3 Benchmarking German innovation performance

This chapter describes the key characteristics of the German innovation system in international comparison. It shows how Germany performs with regard to key indicators of innovation performance. The data presented in the chapter show Germany is an innovative global leader in a number of technologies and industries. However, some caveats exist, such as decreasing returns on business research and development spending, and persistently low investment in both intangible capital and information and communication technology.

Introduction

Measuring the innovative performance of an economy involves considering a large number of data and indicators, many of which act as proxies for the innovative output of the country's firms and research base. The purpose of this exercise is to place Germany in relation to international peers.

As discussed in Chapter 1, Germany has a well-resourced and established science, technology and innovation (STI) system. Benchmarking the output of this system in an international context clearly demonstrates that Germany has one of the most innovatively productive and powerful economies in the world. In terms of patenting, trademarking and scientific publications, Germany features among the leading global economies, both in terms of established areas of technological expertise (such as engineering) and in many other disciplines that are important to the environmental sustainability and digital transitions.

The innovative output of the German STI system is driven by consistently high levels of capital stock and investment, where Germany is positioned by far as the leading economy in Europe and among the most significant globally. At the same time, investment in intangible capital and information and communication technology (ICT) is relatively low, with a potentially negative impact on firms' ability to capitalise on new opportunities for innovation in the twin transitions.

This chapter is structured in two parts. Section 3.1 introduces Germany's innovation performance at a macro level, looking at key indicators of performance – inputs, intermediate indicators and outputs – at an economy-wide level. Section 3.2 then examines the sectoral, regional and social dimensions of German innovation performance.

3.1. Germany's innovation performance

This section introduces key evidence on the performance of Germany's innovation system, using standard input, intermediary output and output measures (Box.3.1).

Box.3.1. Measuring innovation: Input, intermediate indicators and output

The OECD Oslo Manual defines innovation as "a new or improved product or process (or combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)" (OECD, 2018[1]). That being said, assessing innovation capacities and the performance of the innovation system internationally is not straightforward. Several standard indicators are traditionally used to compare and track trends over time. All the indicators for STI have both strengths and shortcomings when it comes to measuring innovation itself and in cross-country comparisons. Consequently, the current discussion presents three types of such indicators, together with the relevant contextualisation.

1. **Indicators of innovation inputs**

Indicators of innovation input measure how much the STI ecosystem has spent to generate innovations. The main downside of this group of measures is that those inputs may not necessarily turn into successful innovations.

Measures such as gross fixed capital formation and research and development (R&D) expenditure can give an indication of the resources available to current or potential actors undertaking innovation activities. One advantage is that the Frascati Manual provides international standards for gathering these data for comparison.

At the same, R&D may not capture all investment that is relevant to innovation. This has led to efforts to gather information on intangible investments, defined broadly as investments in computerised information (databases and software), acquisition of innovative property (such as scientific and non-scientific R&D, copyrights, designs and trademarks), and economic competencies (such as brand equity, firm-specific human capital, networks, organisational know-how and marketing) (OECD, 2011[2]). An increasing body of literature indicates that intangible investments are also an important determinant of both innovative capacity and productivity, since firms with higher intangible investments are more likely to have higher productivity than those that do not (Criscuolo et al., 2021[3]; Haskel and Westlake, 2018[4]; Kaus, Slavtchev and Zimmermann, 2020[5]). Investment in intangibles is an important tool for ensuring that both the public and private sectors can adopt and apply digital technologies to support innovation.

Indicators on research personnel provide a further measure of the human-resource effort in innovation and are also gathered internationally.

2. Indicators of intermediary outputs

Patents and publications are intermediary indicators, insofar as they are pre-commercial discoveries of innovation processes and investments Only a small share will result in successful innovations.

Patent data have the merit that some metrics – notably comparing Patent Cooperation Treaty (PCT) applications[1] and applications to the world's five largest patent offices (IP5), namely the European Patent Office (EPO), Japan Patent Office (JPO), United States Patent and Trademark Office (USPTO), Korean Intellectual Property Office (KIPO) and China National Intellectual Property Administration (CNIPA) – allow international comparisons. IP5 patents are protected in at least two intellectual property offices worldwide, one of which must be a member of IP5.

There are additional caveats to patents: although patent data are widely used, they are known to be relevant in some sectors of the economy – such as pharmaceuticals, chemistry and machinery – but not all. Notably, they play a less important role in the digital economy, where software, artificial intelligence and service innovations are more preponderant. Because of their stronger relevance to manufacturing, patents favour countries that more active in those sectors and will probably shed a more favourable light on the German economy.

Academic publications are another intermediary indicator of innovation performance. They are often used as a measurement of research performance – especially in the natural and applied sciences, where they are an important means of disseminating new knowledge. Academic publications generally fall into three categories: journal articles, which are published to disseminate new knowledge; review articles, which aggregate and summarise research findings published in a given field; and conference papers, which summarise the findings of presentations at conferences. This indicator is also useful because of its metadata, with publications providing a range of details on their authors and institutions that allow researchers to develop insights into collaboration and other indicators (such as patents) linked to these actors (European Commission, 2021[6]).

3. Indicators of innovation output and quality

Innovation output data have been gathered through innovation surveys that ask firms to indicate whether they introduced an innovation, and its degree of novelty (OECD, 2018[1]). While these indicators are the most direct measure of innovation, they have proven more challenging to use in international comparisons, owing to the different criteria applied by the surveyed firms.

A useful indirect measure of innovation output are trademarks. Rather than capture innovations directly, trademarks reflect the first step in their commercialisation. A firm or actor that commercialises a trademark implicitly places a value on the innovation – technological or non-technological – to which it is related. These data are also rich in text and are easily processed. As with patents, their metadata can provide additional insights into issues such as regional and socio-economic inclusion in innovation, as well as research collaboration and internationalisation; they also allow tracking the commercialisation of emerging technologies. Trademarks are particularly important in the service sectors, where innovations are often non-technological.

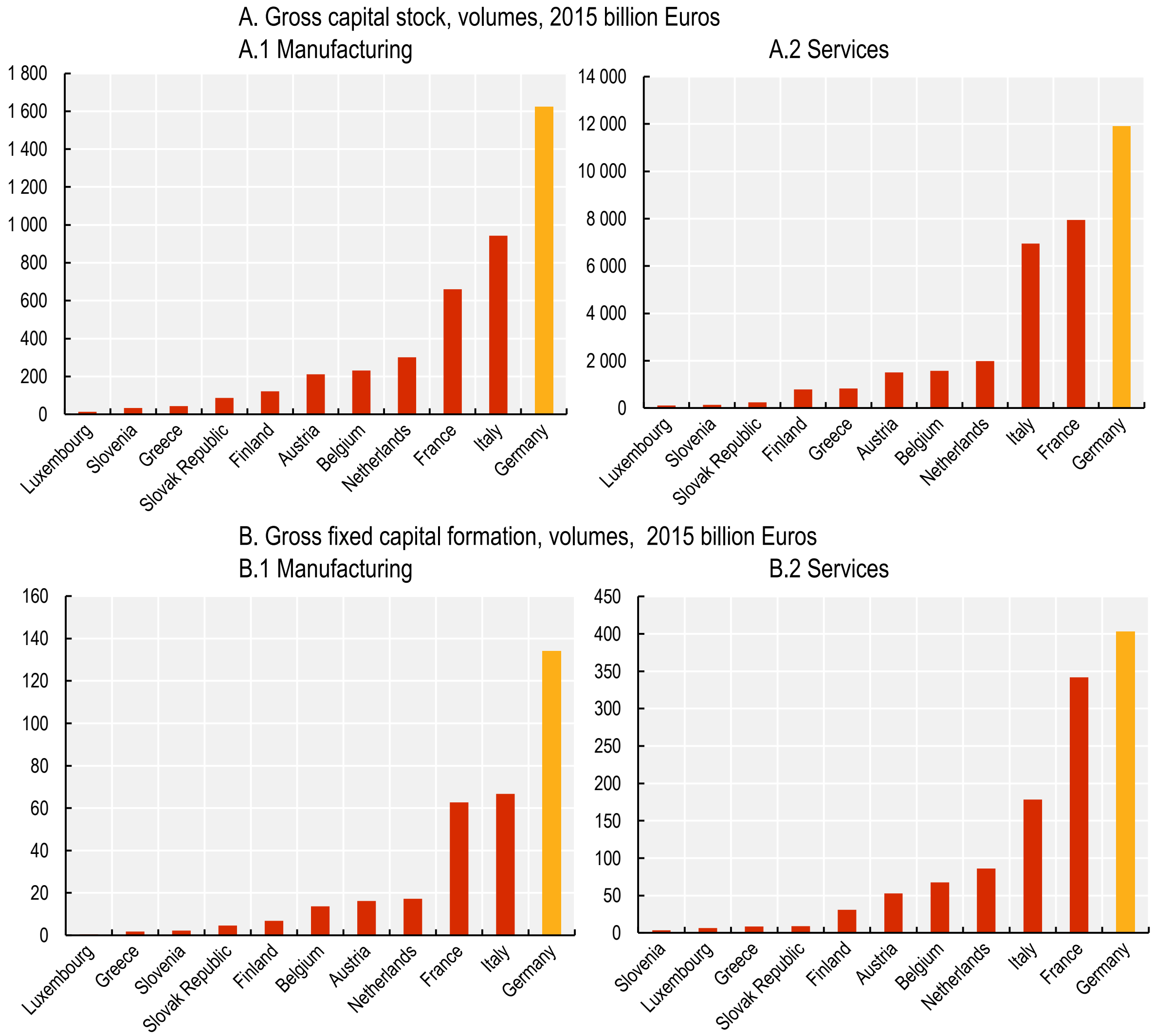
Additional indirect evidence on the quality of innovation may be gathered from assessments of the quality and complexity of export products (Atkin, Khandelwal and Osman, 2017[7]). A higher quality of one country's exported products compared to another country, evaluated assessed using a variety of assessment techniques, is ultimately a reflection of underlying innovation efforts.

3.2. Inputs to innovation: R&D, intangible and other investments in support of innovation

3.2.1 Investment and R&D

In 2018, Germany has the highest levels of annual industrial and manufacturing gross fixed capital formation and gross capital stocks in the European Union (Figure 3.1). In several manufacturing sectors, such as chemicals and machinery, Germany has more than twice the level of capital stock than the second-ranked country (Italy), thereby supporting globally leading knowledge reserves and productive capacity.

