7th EU-Japan Joint Scientific and Technological Cooperation Committee (JSTCC) meeting. News Article 18.12.2023.
41 European Council / Japan (2022). Japan-EU Digital Partnership.
42 European Council/ Republic of Korea (2022). European Union- Republic of Korea Digital Partnership.
43 Euronews (2024). South Korea, Europe to strengthen cooperation on 6G, chips research. News 15 March 2024.
44 RPN (2024). EU and South Korea set up semiconductor research forum. Research Professional News, 27 March 2024.
45 Science | Business (2024). South Korea joins Horizon Europe in multi-billion euro push to globalise science. News, 25 March 2024.
46 Australia / European Union (1994). Agreement relating to scientific and technical cooperation between the European Community and Australia. OJ L 188, 22.7.1994, pp. 18 – 25.
47 Australia / European Union (2017). Framework Agreement between the European Union and its Member States, of the one part, and Australia, of the other part. OJ L 237, 15.9.2017, pp. 7 - 35.
48 Canada / European Union (2016). Strategic Partnership Agreement between the European Union and its Member States, of the one part, and Canada, of the other part. OJ L 329, 03.12.2016, pp. 45 – 65.
49 European Commission (2024d). Canada joins Horizon Europe programme. Press Release, 3 July 2024.
50 European Commission (2021a). EU-US launch Trade and Technology Council to lead values-based global digital transformation. Press Release, 15 June 2021.
51 European Union (2024a). EU-US Trade and Technology Council 2021-24. Factsheet.

Joint Technology Competition Policy Dialogue aimed at strengthening transatlantic cooperation in issues of competition policies for advanced technologies.[52]

In all, the structure of the TTC and related initiatives reflects the strong interdependence of trade, technology and competition policies in times of a rapidly shifting global economic order. Competitiveness on the emerging markets for advanced technologies is not only shaped by domestic R&D and production support, but by the power to define trade rules and technical standards. For the latter, success in innovation activities is a necessary precondition, but not a sufficient one. Enforcing rules and standards also requires macroeconomic weight and the ability to translate own ideas into production and business practices that are adoptable by a wide range of market players. To this end, the formation of technology clubs among major innovators is a promising strategy. Through continuous exchange of information and best practices among relevant authorities in all partner countries, it contributes to a common rules-based market framework that creates a level playing field on the inside and acts as a guideline for the remaining market players on the outside. At the same time, by establishing joint monitoring and sanctioning mechanisms against the circumvention of these rules by outside forces, the club also serves to raise the level of protection of members against unfair competition. This requires a clearly defined set of instruments. With its Economic Security Strategy, the EU has proposed a bundle of control instruments for acting on a unilateral basis. It goes far beyond the handling of market-related technology risks.

## 3.2 The Economic Security Strategy

On June 20th 2023, the Commission and the High representative published a joint Communication sketching the pillars and priorities of a future "**European Economic Security Strategy**".[53] It represents the first attempt of the EU to put the notion of economic security at the center of strategic action. It is motivated by the EU's perceived increase of economic vulnerability, which was demonstrated by recent shock events like the COVID-19 pandemic and the Ukraine war, and perpetuated by ongoing geopolitical tensions and a fierce international technology competition. Against this background, economic linkages with third countries are no longer viewed as a pure blessing, but under some circumstances also as a source of risk for European supply chains and competitiveness.

The central objective of the strategy is to provide guidelines for a better balancing of benefits and risks in the economic cooperation with third countries. The leitmotif is a both competitive and resilient European economy, which does not shy away from global competition, but addresses specific security gaps while using its weight to enforce a rules-based global trade order.

The first analytical step is to identify and monitor the types of risks the European economy is facing. The Communication distinguishes between four types:

- Threats to **supply chains**: Price and supply risks for critical inputs (e.g. raw materials and energy)
- Threat to **tangible infrastructure**: Physical and digital attacks on critical infrastructure (e.g. sabotage of undersea cables)

[52] European Commission (2021b). Competition: EU-US launch Joint Technology Competition Policy Dialogue to foster cooperation in competition policy and enforcement in technology sector. Press release, 7 December, 2021.

[53] European Commission / High Representative of the Union for Foreign Affairs and Security Policy (2023). Joint Communication to the European Parliament, the European Council and the Council on "European Economic Security Strategy". JOIN(2023) 20 final.

- Threats to **technological supremacy and security**: Protection against technology leakages (e.g. knowledge transfers through FDI, espionage)
- Risk of **weaponization of economic dependencies**: Blackmailing by third countries through policy measures targeting European economic vulnerabilities (e.g. export ban on critical inputs, blocking of EU investments)

The broad spectrum of risks covered is thus not limited to criminal practices and malicious attacks, but also encompasses policy measures by third countries and further disruptive market developments which are not policy-induced.

As priorities for risk prevention and management, the Communication proposes a three-pillar approach. The EU should i) **promote** its domestic competitiveness, ii) **protect** itself against identified security risks and iii) **partner** with third countries to reinforce economic security. While pillars i) and iii) are basically summaries of pre-existing strategic approaches, pillar ii) adds a genuine element to the Economic Security Strategy. The horizon of protective measures envisaged by the Communication addresses all four risk types and involves both physical protection of critical components and an arsenal of trade and technology policy measures. At the same time, the Communication propagates the principles of **proportionality** and **precision** for all measures seized, stressing that the danger of overreactions and conflict escalations are supposed to be kept in check.

To implement these priorities, the Communication announced several legislative proposals and other policy initiatives. By now, these announcements have partly been realized. Foremost, this includes an **Economic Security Package** proposed on January 24th 2024[54] comprising five initiatives: i) a Proposal for a new Regulation on FDI screening, ii) a Proposal for a Council Recommendation on enhancing Research Security as well as three white papers on the topics of iii) export controls for dual-use goods, iv) R&D support in the dual-use segment and v) security of outbound investments.

For the field of technology cooperation, initiatives i), ii) and v) are of direct relevance. The proposed new **Regulation on the screening of inward FDI**[55] aims to streamline the existing cooperation mechanism between Member States and to its overall effectiveness by closing loopholes. It foresees an obligation for all Member States to implement a screening mechanism. This involves the imposition of an authorization requirement for all foreign investments in either "projects or programs of Union interest" or "activities of particular importance for the security or public order interests of the Union", both groups defined by lists in the proposal's Annex. The latter group includes all items on the EU list of critical technologies (see next Subsection), the list of dual-use items subject to export controls, the military list of the European Union, the Union list for critical medicines as well as a list of critical institutions for the European financial system. Hence, the scope of risk monitoring clearly exceeds the areas of military or terrorist threats and comprises a range of purely civil technologies.

Moreover, if, as a result of a risk screening, a Member State concludes that a foreign investment is likely to negatively affect security or public order, it shall either prohibit the investment or at least demand mitigating measures (e.g. unbundling of certain assets). In determining whether this is the

54 European Commission (2024e). Commission proposes new initiatives to strengthen economic security. Press Release, 24 January 2024.

55 European Commission (2024f). Proposal for a Regulation of the European Parliament and of the Council on the screening of foreign investments in the Union and repealing Regulation (EU) 2019/452 of the European Parliament and of the Council. COM(2024) 23 final.

case, a negative impact on the availability of critical technologies is one risk to be checked. Hence, while not banning or restricting inward FDI in sensitive, knowledge-intensive fields in general, the proposed Regulation aims to spread a cautious, risk-oriented view among European regulators on these forms of international cooperation. This might give rise to more restrictive measures in the future, also in areas where no military issues are at stake.

The **Proposal for a Council Recommendation on enhancing Research Security**[56] aims to create awareness for security risks in the research sector and strengthen the resilience towards these risks. In the proposal, research security refers to the management of three types of risks: i) undesirable transfer of critical knowledge to third countries, ii) malign foreign influence on the research discourse and iii) ethical or integrity violations. In the explanation of category i), military purposes are mentioned, but only in the form of an example. Hence, unintended knowledge transfers in civil technologies are potentially addressed as well. The proposed recommendations to Member States include the development of national action plans with targeted measures to boost research security. These shall include safeguarding measures in the form of risk appraisals of applicants in national research funding programs and the provision of resources to higher education investments for the build-up of internal risk management schemes. Again, special attention shall be paid to cooperation in research fields covered by the EU's list of critical technologies.

The **White Paper on outbound investments**[57] argues for the need of introducing a monitoring scheme for outward FDI comparable to the monitoring of inward FDI. It sets the stage for a Commission Recommendation to Member States on implementing such a scheme. Its main arguments for this extension are first the danger of a circumvention of the export ban on dual-use goods through outward investments. Second, the attempt to prevent technology access through a ban on inward FDI could be circumvented by outward investments as well. Again, while pointing to foreign military activities as a prominent danger, the concrete steps sketched in the White Paper is to monitor a wide field of investment transactions including primarily civil technology fields. Alternatively, the recommendation is to at least cover investments in the four technology areas currently classified by the EU as most sensitive (see next Subsection).

## 3.3 The list of critical technologies

The background of the recent proposals is a specific list of critical technologies published as part of a Recommendation by the Commission on October 3rd 2023.[58] According to the Commission, these are technology areas whose strategic importance for the overall economic security of the EU require a profound assessment of the risks of technology security and technology leakage. The list found in Annex I of the Recommendation[59] is presented in Table 1. In selecting these technology areas, the Commission applied three criteria. The first is the enabling and transformative nature of the technology. This relates to its potential of causing drastic changes in production conditions and thus stimulating long-term productivity improvements. This is the immediate economic aspect of the definition. The second criterion is the risk of military and civil fusion, i.e. the dual use potential of the technology. It

[56] European Commission (2024g). Proposal for a Council Recommendation on enhancing research security. COM(2024) 26 final.

[57] European Commission (2024h). White Paper on outbound investments. COM(2024) 24 final.

[58] European Commission (2023b). Commission Recommendation of 3.10.2023 on critical technology areas for the EU's economic security for further risk assessment with Member States.

[59] European Commission (2023c). Annex to the Commission Recommendation on critical technology areas for the EU's economic security for further risk assessment with Member States. C(2023) 6689 final.

reflects the risk that unintended knowledge outflows could enhance military threat for the EU. The third criterion is the potential of misusing the technology for the violation of human rights in third countries, e.g. the surveillance of the population and the suppression of free speech.

**Table 1: List of 10 critical technology areas for the EU's economic security**

| No. | Technology area | Examples specific technologies |
|---|---|---|
| **1** | **Advanced semiconductor technology** | Microelectronics; Photonics; High frequency chips; Manufacturing equipment at very advanced node sizes |
| **2** | **Artifical intelligence technologies** | High performance computing; Cloud and edge computing; Data analytics technologies |
| **3** | **Quantum technologies** | Quantum computing; Quantum cryptography; Quantum communications; Quantum sensing and radar |
| **4** | **Biotechnologies** | Techniques of genetic modification; New genomic techniques; Gene-drive; Synthetic biology |
| 5 | Advanced connectivity, navigation and digital technologies | Secure digital communications and connectivity; Cybersecurity technologies; Internet-of-Things and Virtual Reality; Distributed ledger and digital identity technologies; Navigation and control technologies |
| 6 | Advanced sensing technologies | Electro-optical, radar, chemical, biological, radiation and distributed sensing; Magnetometers; Underwater electric field sensors; Gravity meters and gradiometers |
| 7 | Space and propulsion technologies | Dedicated space-focused technologies; Space surveillance and earth observation technologies; Space positioning, navigation and timing; Secure communications; Propulsion technologies |
| 8 | Energy technologies | Nuclear fusion technologies; Hydrogen and new fuels; Photovoltaics; Smart grids and energy storage |
| 9 | Robotics and autonomous systems | Drones and vehicles; Robots and robot-controlled precision systems; Exoskeletons; AI-enabled systems |
| 10 | Advanced materials, manufacturing and recycling technologies | Technologies for nanomaterials; Additive manufacturing; Digital controlled micro-precision manufacturing; Technologies for extracting, processing and recycling critical raw materials |

Source: European Commission (2023b). Bold: high priority fields.

