1 Overall assessment and recommendations

The Overall Assessment and Recommendations (OAR) of the Review of Innovation Policy of Germany shows that while Germany has one of the most powerful science, technology and innovation (STI) systems in the world, the country faces a number of innovation-related challenges for competitiveness and sustainability in the years ahead. The OAR introduces recommendations that respond to these challenges in two important ways. The first is to improve the fundamentals of the STI system and the STI policy that supports it, ensuring that it is more efficient, effective and inclusive. The second is to ensure that STI policy prepares for the challenges of tomorrow, with an emphasis on new capabilities, approaches to policy, and governance.

Summary of recommendations

Recommendation 1: Develop a shared vision "Germany 2030 and 2050"

The government should create a cross-ministerial, federal-state, cross-institutional and cross-sectoral forum to steer the process of developing a shared vision, founded on the identified key priority areas for action.

Recommendation 2: Create a public-private laboratory for innovation-policy experimentation

Such a laboratory would support the experimentation, implementation and monitoring of innovation policy, and would promote the forum's vision. It would support policy agility, and advocate for change and experimentation where needed.

Recommendation 3: Broaden and mainstream the use of agile policy tools to support innovation efforts by SMEs, and achieve the digital and green transitions

Reducing bureaucratic and administrative barriers affecting *Mittelstand* – a German classification of small- and medium-sized enterprises – firms and start-ups that engage in innovation, and continuing efforts to digitalise government-to-business services should be a priority. Regulatory sandboxes should be expanded.

Recommendation 4: Improve data infrastructure and data access, especially for industry

The government should improve data infrastructure and raise firms' digital absorption capacities so that they can use industrial data for innovation. It should also promote open innovation platforms, and networks for data-based and collaborative innovation.

Recommendation 5: Improve cross-disciplinary and cross-sectoral knowledge transfer and collaboration

To improve knowledge transfer, the government should enhance university engagement with industry, including by encouraging the development of funds for academic spin-offs. It should also support multidisciplinary and entrepreneurship training across the education system.

Recommendation 6: Promote financial markets that are conducive to scaling up breakthrough innovations

Germany should support greater institutional investment in start-ups and higher risk tolerance. It should address regulatory barriers in start-up finance, to increase Germany's attractiveness as a destination where high-potential start-ups can grow.

Recommendation 7: Strengthen the use of public procurement as a driver of innovation

The government should increase procurement officials' ability to undertake procurement for innovation, strengthen risk tolerance in procurement, and expand the use of pre-commercial procurement to accelerate the diffusion of new technologies and solutions across the economy.

Recommendation 8: Increase the involvement of key civil-society stakeholders in science, technology and innovation (STI) policy targeting the transitions

The government should expand the engagement of civil society in the STI policy-making process and broaden the diversity of those engaged in innovation, particularly to further its twin transition agenda.

Recommendation 9: Digitalise, modernise and strategically use quality infrastructure

The government should digitalise and modernise its quality infrastructure – such as standards and norms – systems to advance Germany's global position as a standard-setter and rule-maker. Quality infrastructure should be used more strategically.

Recommendation 10: Take a leadership role in shaping EU and global innovation policies

Germany should take a more active role in shaping innovation policies at the EU level, so that policy caters to the current and future innovation requirements of both Germany and the broader European Union.

Introduction

Germany entered 2022 in the wake of nearly two years of disruption caused by the COVID-19 global pandemic. The Russian invasion of Ukraine in February 2022 instigated another shock. Restrictions on mobility affected domestic business operations and consumption, while supply-chain disruptions had a major impact on many of Germany's most competitive industries. Russia's war against Ukraine profoundly affected trade in energy and raw materials. The renewed policy discussions resulting from these events have covered issues such as energy diversification and innovation for renewables and decarbonisation, as well as technological "sovereignty" in the design and production of key intermediary products used as inputs in German industry. The newly constituted government set an ambitious reform agenda to respond to these challenges and address structural goals, notably accelerating the digitalisation of the German economy and the modernisation of the German administration and transitioning towards a more sustainable socio-economic future. The German innovation ecosystem is key to achieving these objectives.