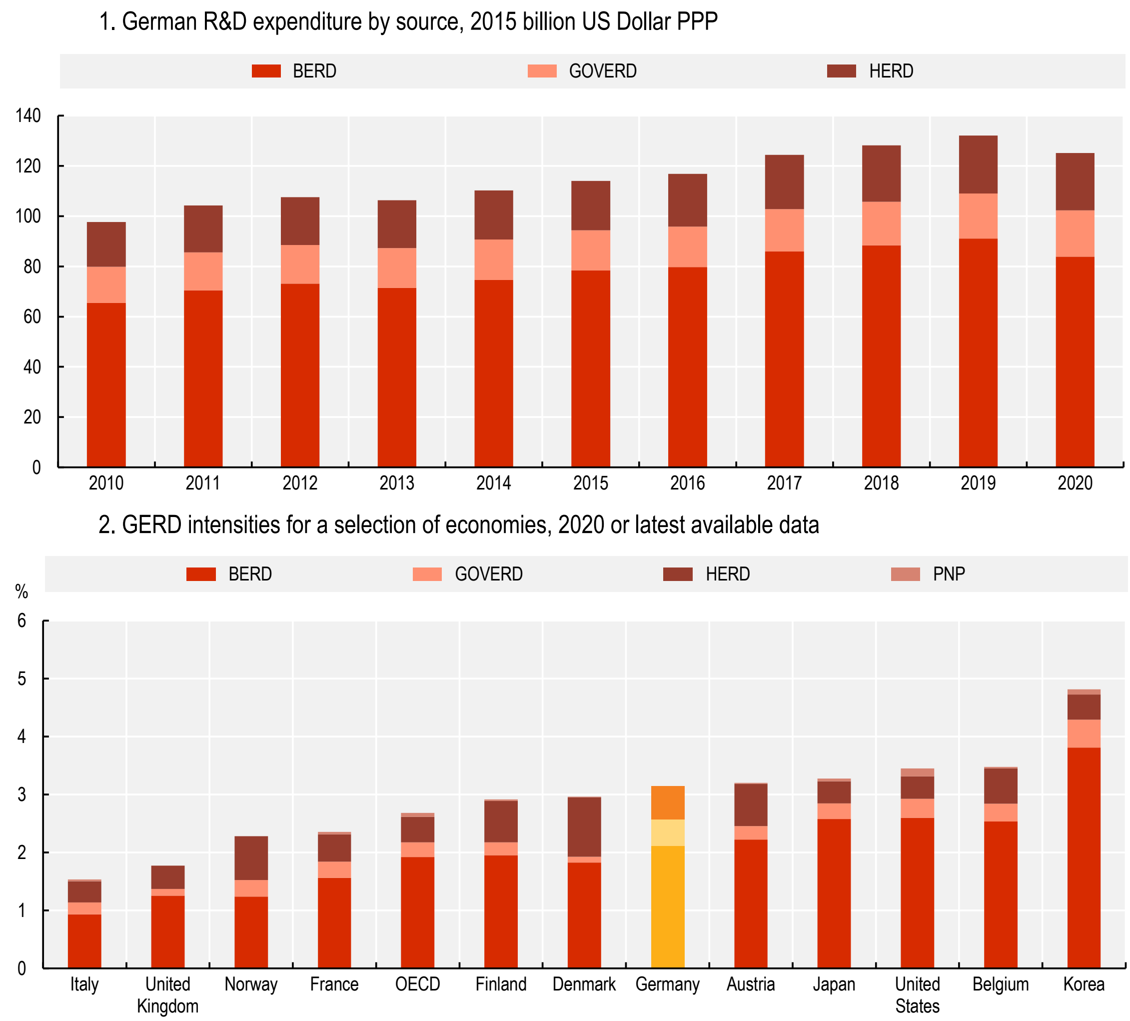
Figure 3.1. Gross fixed capital stock and flows in the euro area (2018)



Source: OECD (2022[8]), "STAN Bilateral trade database by industry and end-use category, ISIC Rev. 4", *STAN: OECD Structural Analysis Statistics* (database), https://doi.org/10.1787/data-00691-en (accessed on 22 April 2022).

In 2019, gross expenditure on research and development (GERD) amounted to 3.19% of gross domestic product (GDP) (EUR 110 billion) – the fourth-highest level in the world in both relative and nominal terms, behind the United States, the People's Republic of China (hereafter China), and Japan (Figure 3.2) (OECD, 2021[9]). In that same year, the German government set a goal of 3.5% GERD by 2025. (BReg, 2019[10])[2] In 2019, business expenditure on research and development (BERD) amounted to USD 91 billion (United States dollars) (EUR 78 billion), the fourth-highest level in nominal terms, reaching 2.2% of GDP – the ninth-highest level in the world (OECD, 2021[11]). The vast majority of GERD (69%) originates in the business sector, growing from 1.42% of GDP in 1994 to 2.2% GDP in 2019 (OECD, 2021[9]). German higher education expenditure on R&D (HERD) amounts to 0.56% of GDP or EUR 22.2 billion – the third-highest level in the world, behind the United States and China. Government expenditure on R&D (GOVERD) amounts to EUR 17.4 billion – the third-highest position globally – and 0.44% of GDP, the second-highest level after Korea.

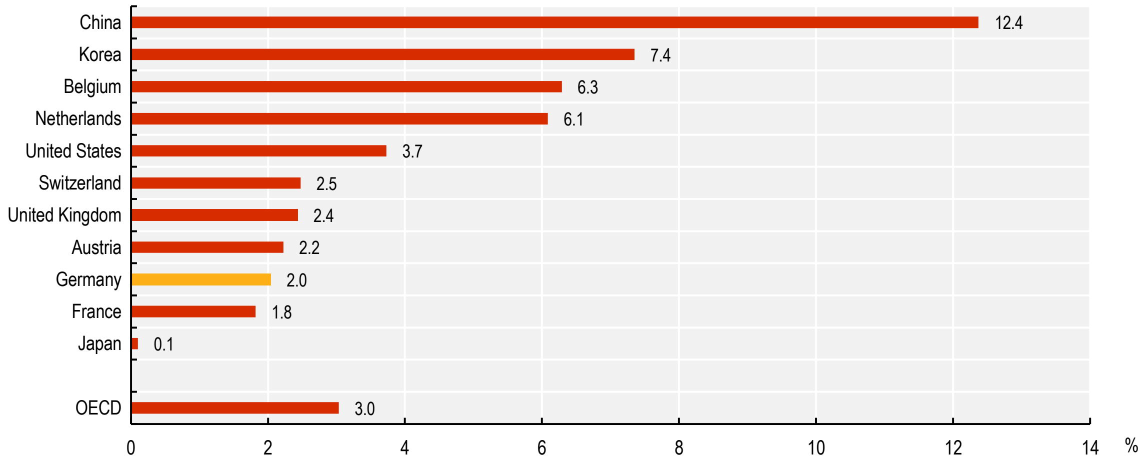
Figure 3.2. Absolute and relative levels of R&D in the OECD



Note: Data for the United Kingdom correspond to 2019.
Source: OECD (2022), "Main Science and Technology Indicators", *OECD Science, Technology and R&D Statistics* (database), https://doi.org/10.1787/data-00182-en (accessed on 22 April 2022).

Germany's compound annual growth rate (CAGR) of industry BERD between 2008 and 2020 was 2.0%. Most other large countries showed a higher rate (12.4% for China, 3.7% for the United States and 2.4% for the United Kingdom). Conversely, France (1.8%) and Japan (0.1%) reported a lower expansion of BERD (see Figure 3.3).

Figure 3.3. CAGR of industry BERD (2008-20)

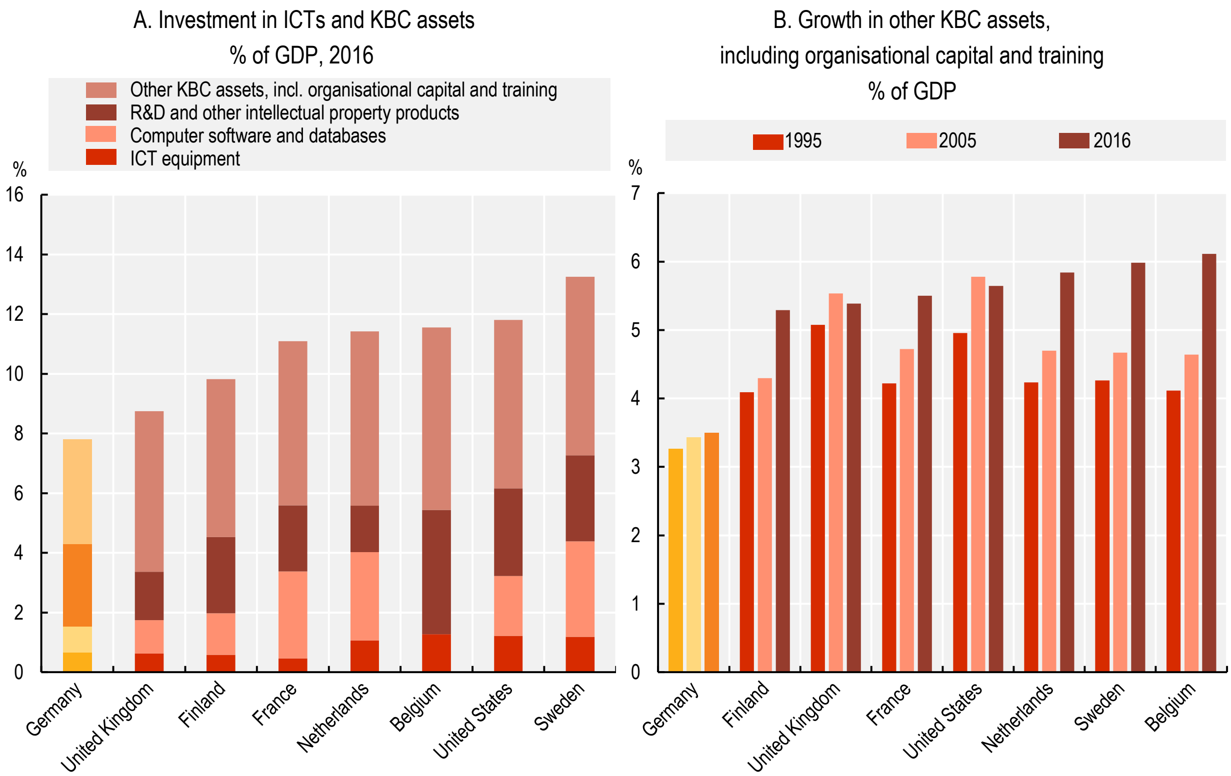


Note: Data for Switzerland correspond to the period of 2008-19
Source: OECD (2022[12]), "Main Science and Technology Indicators", *OECD Science, Technology and R&D Statistics* (database), https://doi.org/10.1787/data-00182-en (accessed on 22 April 2022).