The Commission stresses the fact that the publication of the list does not involve any definitive statement on the severity of risks. It only represents a prioritization of technology areas for such a later assessment. The assessments shall be carried out by Member States and involve private stakeholders from the industries. In this process, four of the ten technology areas are recommended to have highest priority, due to their high likelihood of causing severe and immediate risks: Advanced Semiconductors, Artificial Intelligence, Quantum Technologies and Biotechnologies. For these areas, the Commission proposed collective risk assessments to be carried out already by the end of 2023. The investigations conducted so far entered the Economic Security Package, in particular the extended monitoring of FDI (see previous Subsection).

The list intends to fill a gap in the EU's overall strategy of regaining control over international supply chains in critical technology areas. While previous EU initiatives were focused on managing supply risks for tangible resources like energy (RePowerEU)[60] and raw materials (Critical Raw Materials Act)[61], or promoting domestic production capacities for technologies (Net Zero Industry Act, STEP), this initiative focuses on knowledge as a critical intangible resource. It reflects the insight that having influence on the organization of future supply chains requires sufficient control over knowledge flows. Moreover, the list goes beyond previous approaches in specifying more clearly which technology fields should be prioritized for technology sovereignty at EU level.

Yet, the way the Recommendation is formulated reveals a high degree of caution on the side of the Commission. Firstly, while being more precise than before, the list of prioritized technologies appears still very broad, an impression that is reinforced by the myriads of concrete examples mentioned (see Table 1). Secondly, while describing technology threats in general terms, the Commission carefully avoids to spell out any concrete risk scenarios. In particular, China as the elephant in the room is left unmentioned. This shows that the Commission is careful not to spur ongoing trade conflicts with China through this initiative. Thirdly, the reference to military and human rights threats intends to downplay any industrial policy ambitions associated with the initiative. For some of the technology areas, this is not very credible, as the mentioned links with military issues are rather far-fetched. Fourthly, apart from continuous monitoring, the initiative avoids to further concretize the potential future countermeasures against identified technology threats loosely presented in the Economic Security Strategy (see previous Subsection). In particular, this holds for technology risks in relation to outbound FDI whose future treatment is still up in the air. Instead, the importance of intensive future exchange before imposing any policy measures is stressed by the Commission.

In all, the purpose of the initiative seems to lie more in sending a wake-up call to Member States and a warning signal to China than in building the backbone of a new policy approach for managing technology risks. It sketches a road of technological protectionism Europe is ready to follow if attempts to restore a (from an EU-perspective) fair global trade order fail. It is thus part of an arsenal of weapons to strengthen Europe's position in ongoing trade talks. Yet, given its coincidence with increased promotion of domestic production and announced tariff increases[62], it raises the risk of hostile countermeasures by China endangering a settlement of the economic disputes.

To reduce this risk, the EU should gain and communicate a more balanced view on the role of international knowledge flows and consider the welfare benefits of technology cooperation discussed in Section 2. Instead of focusing exclusively on potential technology leakages, it should also highlight areas where cooperation in the creation and sharing of knowledge is vital for the EU's long-term interests. A sound strategy on critical technologies should simultaneously attempt to maximize the inflow of foreign knowledge, channel R&D cooperation to advanced and trustworthy partners and restrict knowledge outflows in sensible fields. Such a strategy reflects the basic fact that just like the production and exchange of tangible goods, production and exchange of specialized knowledge offers potentials for exploiting comparative advantages. By drawing on international networks of collaboration in R&D and technology adoption, the European economy is able to channel its R&D resources to

[60] European Commission (2022). REPowerEU: affordable, secure and sustainable energy for Europe. Communication COM(2022) 108 final.

[61] European Union (2024b). Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020Text with EEA relevance.

[62] European Commission (2024i). Commission investigation provisionally concludes that electric vehicle value chains in China benefit from unfair subsidies. Press release, 12 June 2024.

technology areas with highest comparative own expertise, while adopting the roles of minor research partners or imitators in other areas. This allows for a better utilization of scale economies in R&D and reduces the risk of being cut-off from foreign innovation.

To pursue such a specialization strategy, a prerequisite are insights into the patterns of current international knowledge cooperation in critical technology areas. In what follows, by drawing on comprehensive international patent data, we attempt to provide such insights for the case of international research cooperation.

# 4 Patent analysis for critical technologies

## 4.1 Method and data

From an economic point of view, it makes sense to start measuring innovation at the point where the prospect of commercialization becomes evident through the registration of property rights. Patent data is therefore often the basis for output-based innovation indicators. Their limitations are well known.[63] They do not provide information about the actual subsequent market success of patented inventions and their general societal impact. They are also not perfect measures of innovation at the development stage, as many types of inventions are not patentable for technical or legal reasons. Nevertheless, main advantages are the high degree of international harmonization and the high level of technological detail in patent statistics. The International Patent Classification (IPC) system enables an extremely fine-grained subdivision according to fields of technology.[64] In addition, information on innovation networks via cross-referencing (citations) and supra-regional cooperation between institutions and inventors is available.

For our analysis of international research cooperation in critical technologies, we use data from PATSTAT, the worldwide patent statistical database of the European Patent Office (EPO).[65] It is one of the world's most comprehensive patent databases and a popular choice for innovation analyses. To identify the IPC classes attached to the different fields of critical technologies defined by the EU (see Subsection 3.3), we draw upon work conducted by the European Commission's Advanced Technologies for Industry (ATI) project.[66] In a series of publications, the ATI project analysed EU patenting activities in a range of advanced technologies, by applying lists of IPC codes established by the detailed technology expertise of the participating institutions.[67] The set of advanced technologies covered by the ATI is similar, yet not identical to the EU's list of critical technologies. Where possible, we adopted or aggregated the ATI technology fields based on the examples mentioned in the EU critical technology list. Fields whose complexity and/or transversal nature did not allow for a clear code assignment (e.g. robotics) were omitted. In one case (energy technologies), an own code assignment based on extensive

63 Wydra, S. (2020). Measuring innovation in the bioeconomy–Conceptual discussion and empirical experiences. Technology in Society, 61, 101242.
64 WIPO (2024). International Patent Classification (IPC). World Intellectual Property Organization.
65 EPO (2024). PATSTAT – Backbone dataset for statistical analysis. European Patent Office.
66 European Commission (2024). European Monitor of Industrial Ecosystems.
67 ATI (2021). Advanced Technologies for Industry – Methodological report. Indicator framework and data calculations. September 2021.

keyword search in the IPC classification was performed. In another case (biotechnologies), an official OECD definition was applied.[68]

In all, this has provided us with six critical technology fields for our patent analysis: Advanced materials, AI technologies[69], Biotechnologies, Connectivity technologies, Energy technologies and Semiconductor technologies. Table A1 in the Appendix shows the selection process and the lists of corresponding IPC codes. Often, patents are assigned multiple IPC codes, reflecting their contributions to several fields. Therefore, some patents are assigned to multiple critical technologies in our analysis as well. We intentionally do not attempt to adjust for this fact, respecting the overlaps and strong interconnections between the single technology fields.

For all classes, data on all registered patents over the period 2011 to 2020 was retrieved via search queries in PATSTAT.[70] The data collected for each patent includes affiliation to a specific technology class, membership in a patent family and number of citations. The dataset generated contains a total of 6.74 million observations. In the next step, it was merged with data from the OECD REGPAT database.[71] This contains additional information on the names and residential addresses of the inventors registered in the patents, thus enabling a detailed spatial allocation. Compared to using the addresses of the applicants, which in the case of multinational enterprises can be a parent company or an affiliate located far away from R&D activities, this results in a more precise spatial picture of innovation.

The number of patent applications is a common indicator for quantifying patenting activity. For a country comparison, we must consider that often several people are registered as the inventors of a patent, who may be located in different countries. As is common in the literature, we account for this by applying an equal share for each inventor as a weighting factor. For instance, in the case of a patent with eight registered inventors, each inventor is assigned a share of 0.125. Then, we calculate the total innovation activity of a country in a field as the sum of the shares of inventors residing in the respective country ("inventor counts").

If persons located in different countries are registered as inventors in a patent application, this patent application is interpreted as a case of international research cooperation. With such a broad definition, cooperation can in practice be based on different kinds of motivations and arrangements. For instance, it covers both firm-internal (cross-border R&D activities of MNEs) and firm-external (independent institutions from different countries engage in collaboration) forms of research cooperation (see Subsection 2.1 for a theoretical discussion).

In the country comparisons, the EU27 (as defined by current membership) are always treated as one bloc. Hence, in the figures reported for the EU, international cooperation only includes cases where inventors located in a Member State cooperate with inventors located in a third country.

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68 Friedrichs, S., van Beuzekom, B. (2018). Revised proposal for the revision of the statistical definitions of biotechnology and nanotechnology. OECD Science, Technology and Industry Working Papers, 2018/01, OECD Publishing, Paris.

69 The definition applied is quite comprehensive, involving both patentable data storage and processing technologies, learn algorithms and speech analysis techniques.

70 For more recent years, available patent data is currently still incomplete.

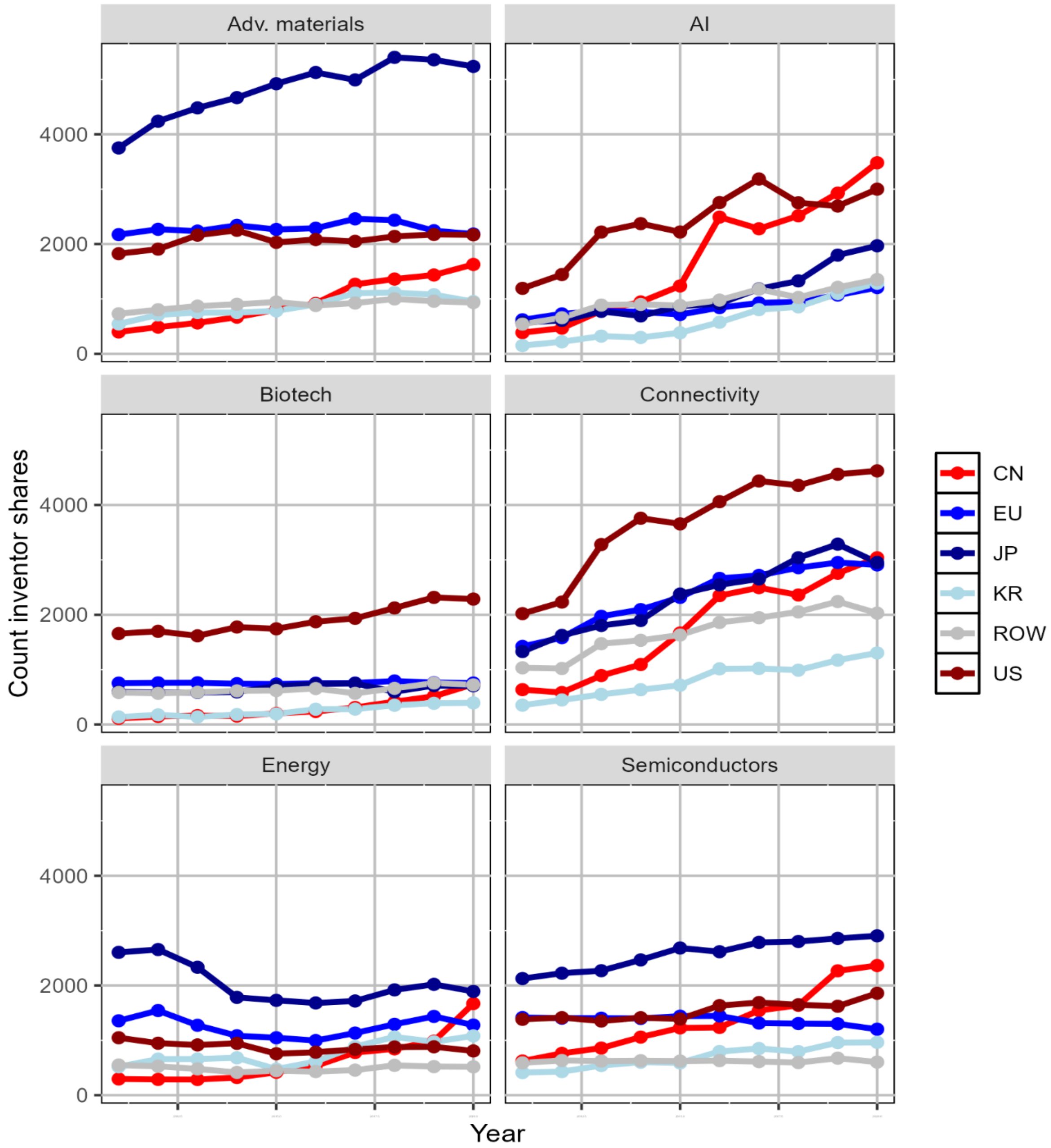
71 OECD (2024). Intellectual property (IP) statistics and analysis. Organization for Economic Co-operation and Development, Paris.

