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The global position of the EU in complex technologies

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The global position of the EU in complex technologies



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*Research and
Innovation*

The global position of the EU in complex technologies

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Working Paper

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ABSTRACT

The COVID-19 crisis has revealed severe EU dependencies in several strategic sectors, making the need to strengthen European capacities in key technological domains more urgent than ever. This paper studies the relationship between knowledge complexity and countries' technological dependency, with a focus on the EU's position vis-à-vis other major economies. Using patent data retrieved from the OECD REGPAT database, we calculate the knowledge complexity index at technological level for a set of countries over the period 1990-2020 to assess the EU's technological capabilities on the international scene. Our findings first show that the EU's overall position has progressively worsened vis-à-vis the US, China, Japan, and South Korea over the last three decades. China, on the contrary, has considerably increased its technology capabilities, including relatively to the US. Second, we find that the EU's technological base is more diversified than that of other major economies, but the EU is disproportionately more specialised in less complex technologies than its counterparts. Specifically, the US and China are leading in areas related to semiconductors, computer technologies, optics, digital communication, and audio-visual technologies. The EU shows a higher specialisation index in less complex technologies in fields such as food chemistry, climate and environmental technologies. Third, by investigating complementarity levels between all countries, we show that the EU is particularly dependent on just a few countries (including the US and China) in the most complex technologies.

1. Introduction

The COVID-19 crisis has revealed severe EU dependencies in several strategic sectors, pointing to the need to strengthen European capacities in key technological fields. The acceleration of digitalisation and the significant supply chain disruptions caused by the COVID-19 pandemic have intensified the discussions on EU technological and data sovereignty (European Commission, 2022c).

Furthermore, the changing geopolitical context has increased uncertainties linked to the global and security outlook. The rising environmental, geopolitical, economic and social instability in the world increases the likelihood of extreme events with disruptive effects, and calls for increased attention to how technological capacities are distributed across major economic players, including the EU, the US, and China (Crespi et al., 2021). As a case in point, the Russian invasion of Ukraine has highlighted important vulnerabilities and dependencies in the energy sector, confirming the need to further accelerate the EU's economic transformation (European Commission, 2022a; European Commission, 2022b; Ravet et al., 2022). This comes along with the commitment to maintaining openness, crucial for a large import and export bloc such as the EU.

As an important economic power at the global level, the EU has an interest in developing technological capacities in key areas, including 'green' and 'digital' solutions. However, the EU's capacities currently fall behind those in the US and China in many digital technologies, such as nanotechnologies, AI, and big data (European Commission, 2022b). In particular, China has remarkably increased its international leadership on digital technologies over the last decades, strengthening its position in technologies relevant to the digital era of the future.

These considerations are part of the broader discussion about how the EU can develop its technological capacities and achieve technological sovereignty (i.e. having access to critical technologies) and strategic autonomy (i.e. having the ability to act autonomously and strategically on the geopolitical scene, without putting open economy models in jeopardy). Both call for more efforts to address strategic dependencies, which need to be identified from both an industrial and technological perspective.

The lack of capacity to access technologies critical to the implementation of the EU's main policy priorities can have severe repercussions on its ability to freely compete on the global market and successfully transition towards a greener and more digital economy, while ensuring prosperity and economic growth.

Strengthening the EU's technological capabilities, either relying on "in-house" knowledge creation or cooperations with external partners, is crucial to acquire the ability to create and adapt to new knowledge, thereby being able to produce new and more advanced technologies. Nevertheless, not all knowledge outputs have the same value. Technologies, which can be relatively easily copied and replicated by many potential producers in many countries, generate lower margins in the long-run. On the contrary, more complex technologies are more difficult to acquire and, as such, confer a competitive advantage to the countries or regions in which they are located (Balland et al., 2019). It follows that more complex technologies play an important role in the technological portfolio of a country/region and help acquire a technological advantage over its competitors.

Given these considerations, this paper aims to provide new evidence on where the EU stands in its race towards technological sovereignty, using complexity metrics to assess the EU's technological performance and its position against other major economies.

In what follows, we adopt the definition of technological sovereignty proposed by Edler et al. (2020), arguing that a country's (or as in the case of the EU, a group of countries') ability to access the type of technologies critical to the achievement of its policy objectives depends on both in-house knowledge capacity, as well as on the quality and depth of a country's external relations. Using patent data from the OECD REGPAT database, we calculate the knowledge complexity index across a range of technologies and countries over the period 1990-2020 with the aim to assess the EU's technological capabilities on the international scene. Additionally, we rely on the concept of technological relatedness to map the EU's technological complementarities with other countries and identify potential dependencies.

Our analysis delivers three main findings. First, we show that, in the last decades, the EU's position has progressively worsened vis-à-vis the US, China, Japan, and South Korea in terms of knowledge capacity, whereas China has considerably increased its technology capabilities. From a policy perspective, such a result confirms that investing in R&D and in developing a stronger R&I ecosystem remains key to strengthening the EU's competitive position vis-à-vis other international innovators.

Second, looking more in detail at the characteristics of the EU's knowledge base, we find that the EU reports a higher degree of technological diversification than other major economies (e.g., US and China). The EU has a relative comparative advantage in more technologies, although such technologies are less sophisticated than those in the portfolio of other big innovators. On the contrary, US and China show a higher relative comparative advantage in technologies characterised by a higher degree of complexity (i.e., technologies that are less easy to replicate and are highly valuable), such as semiconductors, audio-visual technology, telecommunications, computer technology, and digital communication. Such sophisticated technologies are and will be the main driver of growth in the future, being thus crucial in determining countries' economic and geopolitical weight. Although the EU is building capacities in these areas, its performance is still not sufficient to reduce the gap with other major innovators. On the contrary, the EU remains strong in the area of green innovation, showing a higher specialisation index than China and the US in climate adaptation and energy technologies, and other environmental technologies.

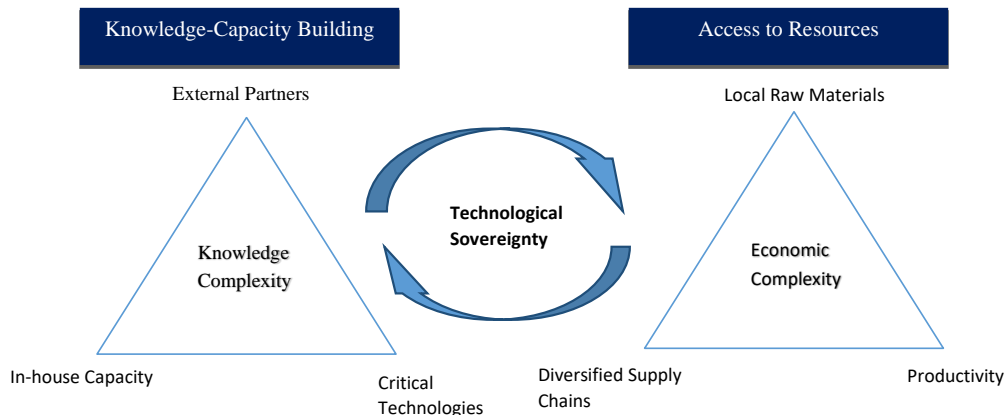
Third, we find that the EU has lower specialisation potential in more complex technologies, pointing to the risk to further widen existing dependencies with other countries, including China and the US. This is particularly true for computer technologies, audio-visual technologies, and technologies related to digital communications, optics, telecommunication and semiconductors, and to a lesser extent for biotechnologies, medical technologies and pharmaceuticals.