Two major transformational processes present opportunities and challenges for Germany's future socio-economic well-being. The first is the digital transformation, which has implications for both the types of goods German manufacturers will produce – for example, the digital component in vehicles or the use of advanced information and communication technologies (ICTs) to unlock new frontiers in pharmaceuticals and health care. Similarly, firms will need to step up their operations, thanks to data and other digital tools that can transform and radically improve business processes. The second transformational process is Germany's transition to a greener and more sustainable economy. In line with the commitment of the Paris Agreement to achieving global carbon neutrality in the second half of the 21st century, Germany is working towards securing greenhouse gas (GHG) neutrality by 2050. Achieving this goal will require radically reducing the GHG footprint of major emitters, such as industry and transport, by moving to more sustainable modes of production; increasing the use of renewable energy for electricity generation; and in some instances – such as with individual mobility – changing the behaviour of society and consumers. These transformational processes are complex, and will rely on STI to ensure they become opportunities rather than only challenges. Examples include challenges to Germany's dominant global market position in automobiles, as the importance of digital value added increases, or in industry, where demands for more environmentally sustainable development will increase the cost of traditional production modes.

The experience of the COVID-19 crisis and Russia's war against Ukraine has demonstrated the importance of building resilience in global value chains. Disruptions to German industry's productive capacities, including supply-chain problems with intermediate goods caused by continued lockdowns in China, or the implications of the war on global energy flows, also affect the innovative capacities of German firms in fundamental ways. In addition, an undiversified range of suppliers for critical minerals and other inputs necessary for technologies that support the green transition add an additional level of complexity to the question of supply chain resilience. These questions of building robust value chain linkages in which German industry holds central positions of key value added thus becomes an area of systemic importance.

This review provides insights and options related to key questions for the German innovation system from the perspective of innovation-policy design. In the coming years, policy makers in Germany will need to answer a number of questions raised by this survey. For example, what is the right policy approach to supporting the innovation ecosystem in the context of the complex digital and sustainability transitions? What are the implications of the different conditions for participation in innovation activities across *Mittelstand* and large firms, and how can these best be addressed? What is the right innovation-policy mix to meet current and future demands on the innovation system, particularly where those demands may require greater systemic agility? How can regulations, standards and infrastructure support innovation, and what does this imply for policy? What conditions should be provided to support the creation and growth of start-ups, and how can start-ups help meet the transformational challenges

mentioned above? What efforts are needed to develop core technologies necessary for future competitiveness and transitions? How can the conditions for knowledge, technology and the successful transfer to the market of inventions developed in the "lab" be improved? What governance arrangements, including co-creation approaches involving the public, are needed for greater agility in the innovation system? And what tools and approaches can support the public sector in its contributions to the innovation system?

German economic strength is underpinned by one of the world's most advanced innovation systems. The country is an international leader in both public and private investment in innovation, with strong linkages between research and industry supporting international competitiveness and domestic socio-economic well-being. The impact of this strong STI ecosystem on the economy is clear, with German firms – from some of the largest vehicle manufacturers in the world to the "hidden champions" of the *Mittelstand* – consistently featuring among the most innovation-intensive in the world. The government's long-standing commitment to supporting research and innovation in the private sector, particularly the *Mittelstand*, has contributed to this success. Another benefit of German policy support for strong innovation intensity is that the economy retains a significant manufacturing sector and remains strongly export-oriented.

Despite these strengths, Germany faces challenges to its global leadership position in innovation. The current STI system suffers from weak innovative business-creation dynamics; difficulties in transferring new ideas and results from public research into new technological solutions and innovation (i.e. new products or services); slow adoption of digital technologies; and unexploited potential of diversity, such as a wider participation of women.