## 4.2 Results

### 4.2.1 Overall performance

First, our comprehensive dataset allows for an overview on the evolution of patenting activity of the EU27 vis-à-vis other major innovators. Figure 1 presents trends in annual patent applications by inventor country for the six technology fields considered. In all these fields, four major actors besides the EU27 bloc have dominated the patenting scene in recent years: the US, Japan, South Korea and (increasingly) China. However, the specific rankings differ. The US were consistently the by far most important location for patenting activity in biotechnologies and connectivity. The fields energy technologies, semiconductor technologies and especially advanced materials were dominated by Japan. Moreover, the strong upward trend in applications by Chinese inventors is remarkable. It applies to all fields, but most prominently to AI technologies, where China has already taken the lead. In contrast, the dynamics of the EU27 were considerably weaker. During the period under review, it was overtaken by China in four of the six fields.

**Figure 1: Evolution of annual patent applications by technology field**



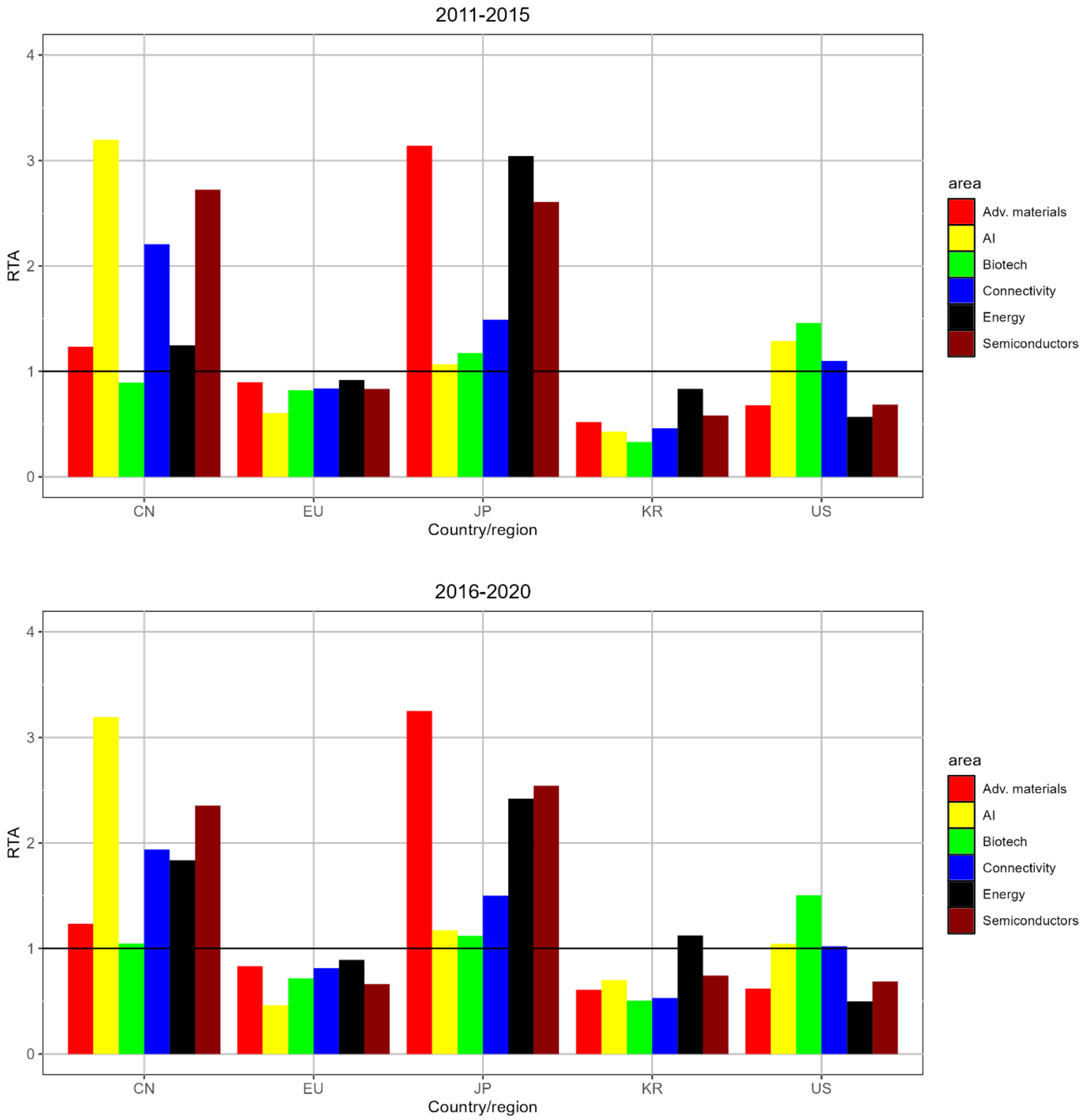

Source: own calculations. ROW: Rest of the world.

Apart from time trends, the patterns reveal different forms of specialization among the major innovators. One way to make the forms of specialization more transparent is through a measure of Revealed Comparative Technological Advantage (RTA), in analogy to the specialization measure of Revealed Comparative Advantage (RCA) often applied to merchandise exports.[72] As RTA measure, we define the ratio of the share of a specific technology field in total patenting applications (i.e. including non-critical technology fields) of an inventor country/region over the share of this field in total patenting applications worldwide. Hence, an RTA larger than one indicates a relative specialization of a country in the respective field vis-à-vis the rest of the world. Figure 2 presents the resulting RTA values for the

[72] Laursen, K. (2015). Revealed comparative advantage and the alternatives as measures of international specialization. Eurasian business review, 5, 99-115.

countries/regions considered, distinguishing between the first and the second half of our period of investigation. It shows that critical technologies exhibited very different degrees of importance in the innovation portfolios of countries. China and Japan have shown strong degrees of specialization in several critical technology fields. In the latter period, specialization (RTA >1) extends in both countries to all critical technologies considered. By contrast, the shares of critical technologies in EU27 patent applications were consistently lower than on global average, indicating that the focus of EU innovation activity was on other fields.

**Figure 2: Revealed comparative technological advantages by technology field**




Source: own calculations

### 4.2.2 Global cooperation networks

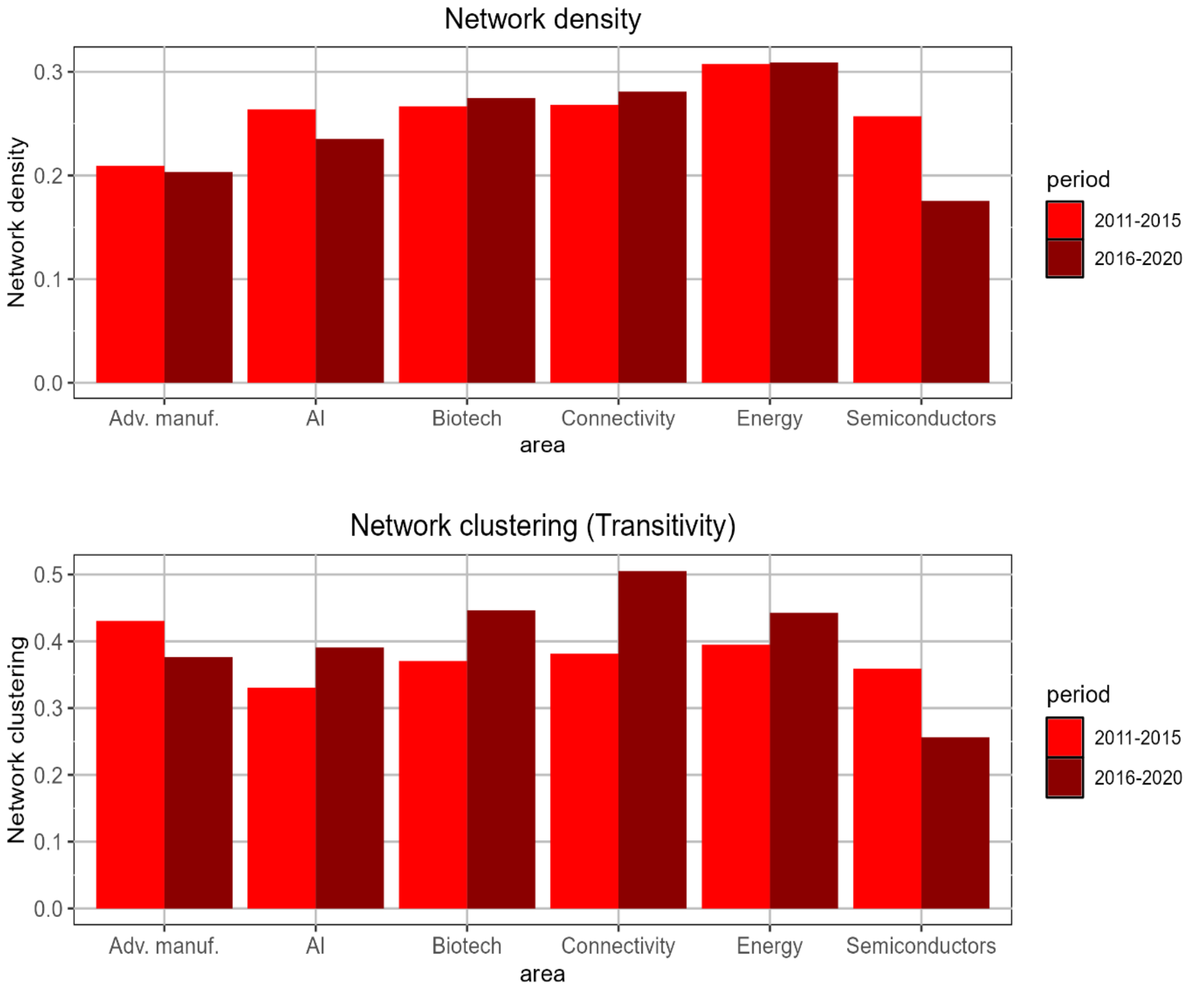
By exploiting the information on inventor locations, we can use the patent dataset to construct a global network of R&D cooperation between countries/regions in the technology fields considered. In such a network, every connection (edge) between two countries/regions (vertices) represents a patent collaboration involving inventors in both countries/regions. As discussed above, such an international collaboration can take place both within (e.g. in-house R&D activities of MNEs) and beyond (e.g. international R&D partnerships of unrelated firms or universities) the boundaries of single firms or research institutions. The intensity of the connections (i.e. the weights attached to single edges) equals the number of joint patent applications.

The shapes of R&D networks obtained for the single technology fields are represented in Figure A1 in the Appendix, differentiating between the two subperiods under investigation. The single networks show some idiosyncrasies, but also some striking commonalities. One common feature is a central role of researchers from the US. It is particularly pronounced in AI technologies and biotechnologies. This role is both rooted in the large number of international patent collaborations involving researchers from the US and the geographical diversity of these cooperations. Except for the field of advanced materials, another commonality is that the research-strong nations Japan and South Korea (see previous Subsection) are merely located in the periphery of the cooperation networks. This reflects their low engagement in international cooperations in general, and in cooperations with network-central countries in particular. Regarding China, it is interesting to see that its high growth of patenting activities (see previous Subsection) has not been coupled with a move towards more central positions within cooperation networks when comparing the two periods. Especially in AI and connectivity technologies, China's position remained rather peripheral.

Given its sheer economic size, the EU is unsurprisingly an important element in all of these networks, but the magnitude of its relevance differs by field. In advanced materials and (in the more recent period) in energy technologies, it represents the global focal point of patent networks, due to its comparatively wide geographical outreach and its particular strong ties with other major innovation forces like the US. In biotechnologies and semiconductors, it represents one local center besides the US within a bipolar structure, while in AI technologies its position is more peripheral.