3.2.2 Intangibles and knowledge-based capital in Germany

Investment in ICT is a related aggregate measure of innovation. At 1.63% of GDP (in 2017), German ICT investment is the fourth-lowest in the OECD relative to the economy's size (OECD, 2021[13]). More broadly, the contribution of ICT capital to growth in Germany is half that of the United States, and has been falling steadily since the early 2000s. The data reflect the lower diffusion of ICT in the German economy compared to other leading innovative countries. This is confirmed by the available evidence on the updating of ICT by businesses, as discussed in detail in Chapter 10.

Figure 3.4. Investment in ICT and knowledge-based capital is low



Note: KBC: knowledge-based capital. For Belgium, no breakdowns of intellectual property products are available. Other KBC assets are estimated on the basis of INTAN-Invest data and cover all industries excluding real estate activities, public administration, education, health and households.

Source: OECD (2020[14]), *OECD Economic Surveys: Germany 2020*, https://doi.org/10.1787/91973c69-en, based on *OECD National Accounts Statistics* database, https://www.oecd-ilibrary.org/economics/data/oecd-national-accounts-statistics_na-data-en and INTAN-Invest data, http://www.intaninvest.net/.

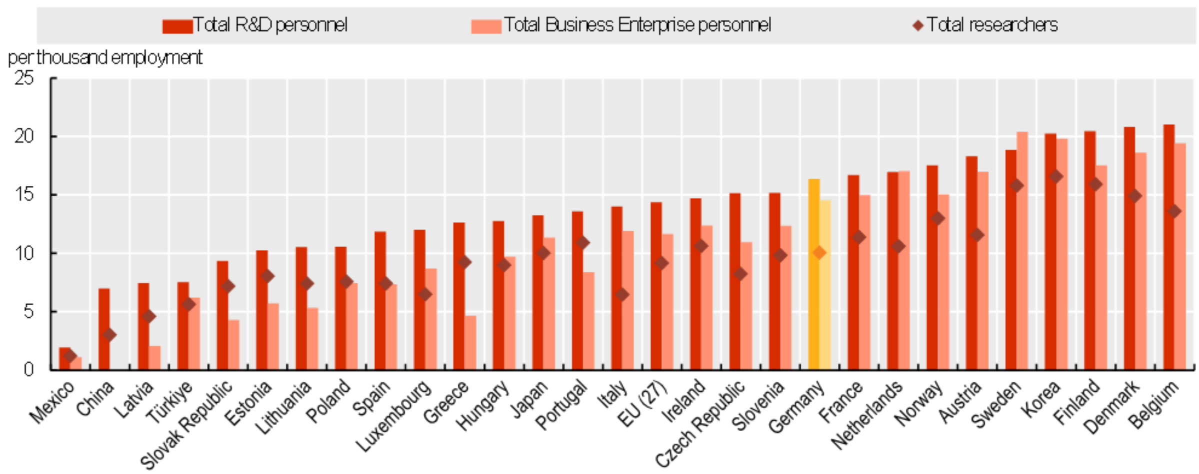
As Figure 3.4 shows, investment in knowledge-based assets, such as organisational capital and training, have remained low in Germany for three decades, particularly when compared to the best-performing countries. Similarly, investment in software and databases is less than two-thirds of the OECD average, partly reflecting Germany's stronger focus on R&D and capital investments in the manufacturing sector.

3.2.3 Human resources for innovation

With 450 700 researchers in full-time employment (FTE), Germany has one of the highest levels of permanent research capacity in the world, behind only China, the United States and Japan. Within the European Union, Germany has by far the highest level, ahead of France (314 100 FTE researchers) and Italy (160 800). Relative to the labour force in countries with populations of over 50 million, Germany ranks tenth in total R&D personnel, similarly to France, but behind Korea. As in other advanced OECD countries, the vast majority of FTE researchers (61%) work in the business sector (OECD average: 64%); 24% work in the higher education sector – slightly lower than the OECD average (30%) – and 13% are employed in the government sector – slightly higher than the OECD average (6.5%).

Figure 3.5. Key indicators for R&D personnel capacity relative to industry (2019)

Per thousand total employment

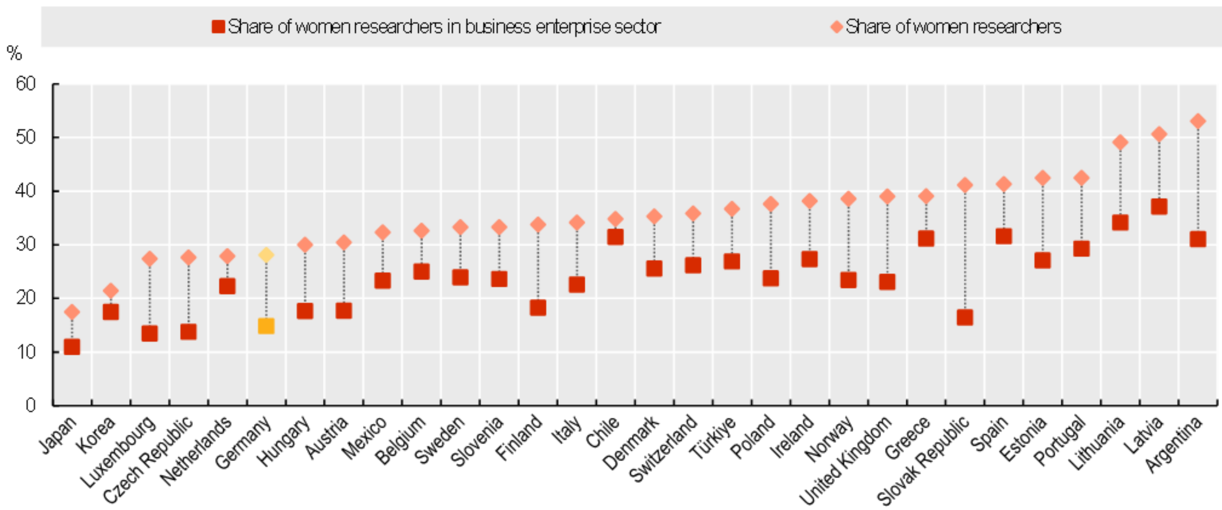


Source: OECD (2022[12]), "Main Science and Technology Indicators", *OECD Science, Technology and R&D Statistics* (database), https://doi.org/10.1787/data-00182-en (accessed on 22 April 2022).

Given the importance of the private sector to German innovation, it is perhaps not surprising that Germany has the fifth-highest number of FTE researchers in business enterprises (262 000), behind only China, the United States, Japan and Korea and ahead of France (189 000) and Italy (78 000). German business-sector researchers account for 27% of total FTE business-sector researchers in the European Union. The proportion of researchers in the working population (9.7%) is broadly similar to countries such as France (10.9%) and Japan (9.9%), though lower than in certain Asian and Northern European economies such as Korea (15.2%), Sweden (14.7%) and Finland (14.4%) (Figure 3.5).

Inclusivity in research face several challenges, including for women. The challenge is visible both at the aggregate level – where women account for only 28% of total FET researchers – and within the business sector (15%) (Figure 3.6). Notably, of all the large and industrial economies in the OECD, only Korea and Japan – two countries with a similar innovation focus on science, technology, engineering and mathematics (STEM) – have lower levels of female researchers than Germany.

Figure 3.6. Women are under-represented in the German research community (2019 or latest year available)



Note: Headcount-based; 2020 data for Japan, Korea, Mexico, Portugal, Slovak Republic and Turkey.
Source: OECD (2022[12]), "Main Science and Technology Indicators", *OECD Science, Technology and R&D Statistics* (database), https://doi.org/10.1787/data-00182-en (accessed on 06 April 2022).

3.2.4 Business dynamics and start-ups

Business dynamism – the number of newly founded and closing companies – has been weakening in Germany. Contrary to a positive trend in other OECD countries, German company entry rates, exits and bankruptcies have been declining over recent decades. Growth potential for German start-ups and smaller firms is hampered by relatively weak domestic financing conditions. Although venture-capital financing has starkly increased in recent years, it only ranks sixth in overall volume in the OECD region, significantly below other economies such as Korea and the United Kingdom (see the detailed discussion in Chapter 7). Public policy initiatives such as the *Zukunftsfond* ("Future Fund") explicitly address this lack of funding, especially in the under-developed second and third growth phases (see Chapter 5 for an overview of policy programmes for business innovation). Moreover, the targeted use of public procurement at the national and regional levels can support innovation capacities among small and medium-sized enterprises and start-ups, as discussed in more detail in Chapter 11.

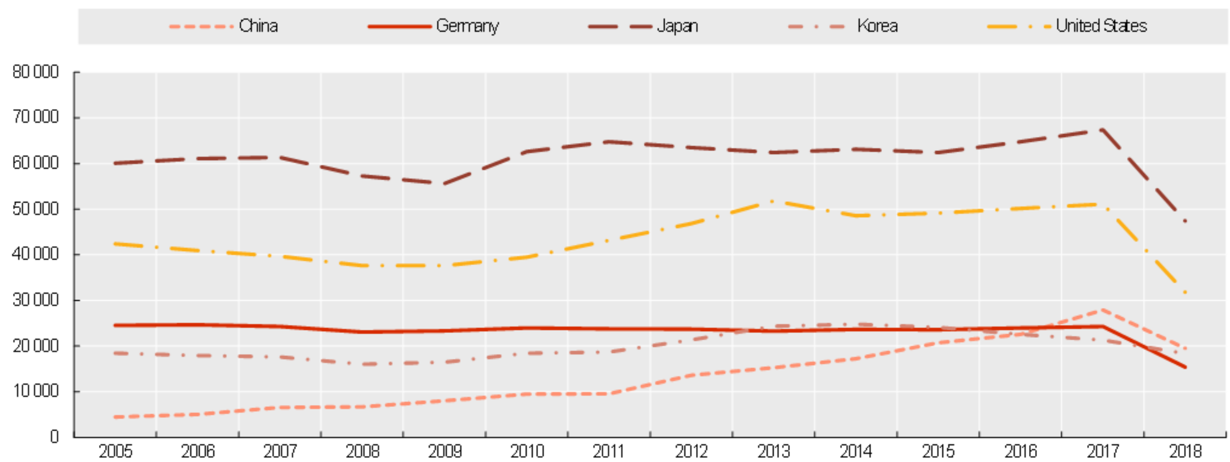
3.3. Intermediary outputs of innovation: Patents, trademarks and publications

3.3.1. German patenting in an international context

In 2020, Germany filed 30% of all PCT applications in Europe and 6.7% globally. In 2018, the last year for which comparable data are available, Germany accounted for the fifth-largest global share of IP5 applications[3], down from third-largest in 2005. This is not due to a decline in the absolute number of German applications, but to the stronger performance of China and Korea.