Preparing for the upcoming major transformations will require a new approach to innovation policy. Germany's traditional STI strengths are heavily intertwined with the needs of its existing industry. Responding to future needs requires developing the necessary capacities for innovative success in the context of the twin transitions of environmental sustainability and digitalisation, as well as improving the resilience of inputs – from energy to digital components – necessary for innovation success in these contexts. Addressing these challenges will require policy makers to build on the strong foundations of the STI system, but chart a new approach to designing and implementing STI policy. This approach will be more risk-tolerant, agile and sometimes directional. It will value entrants as much as incumbents. It will focus on the capabilities necessary in tomorrow's context, rather than yesterday's.

This chapter introduces the overall assessment and recommendations of the Innovation Policy Review of Germany. Section 1 provides a background for the analysis. Section 2 presents the main characteristics of the German innovation system. Section 3 considers the system's strengths, weaknesses, opportunities and threats (SWOT). Section 4 examines its structural strengths and weaknesses. Section 5 discusses its preparedness for future challenges. Section 6 concludes with recommendations for the Federal Government of Germany, based on the analysis in this review.

1.1. Overview of Germany's innovation system

In 2021, Germany was the largest economy in Europe and the fifth-largest economy in the world in terms of gross domestic product (GDP), also ranking among the top-performing OECD countries in terms of headline well-being indicators (OECD, 2020[1]; IMF, 2022[2]).[1] Within the OECD, Germany has the lowest number of people (5.9% of the population) who report struggling to make ends meet and is in the top-tier nations (fifth) in terms of household income. Germany also has a well-educated and highly skilled population, with high scores in the OECD Survey of Adult Skills (PIAAC) in 2018 compared to the OECD average (OECD, 2019[3]). Of those aged 25-35 in Germany, 35% hold a tertiary degree, lower than the OECD average of 45% (OECD, 2021[4]).

In part this reflects the country's strong vocational education system (2018), which is a key strength of the country's innovation system and economy more broadly. The government has a diverse and well-resourced range of programmes and instruments in support of innovation policy, with a particular focus on technology transfer for SMEs. The Federal Government's approach to STI policy has several central components. One has been the "Transfer initiative", developed by the Federal Ministry for Economic Affairs and Climate Action's (BMWK, then BMWI) to respond to the challenges of technology transfer between research and the private sector. Another is the "From Idea to Market Success*"* approach, which covers the different stages of the innovation process and aims to accelerate the transfer of technology to the market. Much of German innovation policy for SMEs is administered by the "Central Innovation Programme for SMEs" (ZIM), which mainly supports inter-firm collaboration in different areas of market-oriented and high-risk innovation. The government has also taken steps to allow the public sector to be a more direct driver of technology diffusion and the commercialisation of new ideas. A key example of this is the development of the Competence Centre for Innovative Procurement (Kompetenzzentrum Innovative Beschaffung [KOINNO]), which, among other areas, establishes mechanisms to support pre-commercial procurement, thereby accelerating the transfer of high-potential ideas to the marketplace. Reflecting the growing policy attention to "breakthrough" innovation, the Federal Government established the Federal Agency for Disruptive Innovation *(*Agentur für Sprunginnovationen [SPRIND]) in 2021.

Targeted grant funding is one of the main policy instruments supporting SME innovation. With more than 3 000 new projects every year and EUR 555 million (euros) in funding administered in 2020, ZIM is the largest and most widely used programme. IM mainly supports inter-firm collaboration in different areas of market-oriented and high-risk innovation, and has supported many first-time applicants to innovation-support initiatives. According to a 2019 evaluation, the share of first-time applicants receiving support was 42%, nearly a decade after the programme started (Kaufmann et al., 2019[5]). Attracting new, young firms to apply is an important focus for the programme, as well as supporting the Mittelstand in the digital and green transition process. Other programmes include the new "Innovation Programme for Business Models and Pioneering Solutions" (IGP), which targets close-to-market non-technical innovations (with funding of EUR 35 million in the pilot phase), the "Co-operative Industrial Research" (IGF) programme for pre-market research collaboration (annual funding of EUR 169 million) and (as mentioned above) the "INNO-KOM" transfer programme, which also supports firms in weaker regions (EUR 71 million in annual funding). Several additional thematic programmes focus on funding innovation in specific technology domains (e.g. energy technologies, biotechnology and materials), and developing research partnerships between industrial and scientific partners.