The remaining of this paper is structured as follows: section 2 provides an overview of the conceptual framework and literature review underpinning the study. Sections 3 and 4 present the methodology and the data used, respectively. Section 5 outlines the results from the analysis, while section 6 concludes the paper.

2. Knowledge complexity and technological dependencies

In order to investigate the presence of potential technological dependencies in the EU, we adopt the framework proposed by Edler et al. (2020), and define technological sovereignty as *“the ability of a state or federation of states to provide the technologies it deems critical for its welfare, competitiveness, and ability to act, and to be able to develop these or source them from other economic areas without one-sided structural dependency”*.

Figure 1. A framework for technological sovereignty



Source: Authors' elaboration based on Edler et al. (2020)

This notion of technological sovereignty can, thus, be summarised as revolving around two main dimensions (Figure 1):

1. **Knowledge capacity-building**, notably the ability to provide strategic technologies (either relying on a country's own knowledge capacities or by being able to access it through external partners).
2. **Access to resources**, i.e. a country's ability to input raw materials into output avoiding one-sided dependencies.

In what follows, we focus on the first dimension. Acquiring the ability to create and adapt to new knowledge, thereby being able to produce new and more advanced technologies is at the heart of the EU's strategy to increase competitiveness and sustainable economic growth. As such, understanding how knowledge is allocated spatially is key to identify what are the determinants of a successful knowledge economy.

One difficulty that naturally arises when pursuing such a task relates to data availability. The relevant academic literature has often relied on patent data and related indicators (such as patent shares and indexes of technological specialisation) to retrieve information on knowledge production. Nevertheless, a well-known weakness of this type of indicator is that they measure knowledge production activities focusing more on the number of knowledge outputs, rather than on their quality (Pintar and Schernegell, 2021). As a result, common innovation indicators implicitly assume all knowledge outputs to have the same value, de facto failing to capture differences in the quality of the knowledge produced. This is a non-trivial limitation, especially when attempting to compare knowledge production characteristics between regions and countries, whose

knowledge bases vary not only in terms of technological composition, but also in terms of value (Balland et al., 2019; Pintar and Schernegell, 2021).

Specifically, the value of a knowledge output strongly hinges on the extent to which it is easy to replicate. Technologies relatively easy to copy, replicate and move over space are typically associated with lower rents in the long-term. On the contrary, more complex technologies are characterised by a higher degree of stickiness and, as such, confer a competitive advantage to the countries/regions in which they are located (Balland et al., 2019). It follows that it would be more beneficial for a country/region to strengthen its capabilities in more complex technologies to acquire a technological advantage over its competitors. Positioning the EU against its main international counterparts in strategic technological fields, thus, requires assessing the EU's technological competencies accounting for the quality of innovation outputs, in order to identify strategic technological gaps and understand how to steer the EU policy action accordingly.

Against this background, the concepts of economic and knowledge complexity are receiving increasing attention in both the academic and policy literature. Economic complexity metrics are derived from the work of Hidalgo and Hausmann (2009), which introduced a method to investigate the complexity of individual products and countries, considering their export patterns. More in general, the intuition behind the concept of economic complexity is that modern societal challenges cannot be fully understood without considering the systemic interactions they stem from (Balland et al., 2022). In this regard, economic complexity constitutes a new analytical tool available to economists, which can overcome dimensionality problems in a different way from standard economics approaches. The latter typically consist of aggregating data, naturally leading to the loss of information. On the contrary, economic complexity methods apply dimensionality reduction techniques to identify the combination of factors able to explain how economic activities are geographically allocated, thereby allowing to preserve more information than aggregates (Hidalgo, 2021).

The notion of economic complexity has been extended to the innovation literature by Balland and Rigby (2017), to investigate knowledge capabilities in US cities. Primarily used to investigate issues related to smart specialisation and regional policies (e.g., Balland et al., 2015; Hidalgo et al., 2018; Heimeriks et al., 2019; Balland et al., 2019; Pintar and Schernegell, 2021; Balland and Boschma, 2021), knowledge complexity indicators offer an interesting tool to assess the EU's potential technological dependencies, as they provide a measure of a country/region's knowledge base that encompasses both value and quality of innovation outputs.

Close to knowledge complexity is the concept of technological relatedness. Two technologies are considered related when they rely on the same knowledge and competencies to be produced (Hidalgo et al., 2018; Balland et al., 2019). More in general, the idea of relatedness is related to the idea that the capacity of absorbing new knowledge hinges on the prior level of related knowledge held by a firm, region, or a country (Hidalgo, 2021).

The principle of relatedness has been used widely in the academic literature to investigate how regions and countries develop over time. Introducing the idea of product space, Hidalgo et al. (2007) find that countries are more likely to move through such space by developing goods and products close to those they currently produce and export. Similarly, Kogler et al. (2013) map the US technology/knowledge space over the period 1975–2005, finding that patent activities tend to increasingly cluster over time within technology classes that are close to one another in the technology space. Balland and Boschma (2021) investigate how interregional interlinkages affect technology diversification in EU regions relying on the concept of relatedness density.

As noted by Hidalgo et al. (2018), relatedness does not imply over-specialisation, but rather allows to understand what development trajectory a region or country can choose to avoid path dependencies, identifying the optimal diversification strategies to be followed to facilitate knowledge flows. As relates to the scope of this paper, the principle of relatedness can, thus, provide interesting insights to understand how a country can adjust to the lack of knowledge necessary to develop technologies critical to the attainment of specific policy priorities, and help identify complementarities with other countries, thereby giving guidance on how to manage the quality and depth of countries' external relations.