Figure 3.7. Total of top five IP5 patent applications (2005-18)

By priority date



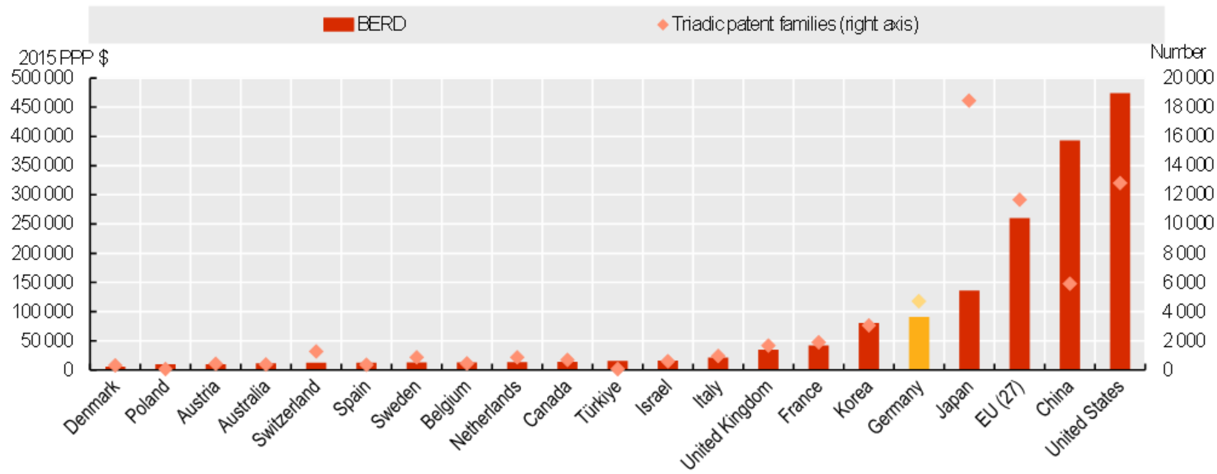
Source: OECD (2022[15]), Patents by main technology and by International Patent Classification (IPC)", *OECD Patent Statistics* (database), https://doi.org/10.1787/data-00508-en (accessed on 22 April 2022).

Interestingly, Germany has a strong level of research internationalisation, demonstrating the global nature of German firms' R&D activities. In 2018, for example, co-patents represented 16% of total patenting – a figure which, although behind the United Kingdom and France, is ahead of major competitors such as Japan and Korea (OECD, 2021[16]). The United States and China also have lower shares – which, however, relate to the bigger size of those economies. Nevertheless, collaboration at a domestic level is lower than in other OECD countries. For example, only 20% of the innovative business population engaged in some form of collaborative innovation, the fourth-lowest share in the OECD, although this may partly reflect the strong degree of internal research capacities among many of Germany's innovation actors. Similarly, with only 8.9% of the German innovative business population engaged in international research collaboration, Germany lags behind other innovation intensive – and large – countries such as the United States (14.6%), France (16.4%) and the United Kingdom (35.9%).

The share of high-value patents held by German firms is higher than the country's global share of all patents. In 2016, the latest year for which data are available, Germany accounted for 9.2% of the world's IP5 patent applications, closely behind Korea (9.9%) and China (10.6%), but far behind the United States (19.2%) and Japan (28.5%) (OECD, 2021[11]). Within triadic patent families[4], Germany's global share for 2016 was slightly lower (7.8%), although still the third-largest share behind Japan (34.7%) and the United States (26%). Germany also has a globally significant share of triadic patents in frontier areas such as environmental management (10%), climate mitigation technologies (10%), pharmaceuticals (5.6%) and biotechnologies (5.6%) (OECD, 2021[17]).Germany's strong patenting performance also benefits from the structural composition of the economy, as the country's dominant industries rely strongly on patents for intellectual property protection.

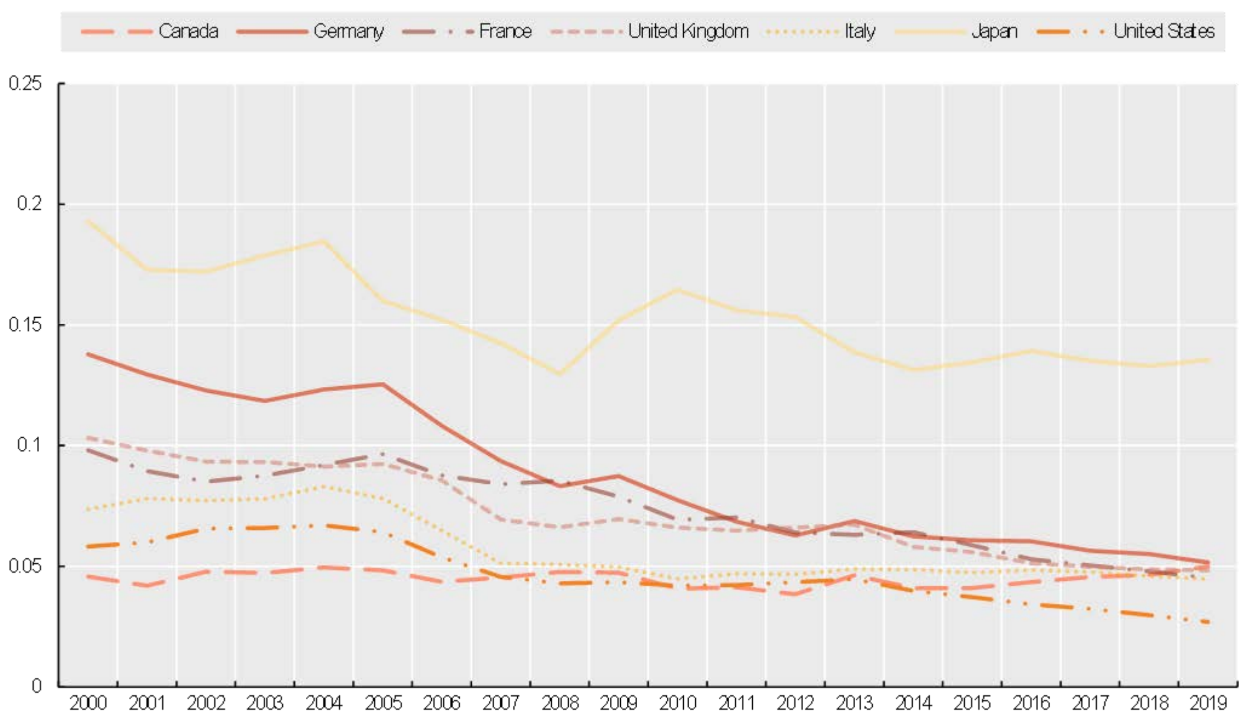
Recent analysis nevertheless shows that Germany's share of "world-class patents", including those that are highly cited and registered in multiple markets, has also declined over the past two decades.

Figure 3.8. BERD and triadic patent applications (2018)



Note: Data refer to priority year.
Source: OECD (2022[12]), "Main Science and Technology Indicators", *Forschung und Entwicklung* (database), https://doi.org/10.1787/data-00182-en (accessed on 22 April 2022).

Figure 3.9. Triadic patents per USD million of BERD (2000-18)



Note: Priority year.
Source: OECD calculations based on OECD (2022[12]), "Main Science and Technology Indicators", OECD Science, Technology and R&D Statistics (database), https://doi.org/10.1787/data-00182-en (accessed on 22 April 2022).

The decreasing trend in triadic patent filing (observable in several leading economies), as well as falling shares in highly cited patents, suggest decreasing technological returns from business R&D. According to a recent study, the contribution of German innovators to the 10% most-cited patents across 58 important technology areas has decreased over the past two decades, although current levels remain high in an international context (Breitinger, Dierks and Rausch, 2020[18]). In 2010, Germany ranked among the top 3 nations in terms of world-class patents (in 47 out of 58 technologies), which had however declined to 22 technologies by 2019. This development also concerns Germany's traditional strength in manufacturing, where highly cited patents are increasingly shifting to East Asian countries. In parallel, technological productivity – as measured by the number of triadic patents per billion dollars of BERD (constant prices) solicited by German applicants – halved over 2000-19.

Despite increasing R&D investments, Germany's capacity to generate high-impact technological innovation has therefore decreased. A similar – but less steep – downward trend occurred in business R&D in the United Kingdom and France. In contrast, Japan and Korea show a more stable evolution, with Japan leading the production of triadic patents per billion dollars of business R&D within these five of comparator countries.

3.3.2. German scientific publications in an international context

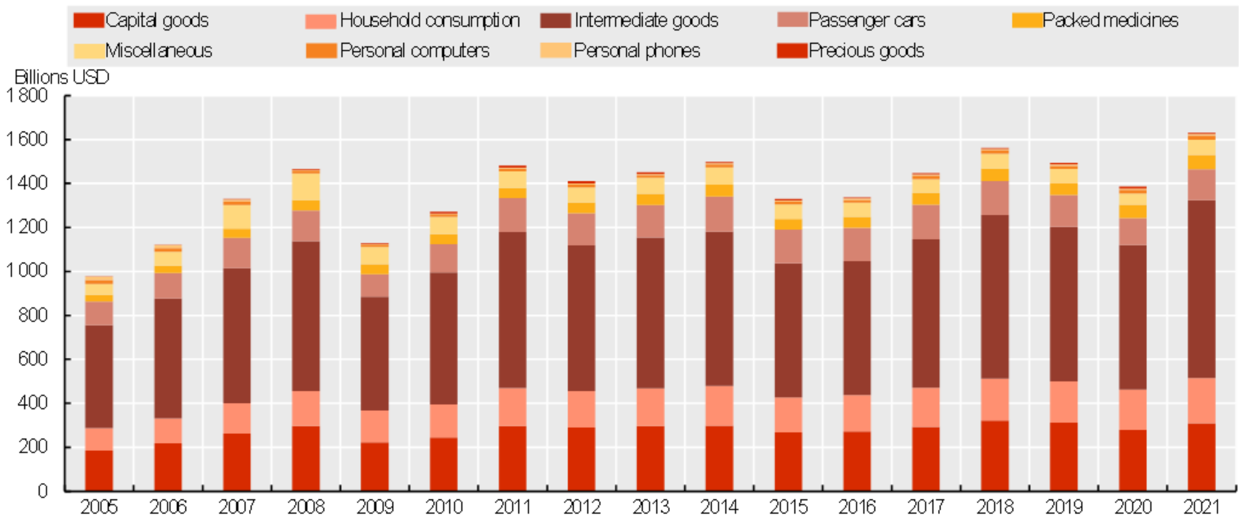
Germany is a major producer of high-quality scientific research and publications. While China (20.7%) and the United States (20.5%) make up the largest share of the 10% top-cited papers in the world's top-cited journals, Germany remains a significant contributor (4.4%), behind the United Kingdom (5.2%). At a high level, the scientific publication output of the German STI system substantiates both the success of the institutions and programmes in place to promote high-quality research, and the vast stock of knowledge available to innovation actors in the economy.