Manufacturing and technological innovation underpin Germany's international competitiveness and support socio-economic well-being. Germany has economic, productive and innovative strengths across a range of vibrant industries, with the machinery and electronics, automotive, and chemical and pharmaceutical sectors posting the highest level of value added and gross output in the euro area.

Generally high levels of investment support the German business sector and STI system, but the country faces a number of investment gaps that could dampen innovation output. The productive base is being supported by the highest level of gross fixed capital formation and of gross capital stocks in the Euro area at the aggregate level as well as in key industries and sectors of the economy, with leading positions in medium- and high-level research and development (R&D) intensity activities (1st) and industry [including manufacturing] (1st) (OECD, 2020[6]).[2] Annual growth of gross fixed capital formation (GFCF) has been relatively low for a number of years, the shocks caused by COVID-19 notwithstanding. In 2019, growth of GFCF in Germany was 1.8%, down from 3.4% in 2018 and behind the United States (3.3%) and France (4%) (OECD, 2022[7]).

Nevertheless, productivity growth in the decade after the Global Financial Crisis of 2008-9 was markedly lower than in the previous decade. This has been attributed a number of investment-related issues. For example, as noted in the 2020 OECD Economic Survey of Germany, public investment – particularly in digital and physical infrastructure – has lagged over the past decade, with the country currently facing a public investment backlog of around EUR 450 billion (OECD, 2020[8]). Similarly, Germany's investment in intangible assets remains low at 9.2% of value added over 2000-15, below the EU average (Roth, 2020[9]). It is also notable that Germany has the lowest share of ICT investment as a share of total GFCF in the G7, with 7.1 % in 2020, the latest year available (OECD, 2022[10]). By contrast, the share of ICT investment to total GFCF in France was 18.4% and 17.1% in the United States. A similar if less dramatic difference is visible in the contribution of intellectual property to total GFCF in Germany, which stood at 18.1% in 2020, the latest year for which data are available. In the United States, the figure for 2020 was 29.4%, in France it was 25.4%, in the United Kingdom it was 22.3%, and in Japan it was 21.6% (Ibid.).

Germany is an international leader in R&D investment. In 2020, Germany had the sixth-highest gross expenditure on R&D (GERD) as a percentage of GDP (3.14% GDP, USD 110 billion) in the world and has surpassed the target set in 2000 by the European Council in Barcelona to raise GERD to 3% of GDP in EU member states, with a domestic target of 3.5% GDP by 2025. In 2019, Germany's GERD amounted to 3.19% of 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 (OECD, 2021[11]). In 2020, business expenditure on research and development (BERD) amounted to USD 91 billion (United States dollars) (EUR 78 billion), the third-highest in in the OECD in nominal terms, and reached at USD 91 billion (EUR 78 billion) and eighth highest relative to GDP at 2.2% of GDP, the ninth-highest level in the world (OECD, 2021[12]). Higher education expenditure on research and development in Germany amounts to 0.6% of GDP (EUR 22.2 billion) – the third-highest level in the world in nominal terms, behind the United States and China. Government expenditure on research and development (GOVERD) of EUR 17.4 billion also places the country in third position, second only to Korea relative to GDP (0.4%).

High levels of R&D expenditure have delivered strong innovation output, with Germany having a large global footprint in patents.[3] Wherever possible, the present review will use additional indicators to this end, such as trademarks and licensing. In 2020, Germany accounted for 30% of all Patent Cooperation Treaty (PCT) applications in Europe and 6.7% globally, and was the second-largest applicant to the European Patent Office (EPO), behind the United States. Indeed, German firms holds a higher share of high-value patents than of all other 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%); the United States (19.2%) and Japan (28.5%) had the largest shares (OECD, 2021[13]).[4] Within triadic patent families[5], Germany's global share for the last year with comparable data (2016) was slightly lower (7.8%), although it is 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[13]). Germany's strong performance in international patenting comparisons also reflects many of its leading industries' propensity for patenting.