3. Methodology

Knowledge Complexity Index

Similarly to Balland and Rigby (2017), we use the eigenvector reformulation of the method of reflection developed by Hidalgo and Hausmann (2009) to derive country-level knowledge complexity indexes. The starting point is the identification of a two-mode network, represented as $c \times i$ matrix with c denoting the country, and i defining the technological class. We then rely on the concept of Relative Comparative Advantage (RCA) to identify whether a country has Revealed Technology Advantage (RTA) in a given technology. A country is considered to have an RTA in a given technology if it has an $RCA \geq 1$, with

$$RCA_{c,i} = \frac{P_{c,i} / \sum_i P_{c,i}}{\sum_c P_{c,i} / \sum_c \sum_i P_{c,i}}$$

and $P_{c,i}$ denoting the number of patents in country c and technology i . In general, a country showing an RCA with a value higher or equal to 1 has a comparative advantage in technology i , with respect to other countries.

From an operational perspective, we define as $M_{c,i}$ the 2-mode adjacency matrix, with entries equal to 1 if $RCA \geq 1$, and 0 otherwise. Following the method outlined in Hidalgo et al. (2012), we row standardise $M_{c,i}$ and its transpose ($M_{c,i}^T$). We then calculate $B = M_{c,i} * M_{c,i}^T$, a square matrix with dimension equal to the number of countries considered in the network. The country Knowledge Complexity Index (KCI) is then computed as

$$KCI = \frac{\vec{Q} - \langle \vec{Q} \rangle}{stdev(\vec{Q})}$$

with \vec{Q} being the second largest eigenvector associated to matrix B , and $\langle \vec{Q} \rangle$ denoting its mean. Similarly, the complexity index of individual technologies (TCI) is calculated considering the second largest eigenvectors of matrix $D = M_{c,i}^T * M_{c,i}$, having dimension equal to the number of technologies in the network (Balland and Rigby, 2017).

Relatedness

For the relatedness analysis, we follow Hidalgo et al. (2007), Rigby (2015) and Balland et al. (2017), and calculate the relatedness density in each country and period considered. Relatedness density ($\omega_{ci,t}$) measures the number of similar activities that are present in a location. In other words, it captures the extent to which a technology domain is close to the existing set of technologies present in a given location (this being a country, region or a city) (Balland, 2016). It is obtained from the technological relatedness (φ_{ij}) of technology i to all other technologies j in which a given country shows a specialisation index greater than 1, divided by the sum of technological relatedness of technology i to all other technologies j in a given period (Boschma et al., 2015, Balland and Boschma, 2021):

$$\omega_{ci,t} = \frac{\sum_{j \in c, j \neq i} \varphi_{ij}}{\sum_{j \neq i} \varphi_{ij}} * 100$$

Where φ_{ij} denotes the degree of relatedness of each pair of technologies i and j , in which a given country c shows relative technological advantage (Balland et al., 2017). Two technology classes i and j are considered to be related when their co-occurrences are higher than one can expect by chance (i.e. they are higher than the expected values based on probability calculus) (Boschma et al., 2015). By construction, $\omega_{ci,t}$ lies between 0 and 100: the higher the value of relatedness density, the higher is the number of technologies j related to technology i in which a given country shows revealed technological advantage.

Additionally, following Balland and Boschma (2021), we build on the concept of relatedness density to calculate an indicator of technological complementarity measuring, for each technology i a country c is not specialised in, the extent to which such a country is linked to other countries in the network that are specialised in technologies j (to which technology i is related). This indicator, referred to in the literature as relatedness density added¹, allows capturing the technological

¹ It takes four steps to measure complementarity ('relatedness density added') for a country c , a technology i and any other country s . The first step is to measure the relatedness density around technology i in all countries s . The second step is to determine for country c which technologies j are missing in country c ($RTA < 1$) to which technology i is related. The third step is to determine which countries s are specialised in these technologies j ($RTA > 1$) related to technology i that are missing in country c . The fourth step is to sum all relatedness density scores around technology i for all countries s (as defined in the first step) that have a specialisation in

capabilities that are missing in a given country, but can be accessed by strengthening external relations. At the same time, the indicator allows identifying potential technological dependencies within the network, as it measures the amount of relatedness density associated with a technology i that can be potentially added to the relatedness density of a country c by other countries, given that these countries are specialised in technologies j related to technology i that are missing in country c (Balland and Boschma, 2021).

4. Data

We use patent data retrieved from the OECD-REGPAT database² to calculate the knowledge complexity index at both the country and technology levels. The OECD-REGPAT database is based on the information available through PATSTAT, and includes patent data linked to regions (NUTS2 and NUTS3) using inventors' or applicants' addresses, around the world. In what follows, we use information on patent applications filed under the Patent Co-operation Treaty (PCT) and regionalised by inventors' address at country level (full counting). Overall, we have information about more than 4 million patent applications. As per the geographical coverage, we consider $c = 194$ countries, while the final number of technological classes included in our $c \times i$ network is 646. The technology domain of each patent application is identified using the Cooperative Patent Classification (CPC) at 4-digit level. As noted by Balland et al. (2017), the IPC classification is quite heterogeneous in size when a granular level of technology is considered. To avoid noise in the technology complexity estimation, we use the more homogeneous classification proposed by Schmoch (2008), which allows us to map the CPC codes into the 36 2-digit WIPO technology classes. The complexity index is then calculated over the periods: 1990-1995, 1996-2000, 2001-2005, 2006-2010, 2011-2015, 2016-2020. The table below reports the total number of patents by WIPO technology class, averaged over the six periods considered.

technologies j ($RTA > 1$) in which country c is not specialised (as defined in the third step). This is called relatedness density added: it measures the amount of relatedness density that can potentially be added by other countries to the relatedness density of country c in that technology i because these countries are specialised in technologies j related to technology i that are missing in country c . To make it more concrete, we can take a very simple example. Assume that technology i is related to two technologies m and n , and that there are three countries c , s and t . Country c has an RTA in technology m , country s has no RTA in both technologies m and n , and country t has an RTA in both m and n . Country s will add 0% relatedness density to country r ($0/2$), while country t will add 50% relatedness density to country r in technology i ($1/2$).

² Data update: August 2022.