In terms of contributions to high-quality academic literature, Germany performs well in areas that reflect the sectoral strengths of its innovation system, as well as in those that are less ostensibly linked to key sectoral or industrial competencies. Germany features among the top ten contributors to high-quality scientific literature in a range of academic disciplines. It performs well in traditional STEM areas, such as engineering (10.2% – fifth globally), computer science (11.5% – sixth) and material science (9.5% – eighth), but also in the humanities (12.6% – fifth) and social sciences (12.6% – fourth). The broad scope of these combined academic competencies demonstrates the diverse range of scientific knowledge and expertise available to the German innovation system.

3.4. Indicators of innovation outputs and quality based on export performance

Germany's strong innovation performance supports an export-oriented economy, despite significantly higher labour costs than in many developing economies. In absolute terms, Germany has the second-highest level of trade in goods and services within the OECD, behind only the United States. As a percentage of GDP, the level of German exports (47% of GDP) is by far the highest in the Group of Seven (G7) and Group of Twenty (G20), evidencing the exceptional importance of the external sector for a large and industrialised economy such as Germany. Manufactured capital and intermediate goods are a major component of Germany's exports, reflecting the country's importance as a source of finished and intermediary inputs for the global economy (Figure 3.10).

Figure 3.10. German goods exports (2005-20)



Source: OECD (2022[8]), "STAN Bilateral trade database by industry and end-use category, ISIC Rev. 4", *STAN: OECD Structural Analysis Statistics* (database), https://doi.org/10.1787/data-00691-en (accessed on 22 April 2022).

German's high level of manufactured good exports is supported by an innovative and complex export basket, with many German manufacturers producing high-end, technologically advanced products. The complexity of Germany's export basket – as measured by the diversity and sophistication of exports – is indicative of its production competencies, which are ultimately based on innovation capacities. Germany has the second most-complex export basket in the G7, and the fourth most-complex globally, reflecting the broad range of sophisticated innovative products exported by German firms.

Germany's leadership in innovation is also reflected in its share of leading companies among global innovating firms: the country has the fourth-largest cohort of top innovating firms, behind the United States (775), China (536) and Japan (309) (European Commission, 2020[19]). Among the top 2 500 R&D investors globally, 124 firms are German (2020) – almost double the nearest EU country (France, 68), with almost triple the level of expenditure (EUR 89 billion for Germany, EUR 33 billion for France) (European Commission, 2020[19]). Within Europe, nearly one in four of the most innovative firms is German. Four German companies – Siemens (sixth), Robert Bosch (seventh), BASF (tenth) and Continental (twenty-fourth) – featured among the 25 largest applicants to the EPO in 2020, the single largest share in the European Union (EU28) (EPO, 2021[20]). Within Germany, the top applicants to the PCT in 2020 were Robert Bosch (4 033 applications), Schaeffler Technologies (1 907) and BMW (1 874) (DPMA, 2020[21]). Also in 2020, Robert Bosch (1 516 applications), Siemens (1 416) and BASF (1 188) were the country's largest applicants to the EPO.

Despite their success, the attractiveness of German companies on financial markets is somewhat weak compared to successful innovators in several other OECD countries. In 2018, the total market capitalisation of listed domestic companies was 44.1% of GDP, slightly below the euro area average (54.5%), but well below other leading OECD countries, including Korea (82.0%), Japan (105.2%) and the United States (147.7%) (World Bank, 2022[22]). This also applies to the share values of publicly traded companies, where Germany ranked second to last among the G7 in 2018 (OECD, 2022[23]).

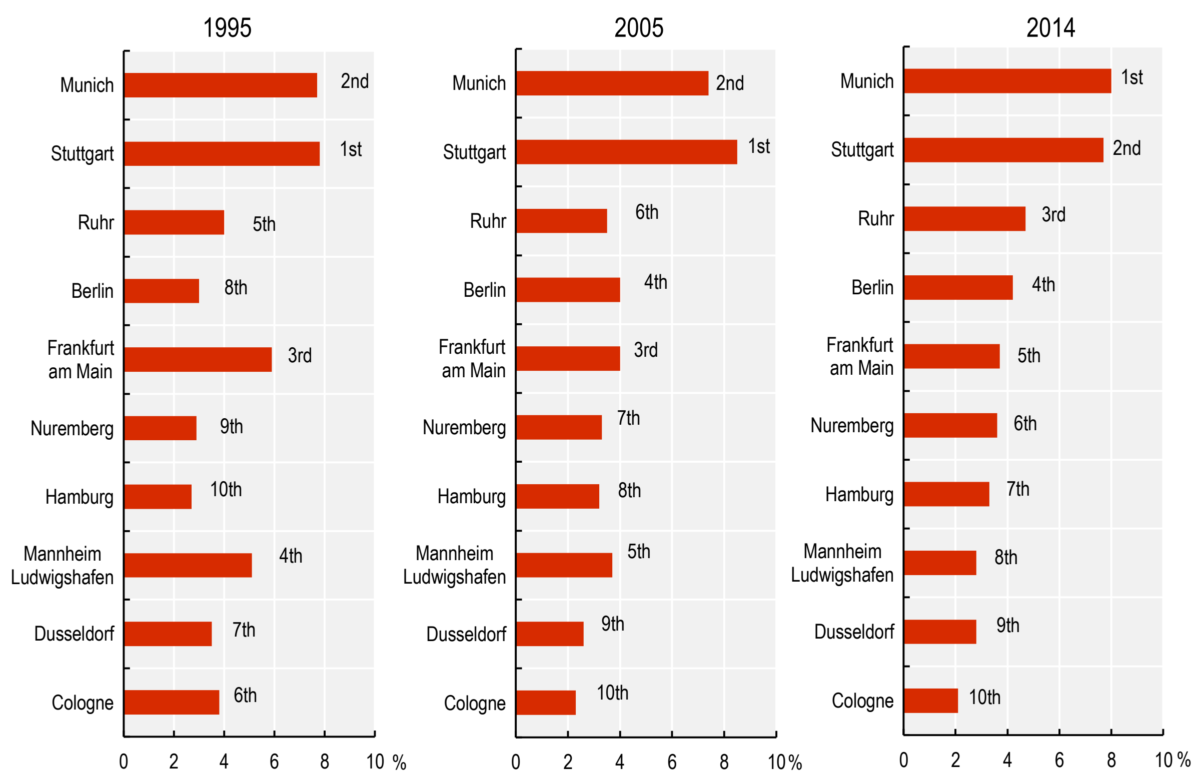
3.5. Regional and sectoral composition of innovation

3.5.1. Regional composition

While there exist regional divergences in patenting activity in Germany, the geographical concentration of patent applications at the city-level is less pronounced than in other OECD countries. As Figure 3.11 shows, Germany has a lower geographical concentration of patenting among the top 10%, 5% and 1% of cities compared to key comparator economies such as Japan, the United States, the United Kingdom and France (Paunov et al., 2019[24]).

Figure 3.11. Ranking and share of top ten cities in patent applications, Germany (1995, 2005 and 2014)

Share of Germany's patent applications



Note: Cities – functional urban areas – selected correspond to the top ten in patent applications in 2014.
Source: Paunov et al. (2019[24]), https://doi.org/10.1787/f184732a-en.

The concentration is more pronounced for some technology areas, likely owing to localised concentrations of specialised knowledge around a small number of research institutions and industrial actors. For example, patenting in digital technologies and biotechnology is the most geographically concentrated. In 2010-14, the top 10% of cities accounted for 41% of digital technology patenting and 45% of biotechnology patenting, higher than the average across all technology fields over the same period (Paunov et al., 2019[24]). On a per capita basis, the top 3 regions registered 122 (Baden-Württemberg), 90 (Bavaria) and 37 (Lower Saxony) applications per 100 000 habitants, whereas the equivalent figures for the bottom 3 regions were 6 (Mecklenburg-West Pomerania), 7 (Saxony-Anhalt) and 14 (Berlin) (DPMA, 2020[21]). Chapter 16 provides more details on the regional distribution of German innovation.

The southern *Länder* are home to Germany's industrial base, with a focus on (automobile) manufacturing and mechanical and electronic engineering. Bavaria hosts companies such as Airbus, Audi and BMW, and Baden-Württemberg is home to Bosch, Daimler and Porsche, alongside many smaller Mittelstand firms. Bavaria also has a well-developed service industry, with global insurance companies Allianz and Munich Re, while Baden-Württemberg is home to one of Germany's few software companies, SAP. Both *Länder* are also research and innovation centres, with 70 institutions of higher learning and multiple Fraunhofer Society and Max Planck institutes in Baden-Württemberg, and almost 40 institutions of higher learning and over 20 research centres in Bavaria (GTAI, 2022[25]). At the border with France and Luxembourg, the Saarland is a logistics and transportation hub featuring over 150 companies; with other clusters, such as information technology (IT) start-ups, currently developing in the region. The home base of companies such as Opel, Rolls-Royce, Jenoptik, Bosch and Zeiss, Thuringia hosts expertise in lens manufacturing, medical and biotechnology, photovoltaic production and software engineering. Rhineland-Palatinate – which is characterised by medium-sized business and "hidden champions", but is also home to BASF – has strengths in the chemical, pharmaceutical, automotive, metal, machinery and equipment, and food industries. Hessen draws in foreign investment and is internationally connected through Frankfurt Airport, but also focuses on digitalisation and data in both the private sector and research: the COVID-19 vaccine manufacturer BioNTech, in the city of Mainz, has recently been a major driver of growth. North Rhine-Westphalia is Germany's most populous state, and a common destination for foreign investment. Its 70 universities and universities of applied sciences, 110 technology centres and non-university research institutes form the densest research network in Europe (Ibid.).