Germany's innovation system is significantly internationalised and competitive, with large innovative companies leading in numerous sectors. Its open and trade-intensive economy features strong and well-developed links to global value chains, and relies heavily on input imports for its production and foreign demand to sell its products. Innovation has allowed Germany to maintain its position at the cutting edge of global industry, with the export of high-quality and high-value added goods driven by strong external demand, primarily from other European countries. Within Germany, the top 2020 PCT applicants were Robert Bosch (4 033 applications), Schaeffler Technologies(1 907) and BMW (1 874) (DPMA, 2020[14]). That same year, 3 of the top 25 largest applicants to the EPO were German – Robert Bosch (seventh), BASF (tenth) and Continental (twenty-fourth), the largest single share in the EU28, with Robert Bosch (1 516), Siemens (1 416) and BASF (1 188) the country's largest applicants to the EPO (EPO, 2021[15]). With 124 firms in the top 2 500 R&D investors globally (2019 data, to be updated), almost 1 in 4 of Europe's most innovative firms is German. Globally, the country has the fourth-largest cohort of top innovating firms, behind the United States (775), China (536) and Japan (309) (European Commission, 2020[16]).

The *Mittelstand*, which represents the vast majority of firms and accounts for half of the economy's output, plays an important role in driving innovation in the country. While large firms are among the most significant business-sector players in innovation, they are in the minority: over 99% of German firms have fewer than 500 employees, a size category referred to in Germany as the *Mittelstand*. This category – which comprises both the OECD definition of SMEs as enterprises employing fewer than 250 employees, and firms numbering 250-500 employees – is highly heterogeneous in terms of size, employment and its contribution to innovation: 64% have fewer than 9 employees and account for only 4.3% employment in the business sector, while 28% have 10-249 employees and account for 34% of employment (OECD, 2021[17]). Roughly 6.5% of German firms number 250-499 employees and are included in the German definition of the *Mittelstand*.

Germany's "hidden champions" are particularly important for innovation in the *Mittelstand*. According to BMWK, Germany has an estimated 1 300 hidden champions – firms that are considered global market leaders, with particularly well-developed competencies in specialised technology areas (BMWi, 2020[18]).[6] While they account for only 1.8% of *Mittelstand* firms with 10-500 employees, their engagement in innovation is higher relative to other firms with similar characteristics. A recent study suggested that hidden champions – classified as firms that have an export share over 50% and sales beyond Europe, rank among the top three sellers in their market, and whose market growth exceeds the industry average by 10% – outperformed competitors in terms of their innovation activities. For example, hidden champions accounted for significantly higher stock of patents over 20 years (91 patents per hidden champion versus 55 for the comparison group of firms), with significant differences in training expenditure per employee and wage levels (Rammer and Spielkamp, 2019[19]).[7]

However, innovation success is unevenly distributed along gender lines and socio-economic groups. Fewer than one in ten German PCT applications published in 2020 came from female inventors, likely reflecting that women remain under-represented in some of Germany's key innovative sectors, such as transport (9.1% female PCT applicants globally in 2020), chemical engineering (15.1%) and electrical machinery (11.7%) (WIPO, 2021[20]). This sectoral divide is due in part to the persistently low inclusion of women in science, technology, engineering and mathematics (STEM) subjects: in 2018, female STEM graduates numbered 11.8 per 1 000 population, compared to 27.8 per 1 000 for men (OECD, 2021[21]). Migrants and disadvantaged social groups in Germany face similar inclusion challenges, which may contribute to missed contribution to innovation by large sections of the population.