Table 1. Total number of patent (full count) by WIPO technology class, by period

	1990-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2020
<i>Analysis of biological materials</i>	771	1810	3551	3763	4826	4413
<i>Audio-visual technology</i>	1454	4128	7564	8932	13120	15362
<i>Basic communication processes</i>	428	1151	1823	2131	2580	2746
<i>Basic materials chemistry</i>	2331	4703	6765	9293	12386	10663
<i>Biotechnology</i>	3068	7772	9506	9668	11369	12454
<i>Chemical engineering</i>	2122	4376	6822	8585	11432	10865
<i>Civil engineering</i>	1376	2735	4380	6577	9313	8515
<i>Climate adaptation and energy technologies</i>	1935	4700	8804	17415	24599	21488
<i>Computer technology</i>	1319	5377	10215	13940	25616	32049
<i>Control</i>	886	2312	3729	4466	7634	10317
<i>Digital communication</i>	817	5278	10317	16672	25112	27318
<i>Electrical machinery, apparatus, energy</i>	1870	4890	8666	14617	22611	22508
<i>Engines, pumps, turbines</i>	1070	2265	3905	6598	9536	6978
<i>Environmental technology</i>	898	1712	2753	4280	5461	4910
<i>Food chemistry</i>	599	1291	2279	2879	3523	3669
<i>Furniture, games</i>	1041	2144	3611	4389	5594	6091
<i>Handling</i>	1429	2761	4236	5469	7558	8476
<i>IT methods for management</i>	185	2262	3428	4296	6698	8115
<i>Machine tools</i>	1210	2273	3468	4658	6337	6043
<i>Macromolecular chemistry, polymers</i>	1525	3491	5196	6892	9204	8900
<i>Materials, metallurgy</i>	1181	2501	4196	5898	8066	7768
<i>Measurement</i>	2549	6239	11059	14021	19695	21332
<i>Mechanical elements</i>	1362	2752	4638	6818	10130	9044
<i>Medical technology</i>	2810	6437	11351	14991	19546	21029
<i>Micro-structural and nano-technology</i>	179	734	2206	2439	1752	1396
<i>Optics</i>	1147	2992	5642	7169	11237	12220
<i>Organic fine chemistry</i>	3260	6911	10461	11265	11812	10360
<i>Other consumer goods</i>	967	2089	3618	4779	6718	7747
<i>Other special machines</i>	1992	4411	6557	8362	11794	12739
<i>Pharmaceuticals</i>	4105	10306	15789	16301	15478	16233
<i>Semiconductors</i>	611	2476	5511	8723	11180	11368
<i>Surface technology, coating</i>	1015	2434	4287	5637	8689	7959
<i>Telecommunications</i>	1220	4882	7087	9492	12942	14055
<i>Textile and paper machines</i>	1224	2472	3519	3701	4410	4388
<i>Thermal processes and apparatus</i>	634	1276	2364	4125	5449	5460
<i>Transport</i>	1495	3538	6045	8832	13987	15793

Note: Patents are allocated to the different technology classes using information on patent applications (full count) regionalized by inventors' address at country level, and the mapping proposed by Schmoch (2008). The additional class "Climate adaptation and energy technologies" is built considering technologies under the codes Y02 and Y04S of the CPC patent classification.

Source: Authors' calculations based on OECD-REGPAT database, updated in August 2022.

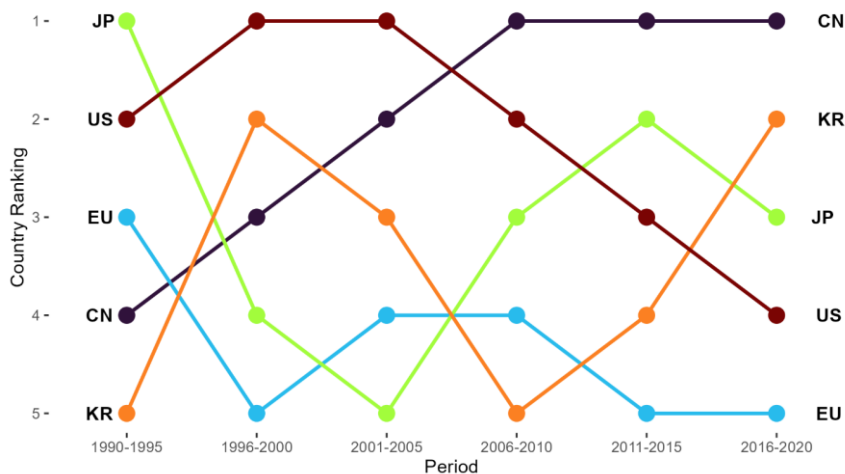
5. Results and Discussion

This section reports the results from the complexity and relatedness analyses, following the approaches described in Section 3.

We first investigate the relative position of the EU looking at how the complexity of its knowledge base has evolved over time vis-à-vis other major international innovators (Figure 2). At country level, a high KCI indicates that a country tends to develop a number of technologies that can only be replicated in a small number of other countries. During the 90s', the EU ranked third behind the US and Japan (in the lead), while outperforming South Korea and China. The latter started improving considerably its performance over time, and was able to overcome the US mid-2000s. Since then, it remained steadily at the top of the ranking, while the relative position of the EU kept deteriorating, ranking last over the period 2016-2020.

These results suggest that the gap between the EU and other major international innovators is significant³, and confirm the need for strengthening the EU's knowledge capacities in order to compete with other main international economies. Quite striking is the performance reported by China, which was able to increase the quality of its innovation base at a faster pace in the last decades, mostly at the expense of the US.

Figure 2. Evolution of KCI overtime – EU vs the US, China, South Korea and Japan

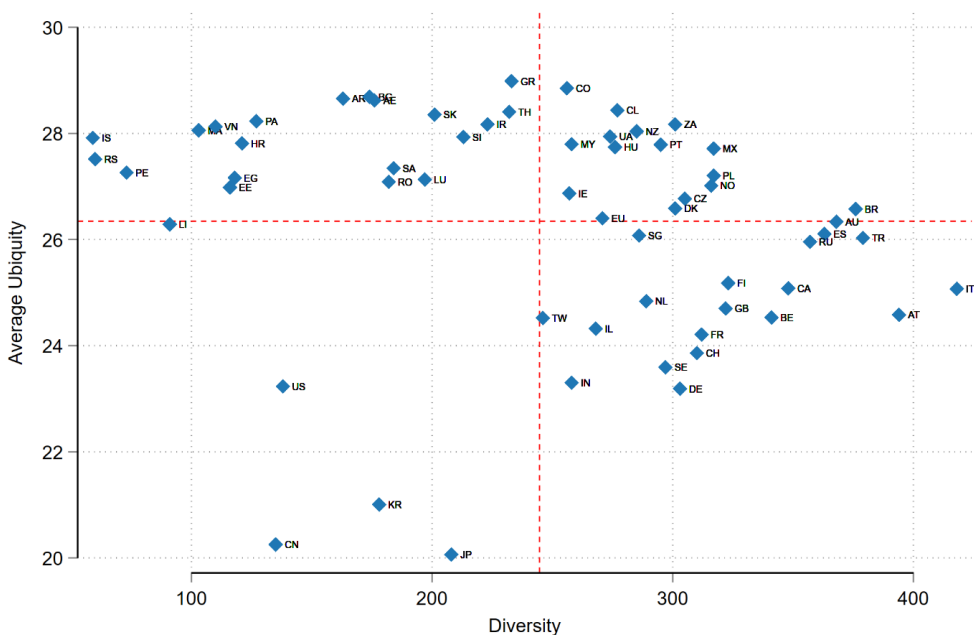


Note: The KCI at country level has been calculated following the methodology described in section 3.1, including the EU as a whole in the country-tech network, while excluding the EU Member States.