The global properties of the networks can be compared based on a range of analytic indicators. Figure 3 depicts the results for two widespread measures, the network density and the clustering coefficient (transitivity). The density of a network reflects the number of different bilateral connections relative to the overall size (number of countries/regions involved) of the network. Comparing the two periods, a downward development of the densities can be diagnosed for AI and especially for semiconductor technologies, mostly driven by an increase in the number of peripheral countries engaging only in collaborations with one particular partner country/region. Simultaneously, the degree of local clustering has increased in four of the six networks. This reflects the fact that the structure of these networks has become less unipolar, largely due to a decline in the centrality of the US.

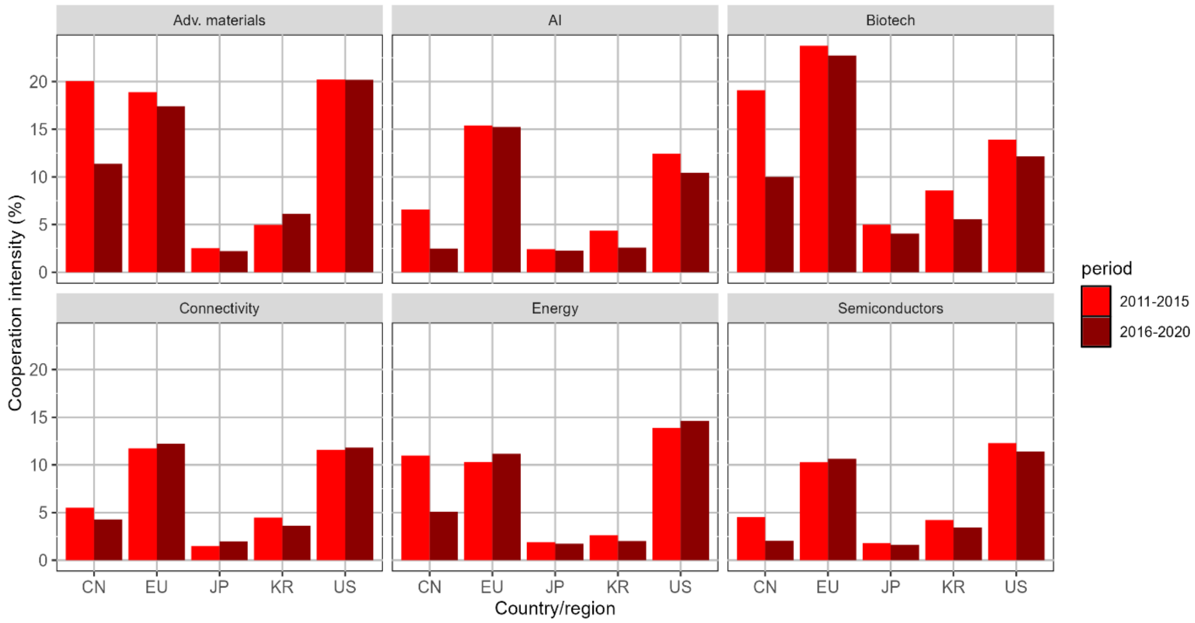
**Figure 3: Density and degree of clustering in patent networks by technology field**




Source: own calculations

The shapes of the cooperation networks are determined by country differences in overall innovation success and the willingness to engage in cooperations. To single out the latter factor, the number of innovations obtained through international cooperations should be viewed in relation to the overall innovation activity of a country. To this end, we define a simple indicator of cooperation intensity, the share of patent applications involving international cooperation in the total patent applications of a country/region within the specific period and field. Figure 4 presents the results for selected countries/regions. Overall, the EU and the US have built their innovation activities to the largest degree on international cooperations. For the EU, particularly high cooperation intensities are reported for advanced materials and biotechnologies. Cooperation intensities of Japan and South Korea are consistently low and have largely even declined in the more recent period. Most striking is the overall time trend for China. While being quite heavily engaged in international cooperation in the earlier period, especially in advanced materials and biotechnologies, the cooperation intensities decreased drastically in the latter period. In AI, energy and semiconductor technologies, they more than halved. A high growth of Chinese patent applications (see previous Subsection) thus coincided with a firm trend towards technological isolation. To what extent this is due to a reduced need of foreign knowledge inflows or due to an intentional autarky strategy would be an interesting subject for further investigations.

**Figure 4: Intensity of international patent cooperations by technology field**




Source: own calculations

A specific look at the cooperation partners of the EU reveals further interesting patterns (see Table A2 in the Appendix). In all fields, the US were consistently the by far most important partner. Their relative importance even slightly increased in period comparison in five of the six fields (exception: AI). In four fields, more than half of the EU's bilateral patent connections were established with US researchers. Connections with researchers in China were significantly less frequent in all of the fields, they accounted for less than 10 % of the EU's patent collaborations. In the more recent period, the maximum level of engagement with China is observed for advanced materials and energy technologies. India is a further relatively significant non-European partner of the EU, at least in the fields of AI and connectivity technologies.

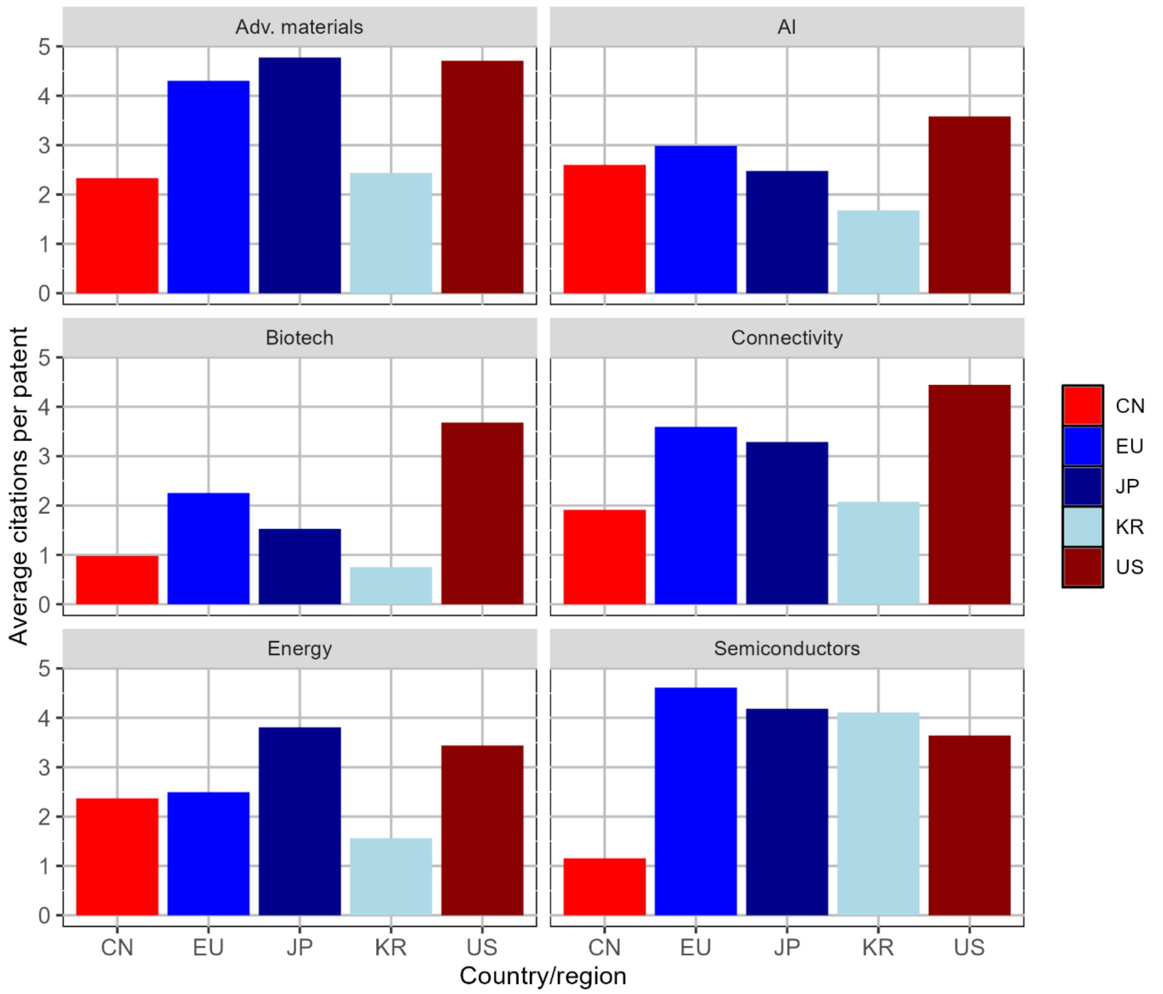
### 4.2.3 Patent quality assessment

The previous analysis of the number of patent applications only partly reflects the economic effects of international research cooperation. By joining knowledge and other R&D resources across borders, institutions not only attempt to increase their quantitative research output, but also to enhance the significance of the inventions made. Investigating this dimension of research cooperation based on patent data asks for measures of patent quality.

Assessing the quality of the invention behind a patent is a difficult task. At the time when a patent is filed, its future economic success and social importance is still uncertain. On the way towards a marketable innovation (new products, processes), further hurdles need to be overcome. A promising invention can fail to succeed on markets due to financing constraints or insufficient advertisement. Yet, the literature has established a set of quality indicators which, leaving idiosyncrasies aside, can provide a general picture of the economic relevance of patents. All of these measures have their pros and cons and reflect certain aspects of a patent's outreach.[73] To remain consistent with our approach, we restrict our attention to measures which can be retrieved from patent databases.

Specifically, we choose forward citations as a common indicator. These are citations made in the documentation of other patents referring to the patent investigated. It is thus a measure of the influence of a patent on later inventions. While not directly reflecting the expected economic returns, it goes in some aspects beyond a market value evaluation, as it provides information on the properties of an invention as seed for follow-up innovation. The distribution of the number of forward citations among patents is typically highly skewed, with a small share of top patents reaching an extraordinarily high number of citations. To reflect this fact, we investigate forward citations in two different forms. First, we report the average number of citations the patents of a country have received in a field. Second, we report the share of patents of a country that are part of the global Top 10 % of most cited patents in a field. The latter measure is specifically reflecting the country's engagement in groundbreaking innovation.

**Figure 5: Average patent citations by technology field**



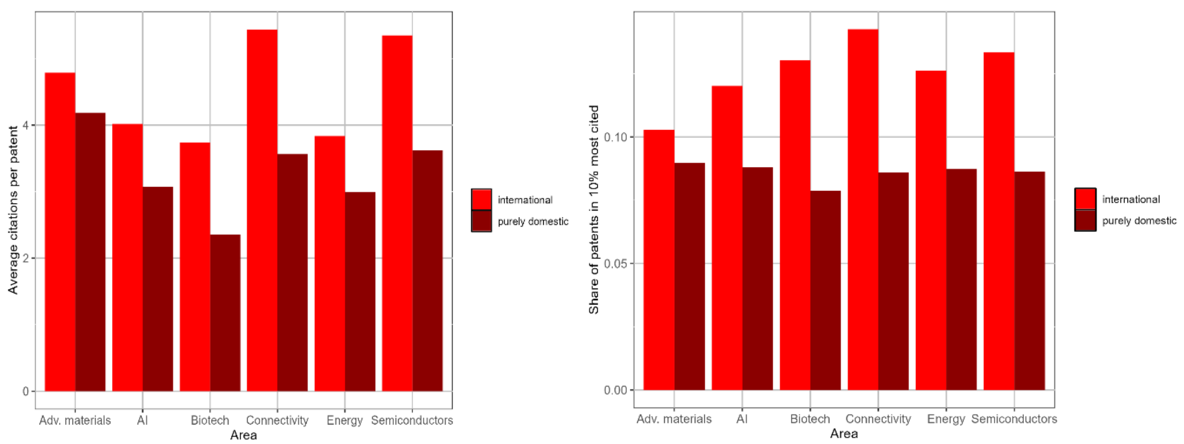

Source: own calculations. Mean of annual averages 2011-2020.

[73] Squicciarini, M., Dernis, H., & Criscuolo, C. (2013). Measuring patent quality: Indicators of technological and economic value. OECD Science, Technology and Industry Working Papers, 2013(3), 0_1.