While there exist regional divergences in patenting activity, the geographical concentration of patent applications at the city level in Germany is less pronounced than in other OECD countries. Germany has a lower geographical concentration in 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[22]). The concentration is more pronounced for some technology areas than

others, likely due to the localised concentration of specialised knowledge around a small number of research institutions and industrial actors. For example, patenting in digital technologies and biotechnology is the most concentrated in the country, with the top 10% of cities accounting for around 41% (digital) and 45% (biotechnology) patenting in 2010-14, higher than the average across all technology fields over the same period. On a per capita basis, applications per 100 000 habitants numbered 123, 97 and 36 in the top 3 regions, compared to 12, 7 and 7 for Brandenburg, Mecklenburg-Vorpommern and Sachsen-Anhalt (Paunov et al., 2019[22]). The regional concentration of patenting activity – and of innovation activities more broadly – is not necessarily a sign of strength or weakness, but it does have implications at the level of local socio-economic well-being and growth, particularly in a context of structural change that may affect some regions.

Some divergences within the business sector suggest that innovation activities from certain firms remain below their potential. Between 2003 and 2018, BERD by large firms (over 500 employees) increased by 53%, compared to only 17% for small firms (up to 250 employees) (OECD, 2021[12]) and 43% for medium-sized firms (250-500 employees), which the German government classifies as part of the *Mittelstand*.

1.2. SWOT diagram of Germany's innovation system

Table 1.1 provides a synthetic SWOT diagram of Germany's innovation system, discussed in further detail in sections 1.3 and 1.4.

Table 1.1. SWOT diagram of the German innovation system

Strengths	Weaknesses
• A highly innovative export-oriented manufacturing sector, especially in automotive, machinery and electronics, chemicals and pharmaceuticals • Large leading and standard-setting firms with well-established value chains in Germany and abroad • Well-established internationally leading research and applied research institutions supporting industry and government • Strong linkages between science, academia and industry, and strong track record in commercialising research • Strong framework conditions for business innovation, including strong education system providing a qualified technical workforce, especially in engineering, and good innovation-funding options, including for *Mittelstand* firms • High political recognition of the importance of innovation for Germany • Strong and effective STI policy-support infrastructure, with large public funding and institutional support mechanisms	• Shortcomings in digital infrastructure, and weak uptake of frontier digital tools among small firms and the public sector • Shortage of certain key workforce skills such as STEM and digital competencies, particularly for *Mittelstand* firms, exacerbated by the impacts of population ageing • Limited business dynamism and limited opportunities for start-ups to scale, also as a result of low levels of venture and growth capital compared to the US market • Limited leverage of diversity in innovation activities, including the contributions of women, minorities and different generations • Limited strengths in knowledge-intensive services and collaborations across sectors and institutions, including research institutions' collaborations with the *Mittelstand*, critical to the sustainability and digital transformations • Limited use by the public sector of new and digital tools and approaches to deal with disruptive change and transitions and improve STI policy, including through public consultation, policy experimentation, and advanced data-analytics tools exploiting large data from the STI system • Complex regulatory frameworks for the implementation of innovative investment (including infrastructure), digital tools and data-sharing practices

Opportunities	Threats
• Advanced and innovative large firms and innovative *Mittelstand* firms are well placed to become world leaders in the sustainability transition and future developments of the digital transition • Huge public purchasing power through procurement and public investment allows stimulating demand for innovations, particularly in markets of the future • Exploiting connections between industry and research institutions, as well as highly successful intermediaries, to bring together diverse interdisciplinary expertise as needed for more disruptive innovation and digital innovation, including more strategic partnerships between industry and science • Industrial and research base are well-positioned to move into new technologies and adapt existing manufactured products to lead in markets of the future (e.g. quantum, batteries, sustainable energy) • Promote a more entrepreneurial culture at universities by rewarding students and research staff for engaging with industry, including SMEs, to support transformation processes • Utilise widespread societal agreement on the needed sustainability transition to build cross-societal partnership missions that steer innovation systems in support of objectives • Transform distributed responsibilities for research and innovation at the federal and state levels into an asset by actively adopting a lead-actor model of the transitions across states • Exploit leadership position within the European Union and globally to set standards and quality infrastructures supporting the German, European and global economy, as well as to develop the desired better socio-economic futures that take advantage of technical opportunities and curb challenges	• US and Chinese leadership in digital tools – including artificial intelligence (AI) – and services and intensive global efforts to lead in other core emerging technology fields may challenge Germany's global competitiveness, including in its core sectors of leadership (e.g. automotive, machinery and electronics, chemicals and pharmaceuticals) • Sustainability transition may transform markets in ways that challenge Germany's leadership, notably due to changing mobility patterns' impact on the automotive sector • New and often disruptive technological paradigms may increase German dependence on foreign expertise in several key future fields (e.g. gene editing, genetically modified food and big-data analytics) • Population ageing and lack of inclusivity reduce the available workforce for the STI system, making it necessary to optimise lifelong learning and exploit the diversity of the system • Global uncertainty in the evolution of international trade creates uncertainties affecting the resilience of the STI system, including future global supply chains