³ This is in line with other analyses carried out using more traditional indicators to capture scientific and technological performances, such as total share of patent applications and scientific publications, which point to a progressive increase in the innovation performance of the EU's competitors in recent years (European Commission, 2022c).

Following Balland and Rigby (2017), we then analyse more in details the features of the EU’s knowledge base, looking at the relationship between technology diversity and technology average ubiquity. The notion of technological diversity provides information on how many different technological specialisations are in the basket of each country. In other words, the higher the value of diversity, the higher is the number of technology fields a country is specialised in (i.e., the country has an $RCA_{i,t} \geq 1$ in that technology domain). Ubiquity captures instead the rareness of a given technology, informing on how many countries show an $RCA_{i,t} \geq 1$ in a given technology domain. The lower the average ubiquity value is for a given country, the more the country is specialised in technologies that are more rare. Figure 3 displays the diversity and average ubiquity of our country-technology knowledge network.

Figure 3. Diversity and Average Ubiquity, 2016-2020



Note: The vertical line and the horizontal line denote the mean of diversity and the mean of the average ubiquity, respectively. Data for the EU are calculated as the arithmetic average of EU Member States. Ubiquity and diversity have been calculated considering the CPC 4-digit technology classification, and removing countries with less than 50 patents per year from the sample.

China is located in the bottom-left quadrant, showing the lowest degrees of diversification (low diversity) and ubiquity in the network. This result is in line with the innovation and industrial strategies launched by China in 2015: “Made in China 2025”. Overarching objective of the Chinese action was to break through the ceiling of low-tech and labour-intensive manufacturing by targeting specific core industries, such as robotics and next generation IT (MERICS, 2019). In doing so, China has concentrated its efforts on sectors crucial to the fourth industrial

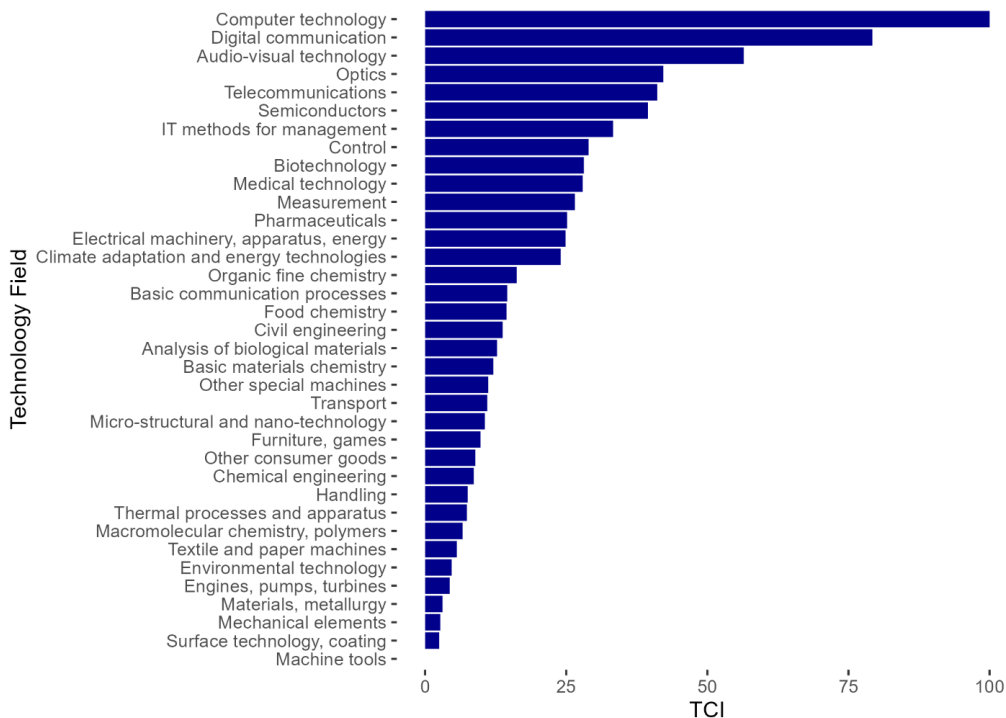
revolution, including smart manufacturing, digitalisation and emerging technologies, with the clear intent of leapfrogging foreign competitors and assuming a leading position in areas where important technology gaps have emerged (MERICS, 2019). Other important EU's competitors such as South Korea, the US and Japan are located in the same quadrant, being also characterised by a low level of both diversification and average ubiquity, although higher than China. Such a result signals their overall ability to specialise in technologies that remain relatively rarer than those in the portfolio of other countries. In the bottom-right quadrant (low ubiquity and high diversity) we find some European countries, e.g. Germany, France, Belgium, Finland, Netherlands, and Sweden, which specialise in a higher number of technology fields than China, the US, Japan and South Korea, but in more common technologies, although still relatively rarer than those in the average portfolio of the countries in the network. The top-left quadrant includes countries characterised by a low degree of diversity, but that produce technologies that are easier to replicate. Here, we find some European countries, such as Romania, Slovenia, Luxembourg and Greece. The EU and the remaining EU Member States are found in the top-right quadrant, showing higher degree of technological diversification, but in more common technologies than other countries.

On the technology side, more complex technologies are generally characterised by a low ubiquity value, but not necessarily the lowest, as the technology complexity index does not simply reflect a linear combination between a country's diversity level and the ubiquity of a given technology, but rather it also captures their arrangements within the defined network. It follows that a technology with a specific ubiquity level found only in countries specialised in other less ubiquitous technologies will be associated with a higher TCI than a technology with the same ubiquity level, but found in countries specialised in technologies relatively more common (Balland and Rigby, 2017).⁴

Figure 4 shows the TCI associated with each of the 36 technology domains considered in the analysis, ranked by complexity level. The TCI has also been normalised between 0 and 100 to ease the interpretation of the results. Overall, the technologies associated with the highest TCI values are those in the fields of computer technologies, digital communication, audio-visual technologies, optics, telecommunications, and semiconductors. Technologies related to IT methods for management, control, biotechnology, medical technology, and pharmaceuticals follow, being found in the upper part of the ranking. Basic communication technologies, technologies related to climate adaptation and energy, organic fine chemistry and food chemistry are found in the middle of the ranking. In lower positions, we find environmental technologies, and technologies in the field of engines, pumps and turbines, mechanical elements, surface technology, and machine tools.

⁴ Similarly, notwithstanding the low diversity level, a country specialised in more complex technologies will receive a higher KCI than a country with a lower diversity level but specialised in less complex technologies (Balland and Rigby, 2017).