Northern Germany's industrial strengths are often connected to the North and Baltic Seas, with important shipbuilding and harbour industries, maritime trade and international freight transportation in Mecklenburg Western-Pomerania, Schleswig-Holstein, Lower Saxony and Hamburg. Lower Saxony also has a strong local base in the automotive industry (with Volkswagen and Continental), as well as travel and tourism (TUI Group); it is also active in freight transportation through its 35 harbours, in shipbuilding, international trade fairsand hosts over 30 institutions of higher learning. Schleswig-Holstein is experiencing strong growth in renewable energies; it hosts the Fraunhofer Institute for Silicon Technology and the IZET Innovation Centre, as well as leading companies in the medical industry, such as Dräger and Johnson & Johnson Medical. Hamburg is Europe's second-largest port and a logistical hub; it is also a centre for aviation and has a diversified service industry in media, marketing, IT and life sciences. Bremen, also a port city, has strengths in the maritime economy, logistics, wind energy, and the food and beverage industries; it also hosts the automotive (Mercedes-Benz) and aerospace (Airbus) industries and serves as a base for the digital and IT service industries, with the German Research Centre for Artificial Intelligence (Ibid.).

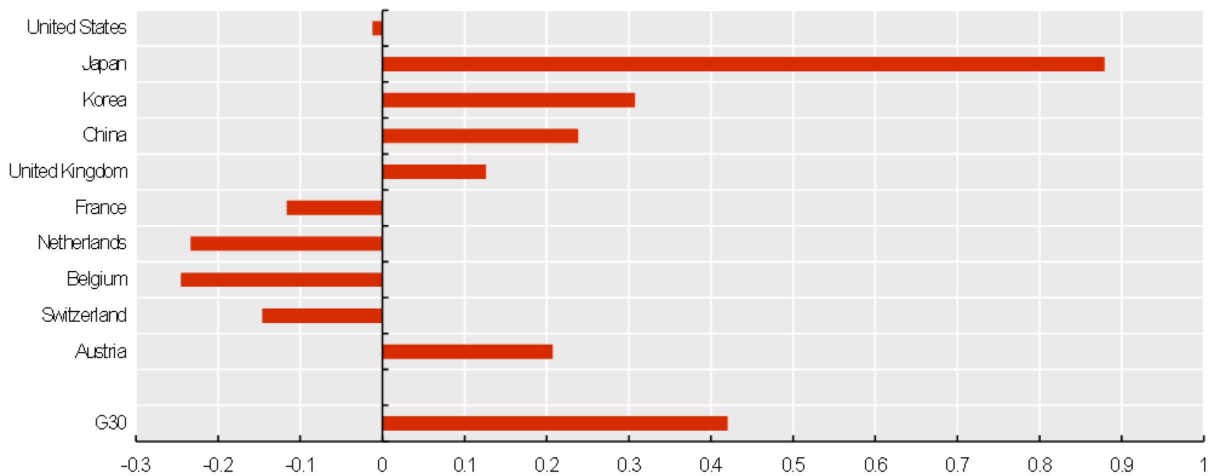
While no longer a centre for industry, Berlin hosts many representations of global and national leading companies as the country's capital. Its own strengths lie mainly in media, fashion, music, services, IT and health care, as well as bio, optical, environmental and medical technologies. Berlin also has a growing start-up community, and hosts 18 higher education institutions and 250 research establishments, including Germany's largest science and technology centre in Adlershof. With its proximity to Berlin and its central location within Europe, Brandenburg acts as a commercial transportation hub. Saxony-Anhalt specialises in chemicals and biotechnology, as well as automotive supplies, and is a centre for polymer production and processing; it hosts 2 universities, 12 colleges and 22 research institutions. In Saxony, research focuses on lightweight construction, energy storage technologies, automation technology and future mobility, while industrial strengths lie in mechanical engineering and microelectronics/ICT; logistics are also a major economic driver (Ibid.).

3.5.2. Sectoral composition

In an international comparison, the sectoral composition of German BERD mostly resembles Japan's, with a 0.88 correlation coefficient between the two countries for the shares of 12 industries (Figure 3.12).

Germany's industry structure of BERD is also somewhat similar to Korea, China and Austria, but is very different from Germany's neighbouring countries in Western Europe (Netherlands, Belgium, France and Switzerland). Germany's 0.42 correlation coefficient with the G30 (see note to Figure 3.12) should be viewed in context with the same figures for China (0.52), Japan (0.72), the United States (0.72) and Korea (0.83), indicating that the sectoral concentration of Germany's BERD is an outlier for a major industrialised economy.

Figure 3.12. International similarity of industrial composition of BERD (2017)

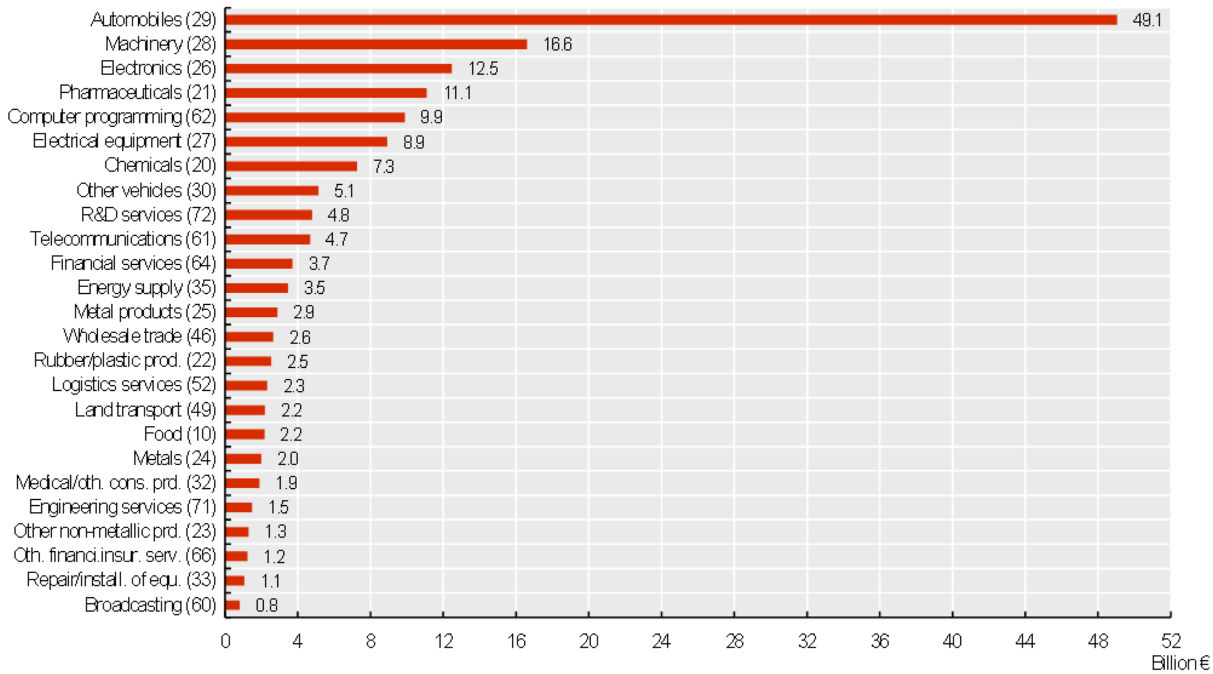


Note: Industries included are automobiles, machinery, business services, electrical equipment, materials, R&D services, pharmaceuticals, electronics, other vehicles, internet and communication services, other manufacturing and all other sectors. Data for Korea are for 2015, data for the United Kingdom are for 2016. G30 is defined here as Germany and 29 important trade partners of Germany and for which a breakdown of BERD by industry is available: Australia, Austria, Belgium, Canada, China, Czech Republic Denmark, Finland, France, Germany, Hungary, Ireland, Israel, Italy, Japan, Korea, Netherlands, Norway, Poland, Portugal, Singapore, Slovakia, Slovenia, Spain, Sweden, Switzerland, Chinese Taipei, Turkey, United Kingdom, United States.
Source: OECD (2022[26]), *OECD Research and Development Expenditure in Industry 2018: ANBERD*, https://doi.org/10.1787/anberd-2018-en (accessed on 22 April 2022).

Germany's BERD tends to be concentrated in a limited number of sectors and industries, with particularly high levels of innovation expenditure in the manufacturing sector. In 2017, the last year for which sectoral data are available, 85% of total intramural BERD occurred in manufacturing, a substantially higher share than in the United States (64%) and European countries such as the United Kingdom (41%), France (49%), the Netherlands (57%) and Switzerland (70%).

National statistics on innovation expenditure include all R&D expenditure (intramural and extramural), as well as expenditure related to the implementation of innovations, such as machinery and equipment purchases, training, marketing and design. From 2017 to 2019, German innovation expenditure was EUR 172 billion for each of the three years. The automobile industry accounted for 28.5% (EUR 49.1 billion), followed by machinery (9.6% or EUR 16.6 billion). Other major industries in terms of innovation expenditure included electronics, pharmaceuticals, computer programming, electrical equipment and chemicals (Figure 3.13).

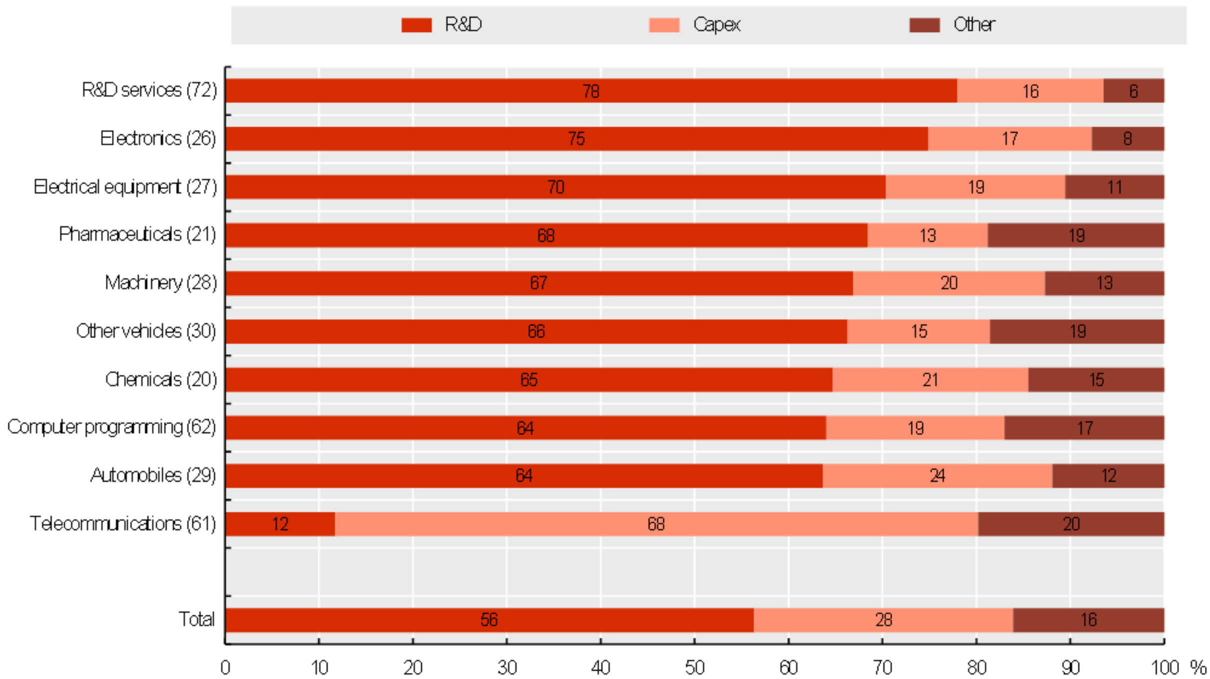
Figure 3.13. The 25 NACE 2-digit industries in Germany with the highest innovation expenditure (2017-19)



Note: NACE: Nomenclature of Economic Activities. NACE classification code in parentheses.
Source: Leibniz Centre for European Economic Research (ZEW) (2020[27]). "Innovation in der deutschen Wirtschaft". https://ftp.zew.de/pub/zew-docs/mip/20/mip_2020.pdf?v=1616141836 (accessed on 23 April 2022).