First, in a general comparison, Figure 5 presents average citations per patent for selected economies.[74] In all, patents from the US stand out with a particularly large number of forward citations. A superiority of US patents is clearly visible in AI, biotechnologies and connectivity technologies. In advanced materials, energy and semiconductor technologies the US is slightly surpassed by Japan. The EU performed particularly well in advanced materials, connectivity and semiconductor technologies, with a leading position in citations for the latter technology. According to this measure, average quality of Chinese patents was comparatively low in all fields except for AI. This overall picture is broadly confirmed when focusing on the distribution of the most-cited patents.

To assess the role of international collaboration for patent quality, we compute the citation measures for patent with purely domestic and international researcher teams separately. The global results reported in Figure 6 indicate that patents stemming from international cooperations reach higher scores for both measures in all the technology fields examined. The differences to purely domestic inventions are particularly pronounced for connectivity and semiconductor technologies. Note that this does not necessarily point to a direct causal effect of internationality. Rather, one could imagine that generating heavily cited groundbreaking innovation regularly requires a large group of researchers with diverse competencies and backgrounds, which provides additional motivation for forming international teams. Seen from another angle, the involvement of a large team of international researchers implies that subsequently more people are likely to work on different follow-up inventions citing the original patent. In any case, may internationality be the main source or a side effect of groundbreaking innovation, it appears to play a vital role in achieving high citation counts.

**Figure 6: Citations by team composition and technology field**



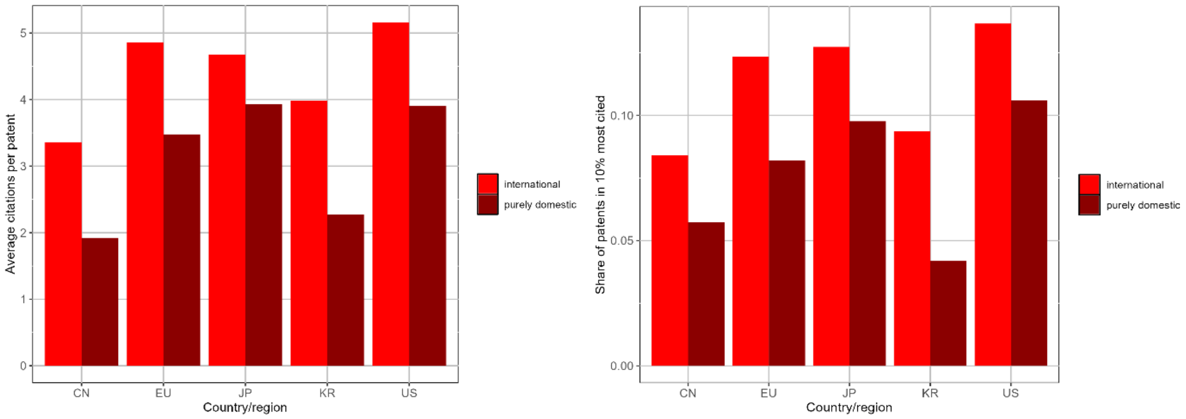

Source: own calculations. Mean of annual averages 2011-2020 for patents worldwide.

This basic fact is confirmed for all the countries previously investigated (see Figure 7). The overall discrepancy between international and domestic teams is particularly large in the case of South Korea. In technology comparison (see Figures A2-A3 in the Appendix), large discrepancies are observed for all fields except for energy. Against this background, South Korea's comparatively low engagement in international cooperation (see previous Subsection) seems a bit surprising. It could perhaps be a reflection of a strategy where the risks related to research cooperation are only accepted for very promising R&D projects. China and the EU also seemed to have benefitted quite heavily from the involvement in

74 As older patents had more time to accumulate forward citations until the present, an investigation of time trends would be misleading. For the same reason, examining the simple mean of citations over the whole observation period would bias the country comparison, as the distributions of patenting activities across time differ between countries.

international R&D networks. In the case of China, citation discrepancies to purely domestic research are particularly large in biotechnologies and semiconductors. In the case of the EU, international collaboration made a particular difference in the field of AI. Concerning average citations in total, international collaborations with EU participation are almost on par with those involving US researchers, which is partly due to the high frequency of joint EU-US collaboration in all fields considered.

**Figure 7: Citations by team composition and country/region**




Source: own calculations. Mean of annual averages 2011-2020 for patents in the six technology fields.

### 4.2.4 Risk analysis of partner portfolios

For any institution, the expected benefits of international research cooperation must be weighed against the risks associated with sharing own resources and knowledge with foreign partners. As discussed in Section 2, these risks include potential inefficiencies caused by institutional mismatch, but also insufficient control over the partner's use of pre-existing or jointly generated knowledge. The latter is especially problematic if foreign laws on intellectual property protection are less strict or difficult to enforce. From a country-wide perspective, the risks related to unintended knowledge outflows also touch upon the issue of national competitiveness. Through this channel, domestic resources spent on R&D activities could accidentally improve the market position of competitors of national champions.

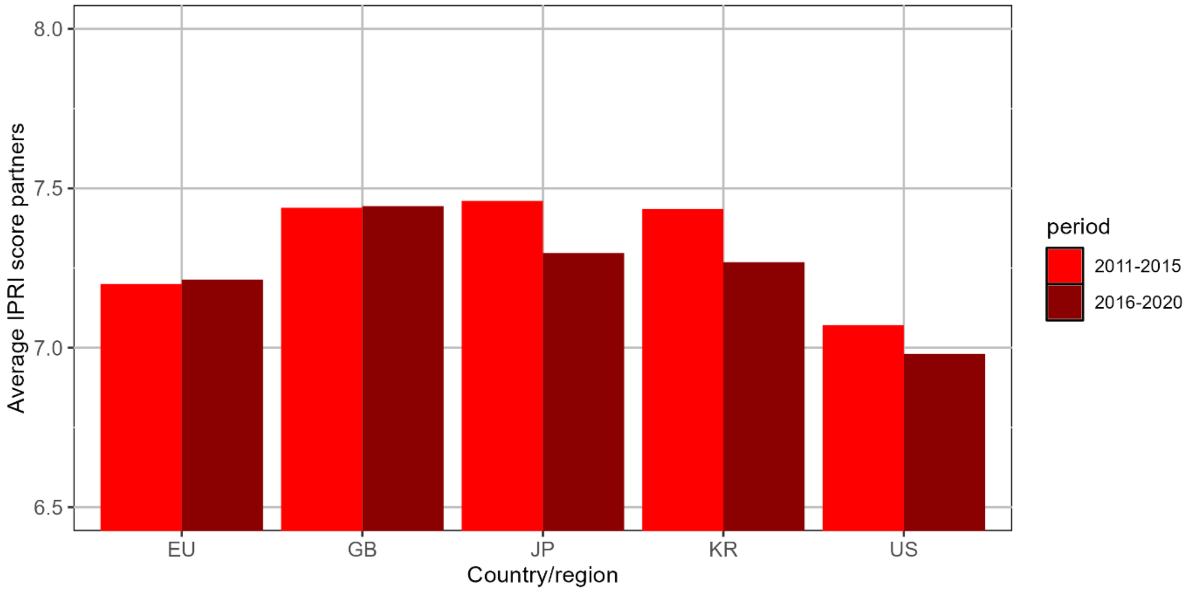
The relevance of these risks can only be gauged based on the boundaries and detailed legal arrangements agreed upon in each partnership. However, our macro-level analysis allows for some insights into the general susceptibility of countries due to their portfolio of research partners. To this end, we draw upon the most recent results of the International Property Rights Index (IPRI), a regular country rating published by the Property Rights Alliance.[75] Specifically, we apply the scores of the subindex "Intellectual Property Rights" as one pillar of the IPRI. It measures the level of IPR protection in a country as a dimensionless score by averaging a diverse set of external indices from scientific sources, involving ratings of patent, copyright and trademark protection. By calculating a weighted average of IPR scores of a country's cooperation partners, with weights defined by the number of joint patents, we obtain a rough picture of general IPR risks associated with the country's partner portfolio.[76]

75 PRA (2023). International Property Rights Index 2023. Report. Property Rights Alliance.

76 The IPRI reports differentiated results for the single EU Member States. For cooperations of Member States with third countries, the respective value for the Member State was chosen to represent the degree of IPR protection for the third country.

Figure 8 reports the results for selected countries/regions. The average IPR score of EU cooperation partners is significantly higher than that of US cooperation partners. However, it is lower than for the partner composition of the United Kingdom, Japan and South Korea. The main reason for these discrepancies lies in the roles of China and (to a lesser degree) India in cooperation networks. Both countries receive lower IPR scores than most OECD members. The US cooperated more heavily with China than the EU, especially in AI, biotech and energy technologies. Yet, EU cooperation with China and India was more pronounced than in the case of Japan and South Korea, even though the latter period shows some degree of convergence. Other OECD members were on average quite strongly attached to the US and the EU as cooperation partners, explaining the high average OECD score.

**Figure 8: Average level of IPR protection in partner countries (Index)**



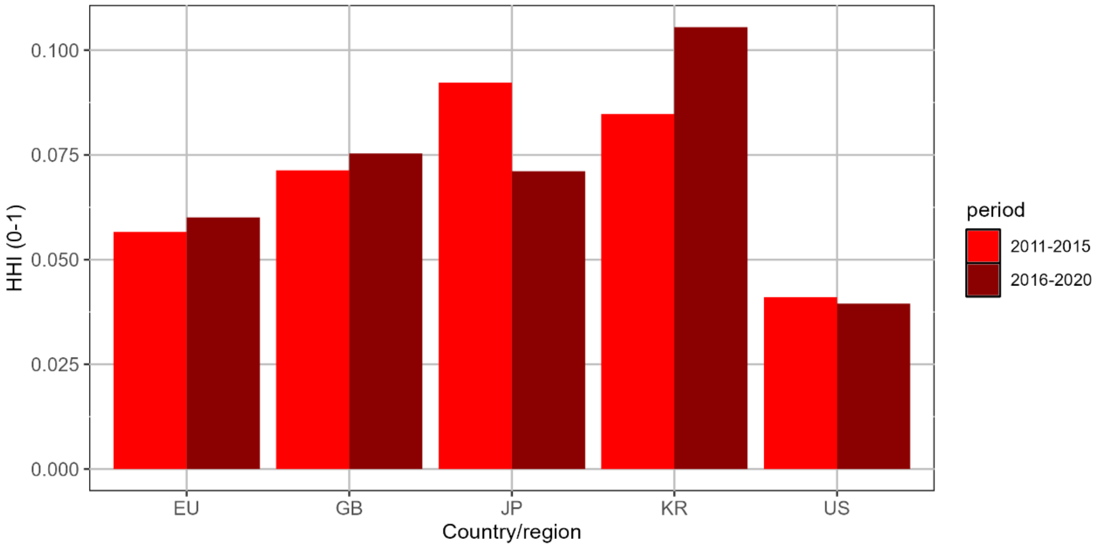

Source: PRA (2023); own calculations

Apart from the issue of IPR protection, partner portfolios can also be assessed from a geostrategic perspective. In this regard, a strong concentration of research ties on single partner countries can be seen as a source of-long-term risk. It implies a high sensitivity of own international research activities to changes in the innovation and property rights policies of specific partner countries. It can also increase the exposure towards general political pressure, especially if researchers in the partner country possess exclusive knowledge indispensable for deep innovation. Establishing a diverse portfolio of partner countries represents a form of insurance against these country-specific policy risks.

To assess the degree of country concentration in international research cooperation, we apply the classic Herfindahl–Hirschman index (HHI).[77] It measures concentration on a scale from 0 to 1 (joint patents with only one country). Figure 9 depicts the results. Accordingly, the US exhibited the by far most diversified partner portfolio, reflecting its central role within global research networks (see Subsection 4.2.2). The EU portfolio was more concentrated, but less than those of the United Kingdom, Japan and South Korea. In a technology comparison, Europe's international collaborations were least diversified in the field of AI research, due to the dominance of partnerships with US researchers.

[77] Rhoades, S. A. (1993). The Herfindahl-Hirschman index. Federal Reserve Bulletin, (Mar), 188-189.