Figure 4. Technology Complexity Index (TCI), 2016-2020

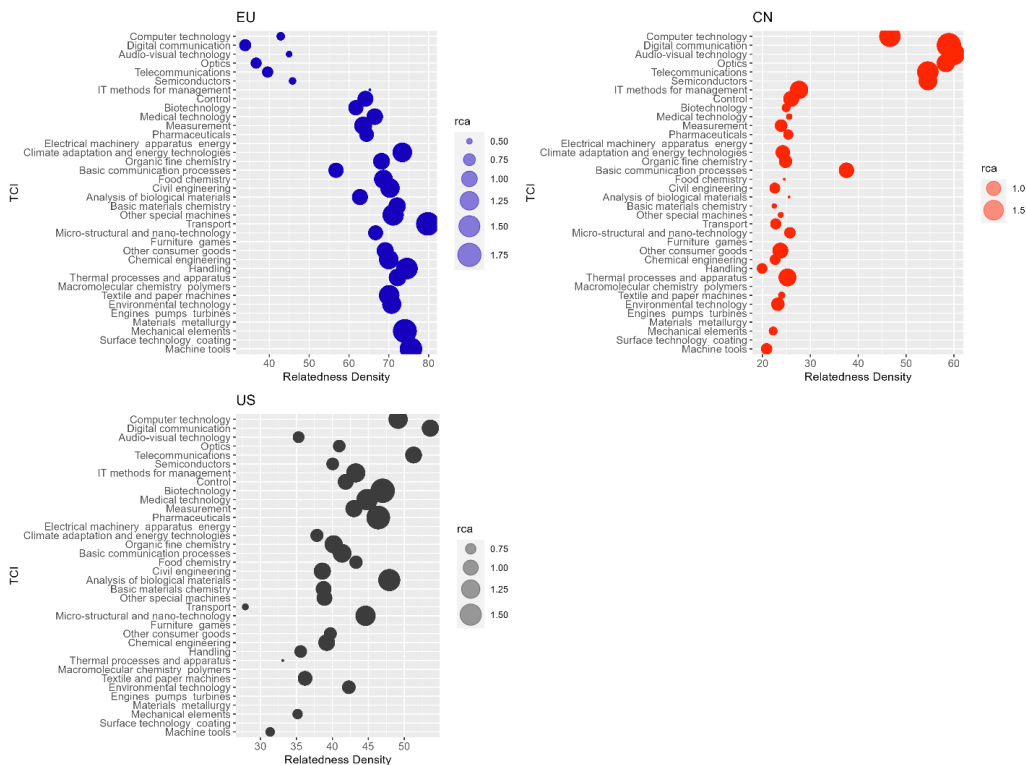


Note: The TCI is calculated by mapping the 648 technologies considered in the analysis into the 35 2-digit WIPO technology (following Schmoch, 2008), plus the class “Climate adaptation and energy technologies”, which is built considering technologies under the codes Y02 and Y04S of the CPC patent classification.

As already discussed in the previous sections, more complex technologies typically provide countries with a higher competitive advantage than less sophisticated ones. To assess where the EU stands in its quest towards technology sovereignty, it is, thus, interesting to look at how the Union performs in those technologies associated with higher values of technological complexity, as well as at how easy it is for the EU to move from one technological domain to another, based on the way different technologies are connected to each other. To do so, we rely on the notions of revealed comparative advantage and relatedness density.

Figure 5 plots the relationship between relatedness density and the degree of technology complexity for the EU, the US and China, accounting for the magnitude of the specialisation index that each country reports in each technology. This allows us to compare the performance of the three innovators on multiple levels.

Figure 5. The EU positioning in complex technologies vs US and CN, 2016-2020



Note. The x-axis indicates the relatedness density of each country in any of the technology fields considered. On the y-axis technologies are ranked by complexity levels, normalised between 0 and 100. The size of the bubble captures the degree of specialisation that each country reports in a given technology field, as measured by the RCA. The RCA for the EU is calculated considering data for all Member States and using the formula $RCA_{c,i} = \frac{P_{c,i} / \sum_i P_{c,i}}{\sum_c P_{c,i} / \sum_c \sum_i P_{c,i}}$.

First, looking at the size of the bubbles in the three plots, we observe that the EU shows a relative comparative advantage higher than the US and China only in technologies characterised by a relatively lower TCI value. On the contrary, the EU lags significantly behind both countries in more complex technology fields (e.g., computer technologies, digital communication, audio-visual technologies, optics, telecommunications, and semiconductors). Nevertheless, our findings confirm that the EU remains leader in the green area, outperforming both China and the US in areas related to climate adaptation and energy technologies, and environmental technologies. Additionally, the EU is strong also in food chemistry, and reports a level of specialisation higher than China in fields related to analysis of biological materials, micro- and nano-technologies, and medical tech, although remaining well below the US.

Concerning the relationship between relatedness density and TCI, our results suggest that the higher the complexity degree associated with a given technology, the weaker the EU's position to lead technological change in those areas,

compared to the US and China. The opposite trend is observed for both the US and China, which report higher relatedness density as the degree of technological complexity increases. As discussed in section 3, relatedness density allows to measure the extent to which a country's existing core capabilities are related to the capabilities necessary to specialise in technologies in which the country does not have a revealed technology advantage (Balland and Boschma, 2021). As such, our finding highlights that the EU struggles in accessing the knowledge necessary to specialise and gain a competitive advantage in technologies able to significantly add to the overall value of the EU's knowledge assets (namely, more complex technology). As such, the risk for the EU to remain technologically dependent on other global players is particularly high in sophisticated technological domains, which are strategic to the attainment of the EU's policy objectives.