The ranking of industries by innovation expenditure closely matches the ranking by R&D expenditure as in most industries with high innovation expenditure, R&D is the main spending category. While on average, 56% of all innovation expenditure in the German business enterprise sector concerns R&D, the top-spending industries spend between 64% and 78% on R&D (Figure 3.14). The only exception is telecommunications, where two-thirds of total innovation expenditure is capital expenditure for tangible or intangible assets. The automobile industry shows a lower share of R&D in total innovation expenditure compared to the other main spending industries, a result of high capital expenditure for innovation (24% or EUR 12 billion per year in 2017-19).

Figure 3.14. Type of innovation expenditure in the ten German industries with highest innovation expenditure (2017-19)



Note: Capex: capital expenditure.
Source: ZEW (2020[27]). "Innovation in der deutschen Wirtschaft". https://ftp.zew.de/pub/zew-docs/mip/20/mip_2020.pdf?v=1616141836

There exist clear sectoral concentrations of BERD within manufacturing. In 2017, for example, the automobile industry performed 37.3% of total BERD, the largest share posted by the automobile industry in any country in the world for which industry-level R&D data are available. The sectoral composition of BERD is strikingly similar to Japan, which has the second-highest concentration of BERD (25.9%) in the automobile industry. This highlights the similarly important role of manufacturing in the Japanese economy, with an almost 90% correlation coefficient of the share of the top 12 industries in BERD between the two economies. Other larger economies with a significant automobile industry show much smaller shares of automotive in total BERD, although some do have high levels of BERD concentration in other industries that are important to the digital transition (such as the electronics sector in Korea). Among OECD countries, the Slovak Republic has the next-closest level of BERD in the automobile sector (35.5%) after Germany.

The automotive sector is the main driver of growth in Germany's innovation expenditure, accounting for more than 40% of the total increase in innovation expenditure between the end of the 2008 Global Financial Crisis and 2019. The three-year rolling average of BERD growth over the previously mentioned period was 1.9%. Over 40% of this total increase can be attributed to the automobile industry, which not only expanded R&D expenditure, but also significantly increased capital expenditure (+2.3% CAGR) and other expenditure (+3.8% CAGR). Other industries that substantially contributed to the increase include pharmaceuticals, computer programming, machinery and electrical equipment. This dynamic of the automotive industry as a significantly larger quantitative source of BERD than other sectors and a key driver of the expansion of BERD in the German economy invariably raises broader political economy challenges for innovation expenditure in the country, due to the sector's linkages with academia and research, and its contributions to growth and employment.

Given the importance of the manufacturing sector – and particularly the automotive sector – to the German economy, it is perhaps unsurprising that it plays a significant role in the country's innovation system. Some

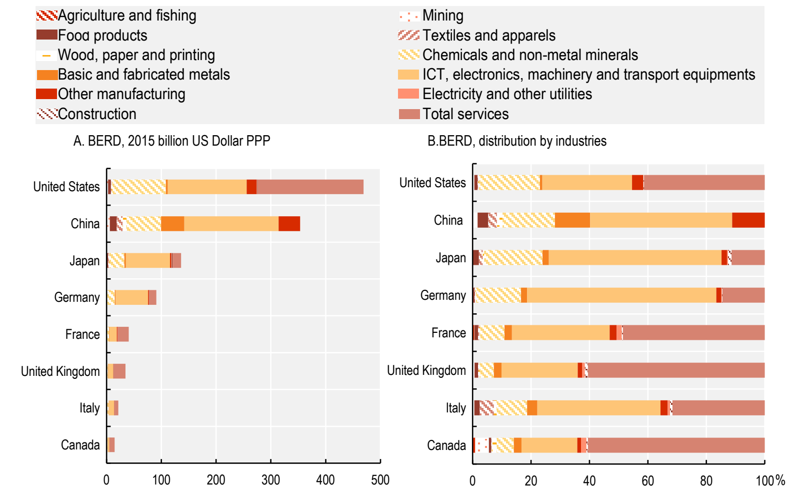
85% of all intramural R&D is undertaken by manufacturing firms, a substantially higher share than in comparable economies such as the United States (64%) and France (49%). In 2019, 53% of German R&D expenditure occurred in the automobile industry – an amount equal to 24% of global automotive BERD. No other large industrialised country had a comparable sectoral concentration of innovation funding and capacity in any one sector (European Commission, 2020[19]). Four of the top ten leading automotive companies in terms of global R&D expenditure – Volkswagen (first), Daimler (second), BMW (sixth) and Bosch (seventh) – are located in Germany (European Commission, 2020[19]).

Yet the automotive sector is far from the only significant manufacturing and industrial player in Germany's innovation system. In 2018, the last year for which comparable data are available, the electronics (11.4%), machinery (9.9%), chemical (7.2%) and pharmaceutical (5.8%) sectors were also major contributors to total BERD (OECD, 2021[11]). While these figures are low relative to the contribution of the automotive sector, they are significant in nominal terms (representing EUR 8.3 billion for electronics, EUR 7.1 billion for machinery, EUR 5.2 billion for chemicals and EUR 4.1 billion for pharmaceuticals). They are also substantially higher than BERD in the same sectors in other leading innovative nations such as France and Italy. Moreover, Germany has a number of globally leading firms in these sectors, including Siemens (second in the world for electronics industry R&D), Bayer (eighth for pharmaceuticals), BASF (first for chemicals) and SAP (eighth for software and computer services) (European Commission, 2020[19]). In addition to their net contributions to R&D in the European Union, five of the top ten companies that contributed to R&D growth in 2019 were from Germany, led by SAP's 18.6% year-on-year growth, the largest contributor to the increase (European Commission, 2020[19]).

Several other industries are also major sources of BERD, both in international comparison (

Figure 3.15) and domestically (Figure 3.16). In 2018, for example, German BERD in the chemical sector totalled USD 5.2 billion. This was the fourth-highest level globally, behind China (USD 23.9 billion), the United States (USD 9 billion) and Japan (USD 8.1 billion), but by far the largest source of sectoral BERD in the European union, ahead of France (USD 4 billion), Belgium (USD 1.2 billion) and Italy (USD 0.7 billion). Similar trends are visible in the machinery industry – where Germany is again the fourth-largest contributor to global sectoral BERD (USD 8.9 billion), behind China (USD 32.6 billion), Japan (USD 12.9 billion) and the United States (USD 12.8 billion) – as well as in R&D-intensive sectors such as electronics (fourth globally, USD 3.4 billion) and pharmaceuticals (fifth, USD 5.8 billion). Taken together, the broad range of sectors in Germany showing high levels of BERD constitute a globally competitive and leading source of private-sector innovation, and a valuable reserve of knowledge and technological expertise.

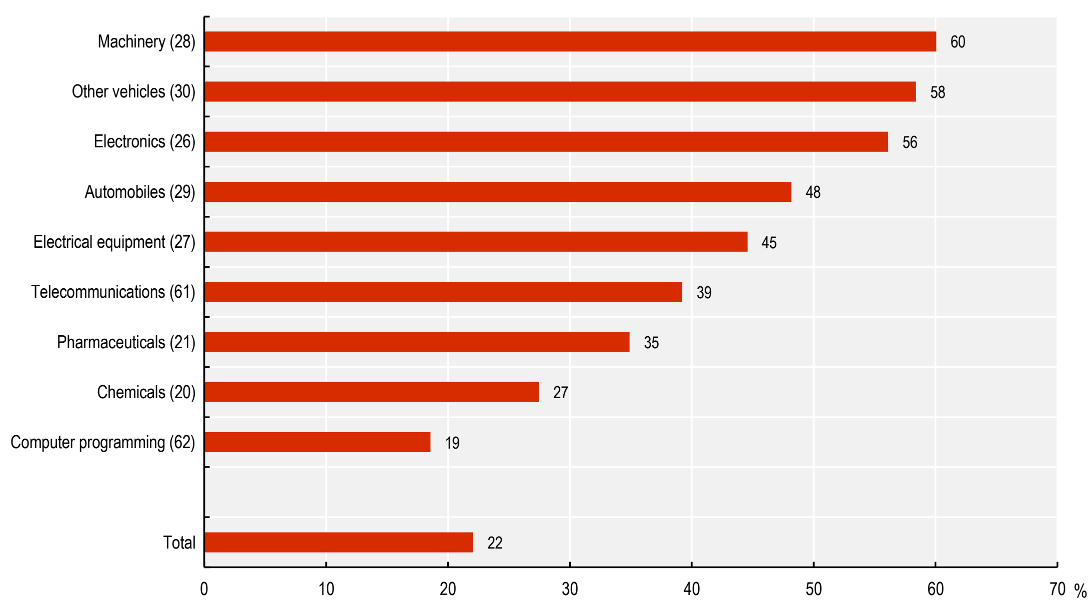
Figure 3.15. Distribution of BERD by industry (2019 or latest available year)



Source: OECD (2022[28]), "STAN R&D: Research and development expenditure in industry - ISIC Rev. 4", *STAN: OECD Structural Analysis Statistics* (database), https://doi.org/10.1787/data-00689-en (accessed on 16 May 2022).