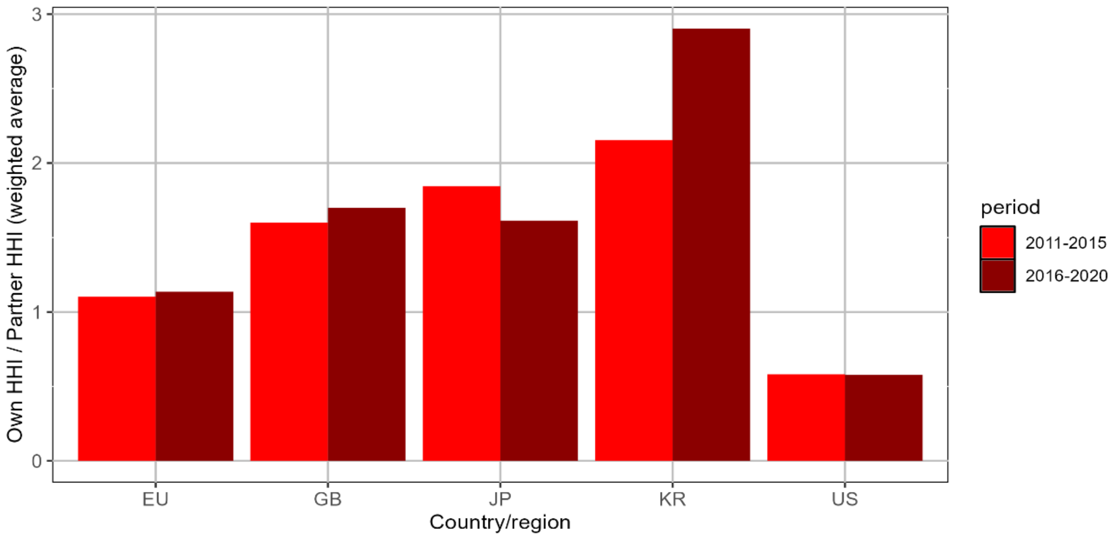
**Figure 9: Country concentration of partner portfolios**




Source: own calculations

Finally, another perspective on cooperation patterns is the degree of symmetry or asymmetry in country cooperations. A form of one-sided dependence, where country A strongly focuses on research work with country B, while country B is linked to a much broader base of cooperation partners, represents another source of risk. Such an asymmetric reliance puts the more reliant partner in a weaker bargaining position concerning the harmonization of legal frameworks and the institutional arrangements of a cooperation. Figure 10 expresses the tendency towards one-sided dependence in a simple indicator, the weighted average of the ratio of a country's HHI score to the HHI score of its partners (with relative cooperation frequencies as weights). It demonstrates that among the countries/regions presented the US is in the by far most comfortable position compared to its cooperation partners. Its partners were on average much less diversified. The EU's level of diversification was on average slightly lower than those of its cooperation partners, largely again a consequence of its strong research ties with the US.

**Figure 10: Degree of one-side dependence in research cooperation**



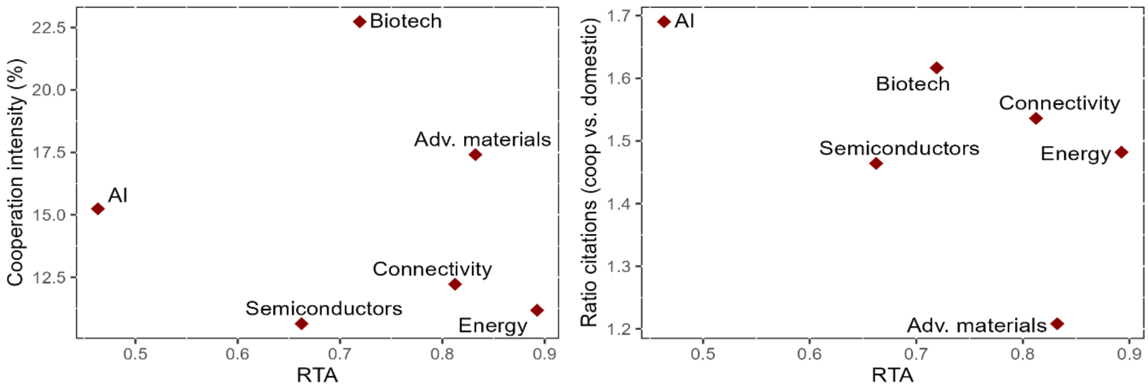

Source: own calculations

# 5 Discussion

## 5.1 Comparison of technology fields

The EU results for the single technology fields show some commonalities. First, in none of the six critical technology fields did EU research possess a Revealed Comparative Technological Advantage (RTA) compared to the rest of the world. Primarily, this is due the stronger emphasis other major innovation forces like the US, Japan and (increasingly) China have placed on critical technologies. Second, patents involving international research cooperation reached in all fields higher average citation numbers than patents with purely EU-based inventors. The specific relevance of cooperation differs by field. The field of biotechnologies represents an outlier regarding its high cooperation intensity. For AI technologies, the citation gap between international and purely domestic research was especially pronounced. In general, fields further outside the European focus (smaller RTA) tended to exhibit a larger citation bonus for patents stemming from international cooperation (see Figure 11). This underpins the relevance of research cooperation as a means to compensate for a lack of domestic resources in the exploration of critical technologies.

**Figure 11: Intensity and quality of technology cooperation from EU perspective**




Source: own calculations. Time period: 2016-2020.

**Table 2: Risk factors by technology field from EU perspective**

| | Risk factors cooperation (EU values) | | |
|---|---|---|---|
| **Technology field** | IPR protection partners<br>*IPR score (PRA, 2023)* | Partner concentration<br>*HHI (0-1)* | One-sided dependence<br>*Av. Ratio own HHI / partner HHI* |
| Advanced materials | 7.11 | 0.26 | 0.94 |
| AI technologies | 7.28 | 0.35 | 1.72 |
| Biotechnologies | 7.35 | 0.34 | 1.16 |
| Connectivity | 7.22 | 0.30 | 1.35 |
| Energy technologies | 7.22 | 0.27 | 0.72 |
| Semiconductor technologies | 7.27 | 0.26 | 0.94 |

Source: own calculations. Benchmark: Average of values for GB, JP, KR, US. Light Red: Slightly worse than benchmark Light green: Slightly better than benchmark (< +10 %). Green: Clearly better than benchmark (> + 10 %). Time period: 2016-2020.

Regarding the distribution of risk factors, communalities between the technology fields outweigh the discrepancies. When comparing the EU to a benchmark representing the average of four major high-income countries (US, Japan, South Korea, Great Britain), the EU partner portfolio is less concentrated and less subject to one-sided dependencies in all fields except for connectivity (see Table 2). At the same time, however, the average degree of IPR protection in EU partner countries is lower than for the benchmark in the majority of fields.

## 5.2 Strategic recommendations

Even though our patent analysis for critical technologies cannot illuminate the field of international technology cooperation in all its diversity, its results, together with the findings of the economic literature, provide the basis for some recommendations for a future European technology strategy. This begins with the special features of the production and consumption of the good "knowledge". The creation of new knowledge is always based on existing (formal and informal) knowledge. Generated knowledge can almost never be completely shielded, but diffuses sooner or later. Both facts together create irresolvable interdependencies between the diverse actors in the international research landscape, which turns the exchange of knowledge into a vehicle for global progress, far from representing a zero-sum game. A long-term EU technology strategy must aim to optimize Europe's position in these global knowledge networks, while at the same time carefully managing the strategic risks resulting from unintended knowledge outflows.

This requires recognizing the intrinsic autonomy of international research and development policy in political communication. Precisely, the EU should stop mixing physical threats with genuinely economic risks under the header of "economic security". Military escalations and the vulnerability of our infrastructure to foreign attacks are undoubtedly real dangers and call for resolute European responses. However, they are of a completely different nature and dimension than questions of competitiveness in connection with knowledge outflows. What the EU needs instead is a dedicated international technology strategy that exploits the potential for cooperation and minimizes risks for system-relevant future technologies. Our analysis has shown that the current EU patent portfolio shows little focus on the technologies currently considered critical. The establishment of long-term technology partnerships with third countries is a promising way of compensating for such a lack of specialization. Ideally, such partnerships should address all stages of the innovation process. Their formation should be guided by the following principles:

1. **Diversification of cooperation partners:** Our analysis reveals that the EU's portfolio of research partners shows a far higher degree of country concentration than the portfolio of the US. This is mostly due to the central role of EU-US research teams in the EU's partner portfolio in all the technology fields considered. Due to its persistent role as a technology pioneer and its overall business dynamics, the USA will remain an essential partner for the EU in the future. However, to reduce one-sided dependencies and the resulting political risks, a simultaneous expansion of research cooperation with other major forces will be integral. Above all, this includes the technological super powers Japan and South Korea, which have so far been little integrated into international research networks, thus filling the existing partnership agreements (see Section 3) with life. Previous practical barriers to cooperation, such as spatial distance and language barriers, are in the process of losing significance due to the triumph of digital labs and AI-supported communication. This makes the current situation ideal for establishing new research relations.

2. **Integration of cooperation partners into internal R&D support schemes**: Technology partnerships should be strengthened and stabilized through reciprocal access to public programs of R&D support. The recent inclusion of New Zealand, Canada and (soon) South Korea[78] as associate members in the EU's Horizon Europe program is a good example of this and should be extended to more partner countries in the future. In order to make such an offer attractive for partners, they should not only be embedded in the funding structure, but also be granted influence on the thematic governance in future planning periods. In addition, grant applicants from partner countries should receive special assistance for the application process in order to compensate for the disadvantage of a lack of administrative experience.

3. **Merging of bilateral partnerships to technology clubs:** To fully reap the benefits of a diversified partner portfolio, the EU should seek to partially merge its bilateral partnerships to plurilateral technology clubs, cooperating in areas where joint efforts are promising strong scale economies. This concerns, for instance, the enforcement of IPR protection in international research cooperation and common work on standardization as a way to guide the future technology development. Specifically, concerning critical technologies, the "mighty technology triangle" US-Japan-EU offers a lot of room for tripartisan cooperation beyond the existing bilateral initiatives.[79] In establishing common rules and principles, the EU will need to maintain a certain degree of pragmatism. Moreover, to avoid a further fragmentation of the global research landscape, it is important that access to these clubs remains possible and is granted in a non-discriminatory fashion (i.e. based on objective criteria like respect of intellectual property and scientific freedom).

4. **Full integration of unilateral economic security instruments:** The unilateral instruments envisaged by the EU for protecting its economic security (see Subsection 3.2) should be incorporated into a joint concept for safeguarding common innovation leadership within the framework of technology clubs, at least to the extent they concern genuinely economic risks. This strengthens mutual trust among club members and increases the effectiveness of defense measures, e.g. by making it more difficult for firms to circumvent export control rules through FDI and trade diversion.

5. **Extending technology cooperation to overcome domestic bottlenecks**: Besides intensified joint work in basic research and product development, partnerships should also address the latter stages of the innovation process, in particular the transformation of ideas into scalable business models. This gives the opportunity to tackle current bottlenecks of European innovation ecosystems like lack of venture capital, regulatory complexity and skilled worker shortages.[80] Partners could work on improving the domestic conditions for implementing innovation e.g. by establishing joint public-private venture capital programs, harmonizing profit tax rules and easing the exchange of professionals. In this way, research collaboration could form the basis for a holistic innovation value chain approach.

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78 ScienceBusiness (2024). South Korea joins Horizon Europe in multi-billion euro push to globalise science. News, 25 March 2024.
79 Regalo, S. (2024). Deepening EU-Japan-US Cooperation on Critical and Emerging Technologies. Commentary, 7 May 2024.
80 Wolf, A. (2024). Advanced materials for the green and digital age. cepInput No. 8/2024.

# 6 Conclusion

Recently, the indispensable benefits of cooperation with third countries for the EU have been pushed into the background by a public debate focusing on geopolitical risks. This also applies to the area of technological cooperation, as demonstrated by the Commission's risk-focused approach in its Economic Security Strategy. In this situation, it is all the more important to regain a pragmatic view of the benefits and risks of joint knowledge creation and knowledge sharing with third countries. This study aims to make a contribution to this. It argues that the specific and diverse forms of technology cooperation witnessed can be seen as the outcome of a trade-off between maximizing R&D productivity and maintaining control over the use of shared knowledge. Managing this trade-off requires technology-specific safeguards at both the micro (knowledge protection by firms) and macro (e.g. IPR policies) scale, and not a panic-driven refuge to protectionist instruments.