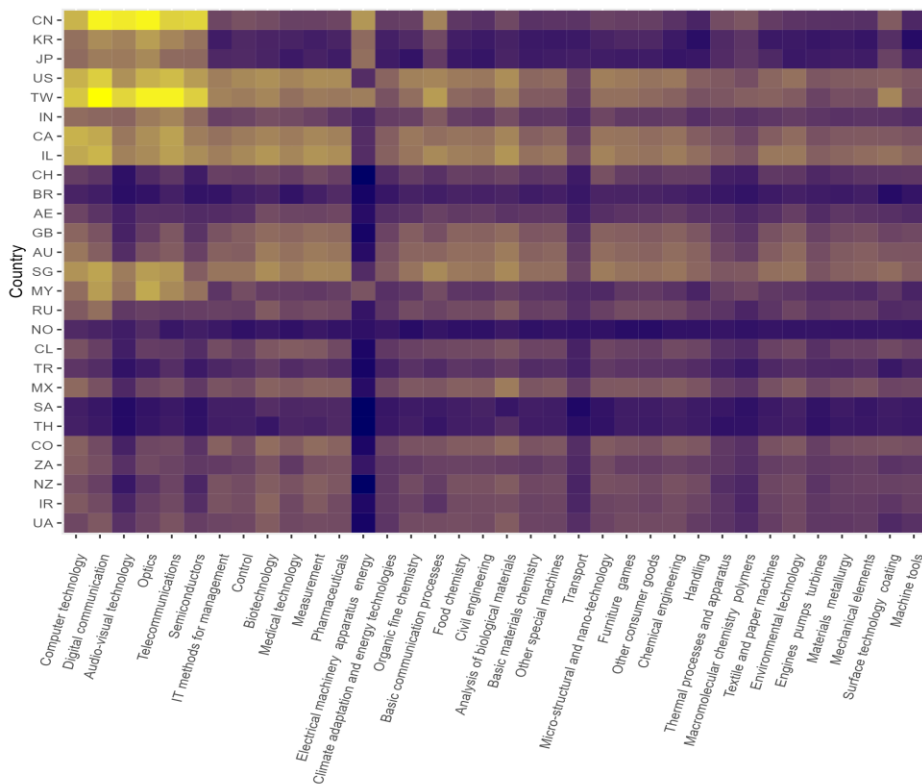
Strengthening the EU's technological capabilities in technologies related to semiconductors, optics, computer technologies and digital communications is crucial to the success of the green and digital transitions. As noted by European Commission (2023), the EU's priorities of the European Green Deal and 'a Europe fit for the digital age' are closely intertwined and have the potential to mutually reinvigorate each other, as the twin transition builds upon the interlinkages between an innovation ecosystem of green technologies (e.g., solar energy, wind turbines and nuclear energy) and an ecosystem of digital technologies (including, artificial intelligence, cybersecurity or the internet of things). The decarbonisation of the EU economy, thus, needs to leverage on the availability of digital technologies to speed up the transition. At the same time, it is essential that the digitalisation process is undertaken sustainably, promoting digital innovations able to account for the environmental footprint of digital technologies to ensure full synergies and complementarity between EU priorities (European Commission, 2023). In this regard, the EU has important strengths to leverage on. In the latest years, the EU has increased its scientific performance in the fields of advanced materials, industrial biotechnologies and nanotechnologies, and its patent application activities has increased in areas related to robotics and drones. Nevertheless, the EU's technological sovereignty remains at risk in other important fields, including AI, big data, cloud computing, cybersecurity, and micro-electronics (European Commission, 2022c).

To remain competitive in the global market, the EU needs therefore to strengthen its innovation ecosystems. This can be achieved either by improving its own technological capabilities and prioritising resources towards the development of critical technologies it is currently lacking, or by relying upon external partners to compensate the EU's technological weaknesses.

To assess what potential partners the EU can consider to access missing technological capabilities, we rely on the notion of relatedness density added, which captures the relevant capabilities associated with a given technology that are missing in the EU, but that can be complemented by the capabilities of another country. As such, this measure also provides an indication of potential technology dependencies the EU may be subject to.

Figure 6 maps the EU's technological complementarities over the period 2016-2020. In line with the results reported in Figure 5, a significantly high degree of potential technology dependency is observed in technologies associated with the highest degree of complexity (i.e., computer technologies, digital communication, audio-visual technologies, optics, telecommunications, and semiconductors). The countries showing the highest degree of complementarity (above 40%) in these fields (i.e., reporting the highest share of EU's missing capabilities related to these technologies) are China, the US, and Taiwan. A lower degree of complementarity (between 30% and 40%) is observed for South Korea, Japan, Singapore, Canada, Israel and, to some extent, Malesia. Biotechnology, medical tech and pharmaceutical are other areas in which potential technological dependency (around 30%) may arise between the EU and other countries, notably the US, Taiwan, Canada and Israel. On the contrary, a lower degree of technological complementarity is observed in the other technology classes, especially in those in which the EU reports a higher level of specialisation.

Figure 6. EU's Technological complementarities (relatedness density added), 2016-2020



Note: On the x-axis, technologies are order from left to right by decreasing the degree of technology complexity (TCI index). On the y-axis, countries are ordered from top to bottom by decreasing degree of knowledge complexity (KCI index). In calculating the relatedness density added, EU Member States have been excluded from the computation, including the EU as a whole.

6. Conclusions

This paper aims to contribute to the broad discussion on the EU's quest for technological sovereignty, assessing the EU's ability to produce new and more advanced technologies to address the societal challenges it is facing. In doing so, we rely on complexity metrics to investigate the EU's technological performance in comparison to other major innovators.

The starting point of our analysis is the consideration that technologies are not all equal. More complex technologies are associated with higher competitive advantage in the long term: they have the potential to generate more growth and strengthen a country's competitiveness (Pintar and Scherngell, 2021). Countries that specialise in more complex technologies are typically endowed with better quality knowledge ecosystems. When looking at how the quality of the EU's knowledge base has evolved over time, we find that the EU's international counterparts have improved their position faster than the EU over the period 1990-2020. This is particularly the case for China. Additionally, when examining the technological portfolio of the EU, we find the European knowledge base to be more diversified than that of other global innovators, such as the US and China, while these two countries specialise in more sophisticated (and thus more valuable) technologies. Our findings confirm that the EU's performance is weaker in the digital domain, which is typically characterised by technologies associated with higher degree of complexity. On the other hand, it remains strong in technologies related to the green transition.

Additionally, relying on relatedness density metrics, we find the EU to be characterised by lower specialisation potential in more complex technologies, and identify the countries showing high technological complementarities with the EU in these fields. These include, in particular, computer technologies, and audio-visual technologies, as well as technologies related to digital communications, optics, telecommunications, and semiconductors, in which countries including China, Taiwan, and the US have capabilities currently missing in the EU.

From a policy perspective, there are several aspects European countries could focus on. A better knowledge and innovation ecosystem requires an innovation policy able to target, prioritise, and provide financial support to the type of technologies having the highest growth potential and, at the same time, facilitating the attainment of the EU's policy priorities. This also brings the role of frontier research at centre stage to support the development of complex technologies.

International cooperation and research collaborations also remain key. The results of our analysis on technological complementarities and potential dependencies provide useful information to assess the EU's diversification options. Achieving technological sovereignty is compatible with a multilateral approach. It is also important to consider the welfare gains stemming from an open and fair international division of labour. In response to the current global trends, the EU can use its international relationships to promote the EU's interests and values, defining areas of mutual interest as well as division of knowledge with key

partners. Research and innovation activities have become increasingly internationalised, and the EU needs to balance the benefits of research collaborations with the risks related to foreign interference. Our findings confirm that without reinforcing the role of the EU as a leading actor to foster international R&I cooperation, current technological dependencies will more likely put the EU's technology sovereignty in jeopardy. Therefore, cooperation is to be seen as an important instrument for promoting a global level playing field, ensuring technology standards and safeguarding the EU's fundamental values.