High capital expenditure for innovation is a common feature of many of the industries with high innovation expenditure. Relating the amount of capital expenditure for innovation (additions to property, plant and equipment as well as intangible assets, but excluding R&D expenditure) to the industry's total capital expenditure (also excluding R&D expenditure) as reported in national accounts shows high shares innovative capital expenditure, ranging from 45% (electrical equipment) and 48% (automobiles) to 56-60% (electronics, other vehicles, machinery). The shares are lower in the pharmaceutical (35%) and chemical (27%) industries. For the total economy, just 22% of all capital expenditure targets innovation.

Figure 3.16. Share of capital expenditure for innovation in total capital expenditure* in Germany, by industries with the highest innovation expenditure (2017-19)



Note: Capital expenditure excluding R&D expenditure. Figures are approximations only, as industry classification of innovation expenditure and capital expenditure are based on national accounts.
Source: OECD calculations based on ZEW (2020[27]).

Several other industries in Germany contributed above the average to global R&D growth, including R&D services (accounting for 16.2% of the global increase in R&D expenditure from 2008 to 2017), business services (12.9%) and machinery (10.0%). Across all industries, R&D dynamics were strongly driven by China, which contributed 50% to the total global increase in BERD over the same period. China's contribution to total BERD growth ranged from 33% to more than 100% in the manufacturing industries, and from 11% to 47% in the service industries.

At a sectoral level, Germany's CAGR of BERD exceeded the global rate in three industries (business services, R&D services, other vehicles) and shows a similarly high rate as the G30 (see note to Figure 3.12) for most other industries, including information and communication services, pharmaceuticals and electrical equipment. However, the CAGR of German BERD is clearly lower than the G30 reference value in three industries: electronics, materials and other manufacturing. While the dynamism in materials and manufacturing is dominated by the R&D expansion of the Chinese industry, the growth of R&D in electronics shows a wider geographical pattern, with Korea, Chinese Taipei and the United States also making substantial contributions. The low CAGR of Germany (+1.6%) and its low share in global electronics industry R&D (4.3%) indicate that Germany does not have the same global presence in this sector as other large OECD countries, particularly the economies of East Asia.

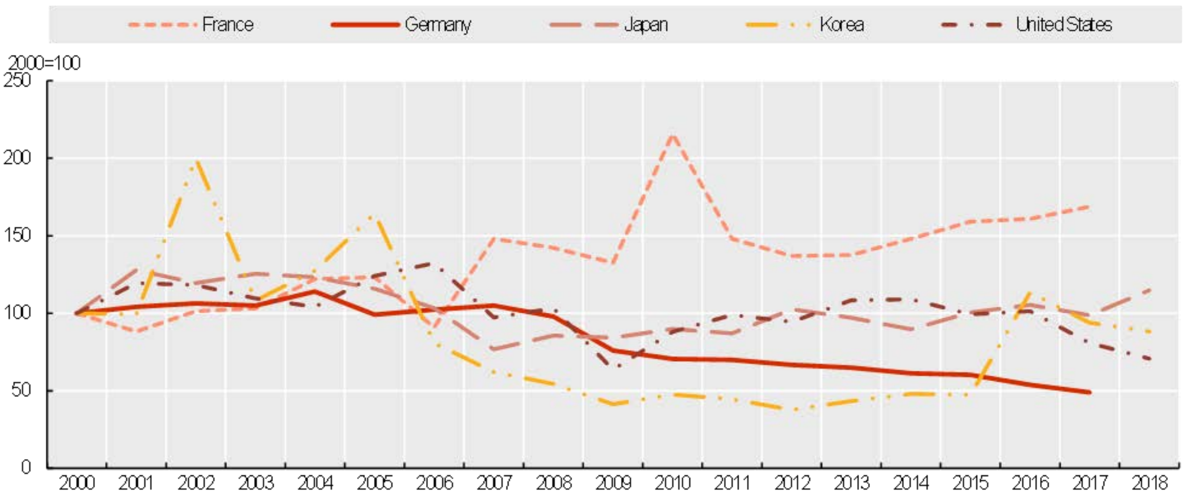
Finally, it is telling that many of the sectors featuring the highest levels of German BERD also make significant contributions to the country’s total exports, further evidencing the relationship between domestic innovation and international competitiveness. For example, the automotive sector, whose innovation expenditure share of industry turnover amounts to 10%, accounted for 37% of global premium car production in 2019, significantly ahead of other producers such as the United States (14%) and China (16%) (GTAI, 2019[29]). Similarly, the strong rankings of research-intensive sectors in Germany as diverse as the aerospace industry (third globally in 2019, 11.8% of the global market share) and pharmaceuticals (first, 14.1%) further attest to the important relationship between successful innovation and international competitiveness for the German economy.

3.6. Innovation productivity: Outputs to investments

Both the United States and Germany have experienced diminishing patenting capacity relative to R&D expenditure since the mid-2000s. Figure 3.17 suggests divergent levels, with the United States posting the biggest decline, while France and Japan have maintained relatively strong or stable returns to BERD since the 2008-09 global downturn.

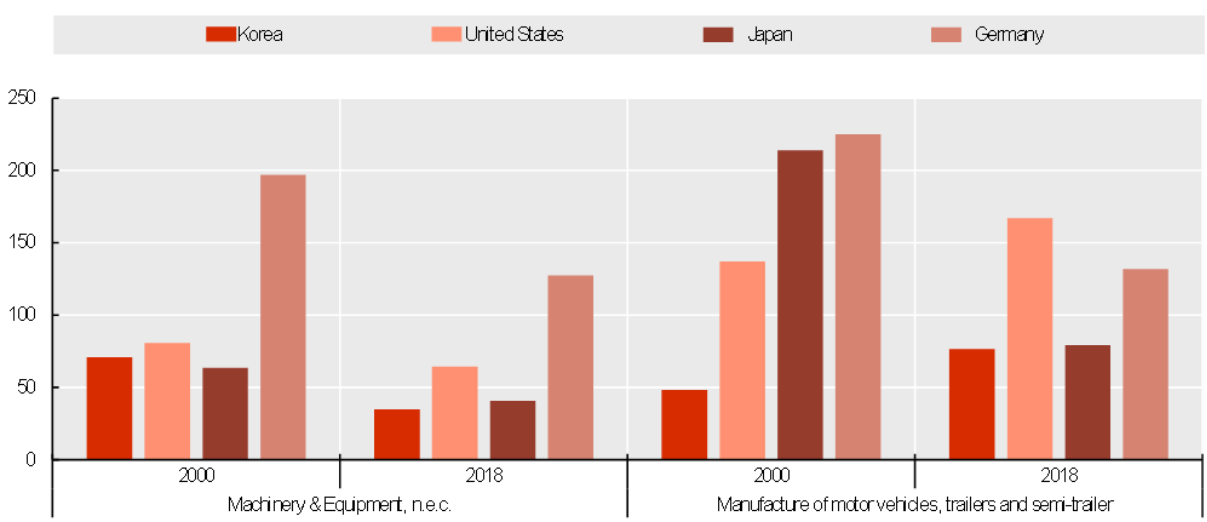
Figure 3.17. Evolution of R&D productivity in manufacturing: Patents per BERD

Industry structure-adjusted average index (normalised to year 2000 =100)



Note: The figure reports the structure-adjusted average (sectors weighted by their share in total manufacturing value added) of EPO-PCT filings per business R&D expenditure in the same year (expenditure and patent filing year). BERD data are expressed in 2015 USD constant prices and PPP. The index reported is normalised to year 2000 (=100). Patenting data were transformed to sector-level patents using the concordance matrix developed by Dorner and Harhoff (2018[30]). The computation of this indicator took into account 18 manufacturing sectors (18 sectors -2 digit ISIC4,[5] reporting BERD data for the whole period; food and beverages and tobacco products are excluded). However, care should be taken in reading this evolution, as data for some low-tech sectors (D13, D14, D15 and D16) are partially covered for the United States and Japan. These sectors, however, represent a minor share in total national manufacturing value added and production. Therefore, this may have only a limited effect on the aggregate for the United States and Japan.
Source: OECD calculations, based on business R&D Statistics from the BERD database (*OECD STAN Database* ISIC-4), and patenting data (EPO patent applications by filing year) consolidated at the sector level.

Figure 3.18. EPO patent applications relative to BERD for selected industries (2000 and 2018)



Source: Source: Own calculations, based on R&D Statistics from BERD database (*OECD STAN Database*) at the ISIC4, 2-digit level, and patenting data (EPO patent applications by filing year) consolidated at the industry level (ISIC4, 2-digit) using fractional allocation.

Additional insights can be derived by applying the same approach at the industry level. In Figure 3.18, for example, this indicator was computed for two of the most important economic sectors in Germany. As largely acknowledged in innovation studies, there exist important cross-sectoral differences in both R&D investment and patenting patterns, with intensive industries being more sensitive to patent protection and experiencing higher rates of technological change, especially in emerging industries. Accordingly, France displays the strongest performance in terms of patenting per R&D dollar, a consistent pattern since around 2007 (Figure 3.17). In contrast, Germany displays deteriorating return of EPO patent applications per BERD dollar in two of its key industries (machinery and equipment, motor vehicles), although the country still had higher innovation performance than France and the United States in 2018 (Figure 3.18).

Both in Germany and globally, research productivity (measured as total factor productivity per number of researchers) has been declining over the past two decades. In the United States, research productivity declined on average by 5.3% per year between 1930 and 2015 (Bloom et al., 2020[31]). This trend was closely mirrored in Germany, where research productivity dropped by 5.2% per year on average between 1992 and 2017 (Boeing and Hünermund, 2020[32]).

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Endnotes

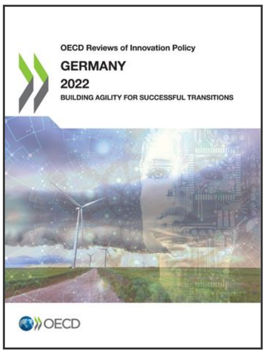
[1] PCT applications are filed with a national patent office of a PCT treaty country. If accepted, the patent can be extended to all signatories of the treaty, making it a de facto "international" patent.

[2] A target has been set to increase R&D spending to 3.5% of GDP by 2025.

[3] Patents that are protected in at least two IP offices worldwide, one of which must be a member of IP5 – namely, the EPO, JPO, USPTO, KIPO and CNIPA.

[4] Triadic patent families are a set of patents filed at the EPO, the JPO and the USPTO for the same invention by the same inventor.

[5] ISIC: International Standard Industrial Classification of All Economic Activities.



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