Empirically, our analysis of patenting activities in critical technology fields highlights the relevance of international research cooperation from the EU perspective. In terms of the number of patent applications, the EU does not possess a comparative technological advantage in any of the six investigated technology fields compared to the rest of the world. Foremost, its patent portfolio exhibited a much smaller focus on critical technologies than those of China and Japan. At the same time, EU patenting activity was consistently characterized by intensive cooperation with researchers from third countries. Cooperation was in all fields particularly intense with the US, in fields like advanced materials and AI technologies also increasingly with China. This has put the EU in a central position within global research networks. Moreover, EU patents resulting from international cooperations received a significantly higher average number of forward citations than those with only EU inventors on board. Their share among the top 10 % most cited patents globally was also more than proportional.

Our risk analysis emphasized the trade-offs associated with the EU's current portfolio of research partners. While the EU portfolio is more diversified and less prone to one-sided dependencies than e.g. those of Japan and South Korea, it can be considered riskier concerning the protection of intellectual property rights in its partner countries. In the current geopolitical situation, this trade-off is difficult to resolve. The aim to diversify partnerships away from established technology leaders threatens to lead the EU into the hands of countries whose lax treatment of intellectual property rights is an integral part of their technology strategy.

Against this background, we outline major elements of a future-oriented EU strategy for technology cooperation. It should involve a smart approach to diversification, maintaining close ties to the US in areas with large knowledge gaps, while simultaneously extending cooperation with other research-strong and trustworthy partners. In the critical technology fields considered, Japan and South Korea are natural candidates for this. To raise its attractiveness as a technology partner, the EU should open up its comprehensive R&D funding programs even more to partner countries, both regarding participation in financing and strategic alignment.

In the medium term, bilateral partnerships should be merged to plurilateral technology clubs, to benefit from scale advantages and maximize influence on global standards. In the process, the unilateral economic security instruments envisaged by the EU should be incorporated into a joint concept of protection against technology risks. The "mighty technology triangle" US-Japan-EU would represent a suitable prototype for such a new form of collaboration. Finally, the EU should aim to exploit potential benefits from technology partnerships beyond pure research success. They could assist in overcoming barriers to the commercialization of inventions, for instance by attracting venture capital through common funds and exchanging experience with investor-friendly tax policies. In this way, research collaboration could set the stage for the emergence of joint strategic innovation value chains.

# 7 Appendix

## Table A 1: Definition of technology fields

| Critical technology (EU definition) | Considered | Source | Abbreviation | Assigned IPC codes |
|---|---|---|---|---|
| Advanced semiconductor technologies | Yes | ATI (2021): Micro- and Nanoelectron-ics, Photonics | **Semiconductors** | B82Y 25, F21K, F21V, F21Y, G01D 5/26, G01D 5/58, G01D 15/14, G01G 23/32, G01J, G01L 1/24, G01L 3/08, G01L 11/02, G01L 23/06, G01M 11, G01P 3/36, G01P 3/38, G01P 3/68, G01P 5/26, G01Q 20/02, G01Q 30/02, G01Q 60/06, G01Q 60/18, G01R 15/22, G01R 15/24, G01R 23/17, G01R 31/26, G01R 31/27 , G01R 31/28 , G01R 31/303 , G01R 31/304,G01R 31/308, G01R 31/317, G01R 31/327, G01R 33/032, G01R 33/26, G01S 7/481, G01V 8, G02B 5, G02B 6 (excl. subclasses 1, 3, 6/36, 6/38, 6/40, 6/44, 6/46), G02B 13/14, G03B 42, G03G 21/08, G06E, G06F 3/042, G06K 9/58, G06K 9/74, G06N 3/067, G08B 13/186, G08C 19/36, G08C 23/04, G08C 23/06, G08G 1/04, G09G 3/14, G09G 3/32, G11B 7/12, G11B 7/125, G11B 7/13, G11B 7/135, G11B 11/03, G11B 11/12, G11B 11/18, G11C 11/42, G11C 13/04, G11C 19/30, H01F 10/193, H01G 9/028, H01G 9/032, H01H 47/32, H01H 57, H01J 3, H01J 5/16, H01J 29/46, H01J 29/82, H01J 29/89, H01J 31/50, H01J 37/04, H01J 37/05, H01J 49/04, H01J 49/06, H01L 31/052, H01L 31/055, H01L 31/10, H01L 33/06, H01L 33/08, H01L 33/10, H01L 33/18, H01L 51/50, H01L 51/52, H01S 3, H01S 5, H02N 6, H03B 5/32, H03C 3/22, H03F 3/04, H03F 3/06, H03F 3/08, H03F 3/10, H03F 3/12, H03F 3/14, H03F 3/16, H03F 3/183, H03F 3/21, H03F 3/343, H03F 3/387, H03F 3/55, H03K 17/72, H05B 33, H05K 1 |
| Artifical intelligence technologies | Yes | ATI (2021): Artificial intelligence | **AI** | G06F 15/18, G06F 17/20-17/28, G06F 17/30∗#, G06F 17/50∗#, G06F 19/10∗#, G06K 9, G06N∗#, G06Q 30/02∗#, G06T 7, G10L 13/027, G10L 15, G10L 17, G10L 25/63, G10L 25/66 |
| Quantum technologies | No (no meaningful assignment of IPC codes) | | | |
| Biotechnologies | Yes | Friedrichs & van Beuzekom (2018) | **Biotech** | A01H 1/00, A01H 4/00, A01K 67/00, A61K 35/12 - 768, A61K 38/00, A61K 39/00, A61K 48/00, C02F 3/34, C07G 11/00, C07G 13/00, C07G 15/00, C07K 4/00, C07K 14/00, C07K 16/00, C07K 17/00, C07K 19/00, C12M, C12N, C12P, C12Q, C40B 10/00, C40B 40/02, C40B 40/06, C40B 40/08, C40B 50/06, G01N 27/327, G01N 33/50, G01N 33/53, G01N 33/54, G01N 33/55, G01N 33/57, G01N 33/68, G01N 33/74, G01N 33/76, G01N 33/78, G01N 33/88, G01N 33/92, G06F 19/10 - 24 |
| Advanced connectivity, navigation and digital technologies | Yes (aggregate with sensing technologies) | ATI (2021): Internet of Things, IT for mobility, Security | **Connectivity** | A61B 1/00%, A61B 5/00%, A61B 5/02%, A61B 5/04%, A61B 5/05%, A61B 5/103, G01C 11, G01C 19, G01C 21, G01S, G01V 3/17%, G01V 15/00%, G05D 1/03%, G06F12/14, G06F 17/00, G06F 19/00, G06F21, G06K19, G08B 5/22%, G08B 6/00%, G08B 13/14%, G08B 13/24%, G08B 21/00%, G08B 25/10%, G08B 29/00%, G08C 17/% , G08G, G09F 3/00%, G09C, G09F 3/03%, G11C8/20, H01Q 7/00%, H01Q 9/04%, H02J 17/00%, H04B 1/48%, H04B 1/59%, H04B 5/00%, H04B 7/00%, H04B 7/08%, H04B 7/185, H04B 10/105, H04K, H04L9, H04M1/66, H04M1/67, H04M1/68, H04M1/70, H04M1/727, H04N7/167, H04N7/169, H04N7/171, H04Q 5/22%, H04Q 7/00%, H04Q 9/00%, H04W12 |
| Advanced sensing technologies | Yes (aggregate with connectivity technologies) | | | |
| Space and propulsion technologies | No (not separated by API (2021)) | | | |
| Energy technologies | Yes | Own keyword search | **Energy** | C10L 5/40 (Biofuels), C25B 1/02(Water electrolysis), F03D (Wind motors), F24S (So-lar heat collectors),<br>F25B 30/00 (Heat pumps), G21B (Fusion reactors), H01L 31/04-31/05 (PV modules), H01M (Batteries, Fuel cells) |
| Robotics and autonomous systems | No (no meaningful assignment of IPC codes) | | | |
| Advanced materials, manufacturing and recycling technologies | Yes | ATI (2021): Advanced materials | **Adv. materials** | B32B 9, B32B 15, B32B 17, B32B 18, B32B 19, B32B 25, B32B 27, B82Y 30, C01B 31, C01D 15, C01D 17, C01F 13, C01F 15, C01F 17, C03C, C04B 35, C08F, C08J 5, C08L, C22C, C23C, D21H 17, G02B 1, H01B 3, H01F 1/0, H01F 1/12, H01F 1/34, H01F 1/42, H01F 1/44, H01L 51/30, H01L 51/46, H01L 51/54 |