7. References

Balland, P. A. (2016), 'Relatedness and the geography of innovation', In *Handbook on the Geographies of Innovation*, pp. 127-141, Edward Elgar Publishing.

Balland, P. A., & Boschma, R. (2021), 'Complementary interregional linkages and Smart Specialisation: An empirical study on European regions', *Regional Studies*, 55(6), 1059-1070.

Balland, P. A., & Boschma, R. (2022), 'Do scientific capabilities in specific domains matter for technological diversification in European regions?', *Research Policy*, 51(10), 104594.

Balland, P. A., & Rigby, D. (2017), 'The geography of complex knowledge', *Economic Geography*, 93(1), 1-23.

Balland, P. A., Boschma, R., Crespo, J., & Rigby, D. L. (2019), 'Smart specialization policy in the European Union: relatedness, knowledge complexity and regional diversification', *Regional studies*, 53(9), 1252-1268.

Balland, P. A., Broekel, T., Diodato, D., Giuliani, E., Hausmann, R., O' Clery, N., & Rigby, D. (2022), 'The new paradigm of economic complexity', *Research Policy*, 51(3), 104450.

Balland, P. A., Rigby, D., & Boschma, R. (2015), 'The technological resilience of US cities. Cambridge Journal of Regions', *Economy and Society*, 8(2), 167-184.

Balland, P.A. (2017), Economic Geography in R: Introduction to the EconGeo Package, *Papers in Evolutionary Economic Geography*, 17 (09): 1-75

Boschma, R., Balland, P. A., & Kogler, D. F. (2015), 'Relatedness and technological change in cities: the rise and fall of technological knowledge in US metropolitan areas from 1981 to 2010', *Industrial and corporate change*, 24(1), 223-250.

Crespi, F., Caravella, S., Menghini, M., & Salvatori, C. (2021), 'European Technological Sovereignty: An emerging framework for policy strategy', *Intereconomics*, 56(6), 348-354.

Edler, J., Blind, K., & Frietsch, R. (2020), *Technological Sovereignty: From Demand to Concept*, <https://www.isi.fraunhofer.de/en/presse/2020/presseinfo-11-Technologiesouveraenitaet.html>.

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.

European Commission (2022a), Towards a green, digital and resilient economy: our European Growth Model, COM(2022) 83 final.

European Commission (2022b), Commission Notice - Guidance on Recovery and Resilience Plans in the context of REPowerEU.

European Commission (2022c), Science, Research and Innovation performance of the EU, 2022 (SRIP), Publications Office of the European Union. <https://data.europa.eu/doi/10.2777/38888>

European Commission (2022d), ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries, Publications Office of the European Union. <https://data.europa.eu/doi/10.2777/92567>

European Commission (2023), Stres, Š., Gołębiowska-Tataj, D., Walz, R. et al., Research and innovation to thrive in the poly-crisis age, Directorate-General for Research and Innovation, Publications Office of the European Union, <https://data.europa.eu/doi/10.2777/92915>

European Council (2020), Council Conclusions on the EU's economic and financial strategic autonomy: one year after the Commission's Communication.

European Innovation Council (2022), Work Programme 2022.

Glaeser, E. L., Kallal, H. D., Scheinkman, J. A., & Shleifer, A. (1992), 'Growth in cities', *Journal of political economy*, 100(6), 1126-1152.

Heimeriks, G., Li, D., Lamers, W., Meijer, I., & Yegros, A. (2019), 'Scientific knowledge production in European regions: patterns of growth, diversity and complexity', *European Planning Studies*, 27(11), 2123-2143.

Hidalgo, C. A. (2021), 'Economic complexity theory and applications', *Nature Reviews Physics*, 3(2), 92-113.

Hidalgo, C. A., & Hausmann, R. (2009), 'The building blocks of economic complexity', *Proceedings of the national academy of sciences*, 106(26), 10570-10575.

Hidalgo, C. A., Balland, P. A., Boschma, R., Delgado, M., Feldman, M., Frenken, K., ... & Zhu, S. (2018), 'The principle of relatedness', In *International conference on complex systems*, pp. 451-457, Springer, Cham.

Hidalgo, C. A., Klingler, B., Barabási, A. L., & Hausmann, R. (2007), 'The product space conditions the development of nations', *Science*, 317(5837), 482-487.

Kogler, D. F., Rigby, D. L., & Tucker, I. (2013), 'Mapping knowledge space and technological relatedness in US cities', *European Planning Studies*, 21(9), 1374-1391.

March, C., & Schieferdecker, I. (2021), *Technological Sovereignty as Ability, Not Autarky*.

MERICS (2019), *Evolving Made in China 2025. China's industrial policy in the quest for global tech leadership*.

OECD (2020), *Shocks, risks and global value chains: insights from the OECD METRO model*, <https://www.oecd.org/trade/documents/shocksrisks-gvc-insights-oecd-metro-model.pdf>

Pintar, N., & Scherngell, T. (2021), 'The complex nature of regional knowledge production: Evidence on European regions', *Research Policy*, 104170.

Ravet, J., Di Girolamo, V., Mitra, A., Peiffer-Smadja O, Canton E, Hobza A. (2022), *EU research and innovation and the invasion of Ukraine : main channels of impact*, European Commission, Directorate-General for Research and Innovation, <https://data.europa.eu/doi/10.2777/54321>

Rigby, D. L. (2015), 'Technological relatedness and knowledge space: Entry and exit of US cities from patent classes', *Regional Studies*, 49(11), 1922-1937.

Schmoch, U. (2008), *Concept of a technology classification for country comparisons. Final report to the world intellectual property organisation (WIPO)*, WIPO.

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The COVID-19 crisis has revealed severe EU dependencies in several strategic sectors, making the need to strengthen European capacities in key technological domains more urgent than ever. This paper studies the relationship between knowledge complexity and countries' technological dependency, with a focus on the EU's position vis-à-vis other major economies. Using patent data, we calculate the knowledge complexity index at technological level for a set of countries over the period 1990-2020. Our findings first show that the EU's overall position has progressively worsened vis-à-vis US, China, Japan, and South Korea over the last three decades. Second, we find that the EU's technological base is more diversified than that of other major economies, but the EU is disproportionately more specialised in less complex technologies than its counterparts. The EU shows a higher specialisation index in less complex technologies in fields such as food chemistry, climate and environmental technologies. Third, by investigating complementarity levels between all countries, we show that the EU is particularly dependent on just a few countries (including the US and China) in the most complex technologies.

Studies and reports