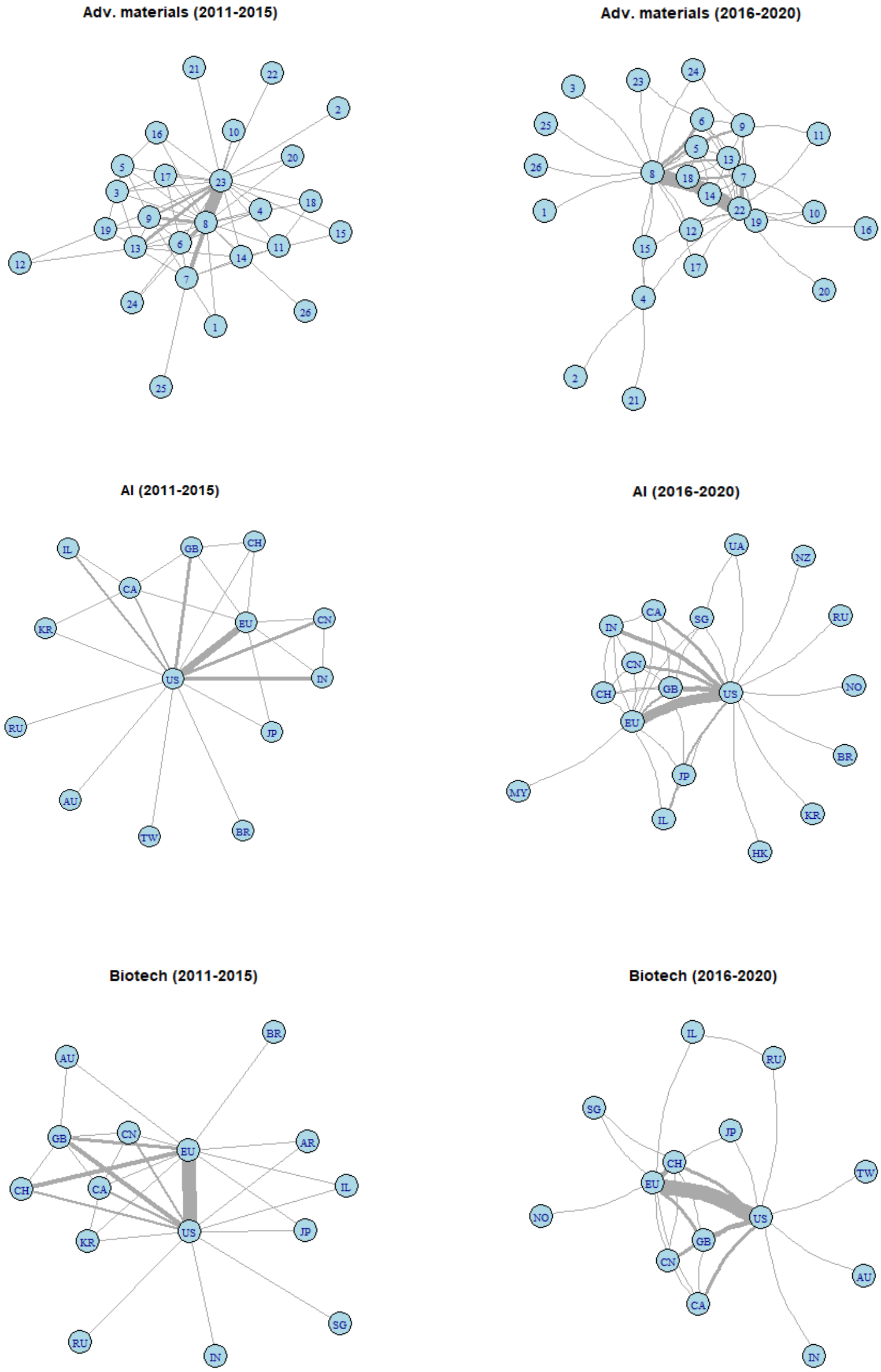
Source: own depiction

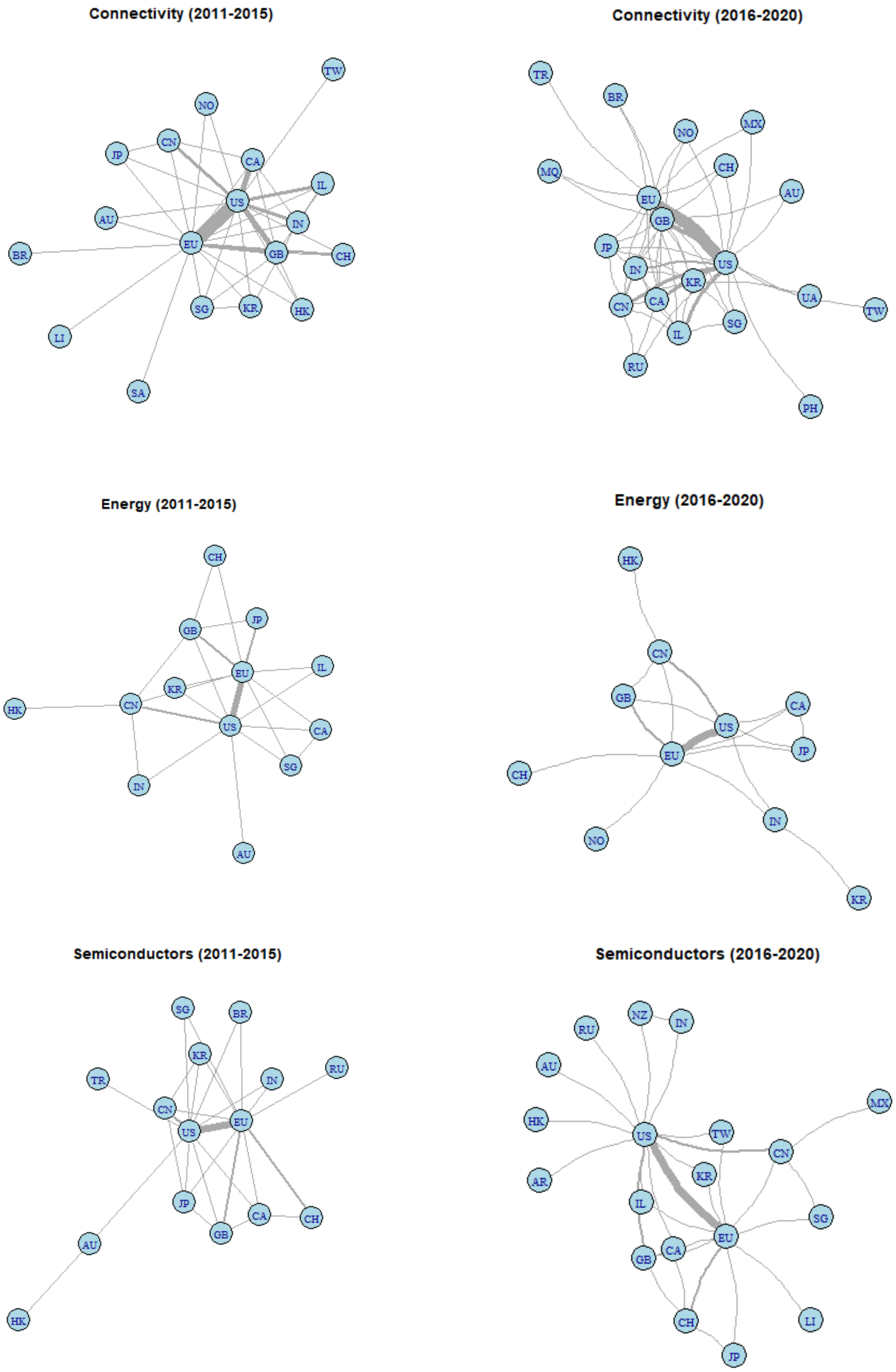
## Table A 2: Top 5 EU partners in patent cooperations by technology field

| | | Period: 2011-2015 | | Period: 2016-2020 | |
|---|---|---|---|---|---|
| **Technology field** | **Rank** | **Cooperation partner** | **Share in total EU27 cooperations** | **Cooperation partner** | **Share in total EU27 cooperations** |
| Adv. materials | 1 | US | 42.5% | US | 46.8% |
| Adv. materials | 2 | CH | 12.1% | CH | 11.3% |
| Adv. materials | 3 | GB | 10.6% | CN | 9.4% |
| Adv. materials | 4 | CN | 8.4% | GB | 7.2% |
| Adv. materials | 5 | JP | 5.5% | JP | 7.1% |
| AI technologies | 1 | US | 62.3% | US | 56.7% |
| AI technologies | 2 | GB | 13.5% | GB | 11.5% |
| AI technologies | 3 | CH | 7.4% | CH | 9.3% |
| AI technologies | 4 | IN | 5.9% | IN | 4.9% |
| AI technologies | 5 | CN | 3.9% | CA | 4.9% |
| Biotech | 1 | US | 50.7% | US | 53.5% |
| Biotech | 2 | CH | 18.1% | CH | 16.1% |
| Biotech | 3 | GB | 13.0% | GB | 13.5% |
| Biotech | 4 | CA | 4.4% | CA | 5.2% |
| Biotech | 5 | CN | 3.7% | CN | 3.8% |
| Connectivity | 1 | US | 50.5% | US | 52.0% |
| Connectivity | 2 | GB | 12.2% | GB | 10.6% |
| Connectivity | 3 | CH | 10.0% | CH | 9.0% |
| Connectivity | 4 | CA | 5.6% | CN | 5.3% |
| Connectivity | 5 | IL | 4.0% | IN | 5.1% |
| Energy | 1 | US | 42.5% | US | 46.4% |
| Energy | 2 | JP | 14.5% | GB | 12.4% |
| Energy | 3 | GB | 14.0% | JP | 10.9% |
| Energy | 4 | CH | 7.4% | CN | 8.9% |
| Energy | 5 | CA | 7.2% | CH | 8.4% |
| Semiconductors | 1 | US | 44.1% | US | 45.9% |
| Semiconductors | 2 | CH | 16.2% | CH | 16.5% |
| Semiconductors | 3 | GB | 12.3% | GB | 10.2% |
| Semiconductors | 4 | CA | 5.9% | JP | 7.6% |
| Semiconductors | 5 | CN | 5.3% | CA | 4.5% |

Source: own calculations

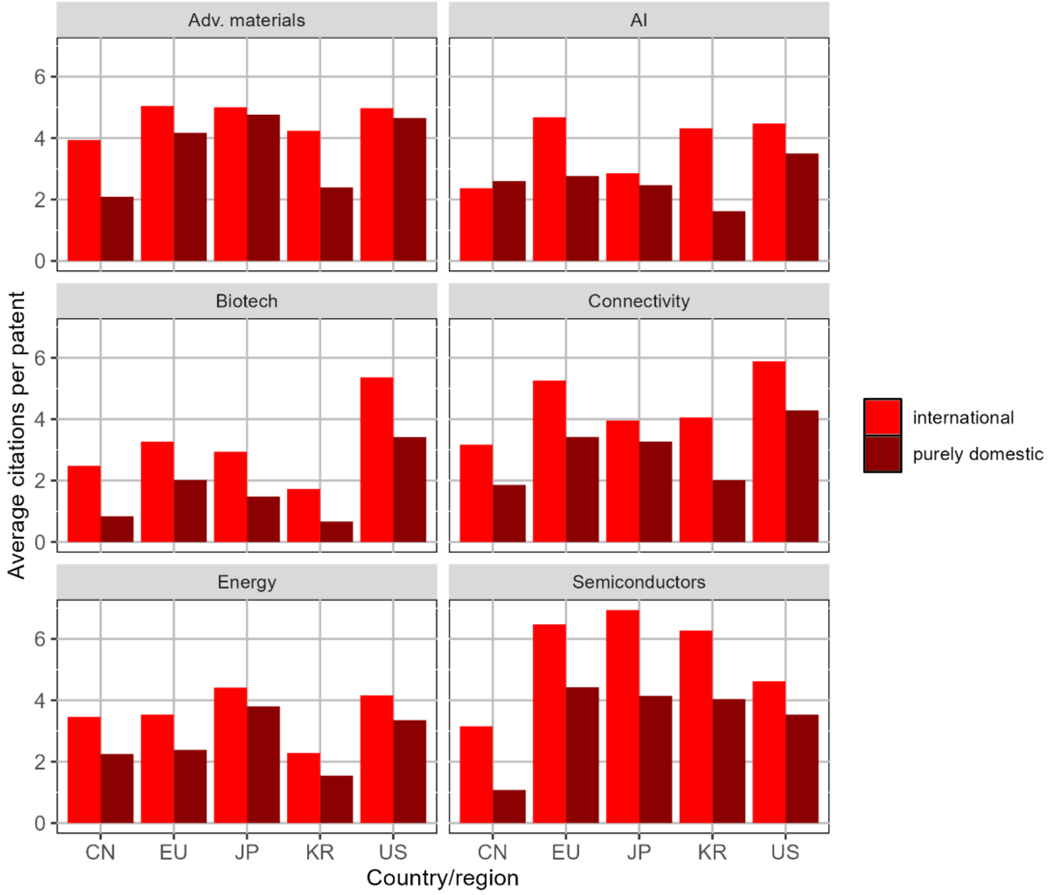
## Figure A 1: Network graphs for country cooperations by technology field





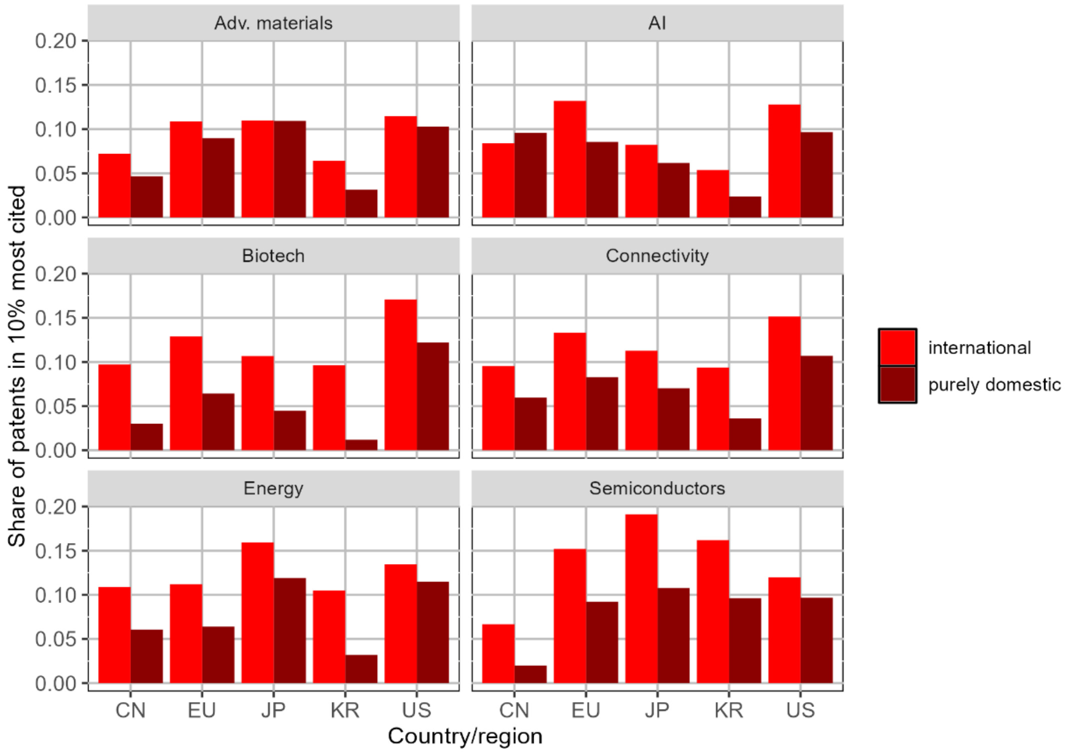

Source: own calculations. Width of edges: Number of joint patent applications.

## Figure A 2: Average numbers of patent citations by technology field and team composition




Source: own calculations

## Figure A 3: Share of patents in global 10 % most cited by technology field and team composition




Source: own calculations

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