1.3. Strengths and structural weaknesses of the German innovation system

The business sector has sustained Germany's international competitiveness for several decades

The business sector continues to be the main driver of innovation expenditure in the German economy. After falling for the first five years after reunification, BERD has risen steadily, from 1.42% of GDP in 1994 to 2.1% of GDP in 2020 (OECD, 2021[11]). The vast majority of GERD originates in the business sector, which accounted for 69% of GERD in 2019, roughly the same level as before the 2008-09 Global Financial Crisis. The share of BERD by firms with over 500 employees has remained steady since the early 2000s (89% of total BERD in 2018 versus 88% in 2003). Given Germany's innovation success, the concentration of R&D within large firms partly reflects the industrial structure of its economy. Nevertheless, the country may be missing out on contributions to innovation from smaller-sized firms, which could enhance the overall system and expand opportunities for more inclusive growth. Such growth is particularly relevant in innovation-intensive service sectors, where evidence from other countries suggests that SMEs and start-ups – defined here as firms that has been active for two years or less – have particular innovation strengths. However, the contributions of smaller-sized firms will depend on the sector in which they operate. For example, sectors where platforms and networks have gained importance thanks to the digital transformation may present different opportunities than traditional manufacturing sectors.

Manufacturing contributes significantly to Germany's innovation expenditures, driven in large part by the automotive sector. Manufacturing sector makes a substantial contribution to BERD in Germany, accounting for 85% of all intramural R&D – a substantially higher share than in comparable economies like the United States (64%) and France (49%). In 2018, the German automotive industry accounted for 37% of domestic BERD and 24% of global automotive BERD. No other large industrialised country has a comparable level of sectoral concentration of innovation funding and capacity in any single sector. Of the world's leading automotive companies in terms of global R&D expenditure, four of the top ten – Volkswagen (first), Daimler (second), BMW (sixth) and Bosch (seventh) – are located in Germany (European Commission, 2020[16]). Thanks to Germany's private-sector leaders (comprising both large corporations and "hidden champions"), the private sector plays a key role at regional, national and even global levels.

Electronics, machinery, chemicals and pharmaceuticals are also important contributors to innovation in Germany. In addition to their globally leading investment positions, these sectors accounted for 11.4% (electronics), 9.9% (machinery), 7.2% (chemicals) and 5.8% (pharmaceuticals) of total BERD in 2018, the last year for which comparable data are available (OECD, 2021[12]). While these figures are low relative to the automotive sector's contributions, they are significant in nominal terms (with electronics accounting for EUR 8.3 billion, machinery EUR 7.1 billion, chemicals EUR 5.2 billion and pharmaceuticals EUR 4.1 billion) and substantially higher than BERD in the same sectors in other leading innovative nations, such as France and Italy. In addition, Germany has a number of global leaders in these sectors, including Siemens (second globally for R&D in the electronics industry), Bayer (eighth for pharmaceuticals) and BASF (first for chemicals) (European Commission, 2020[16]).

High-quality and international research is a hallmark of German business innovation. In addition to the IP5 patent applications mentioned in Section 2, Germany's high level of BERD has also supported a significant number of high-quality inventions, as demonstrated by the global share of triadic patent families attributed to German inventors.[8] Germany also demonstrates a strong level of research internationalisation, evidencing the global nature of domestic firms' R&D activities. In 2018, for example, co-patents accounted for 16% of total patenting – a share which, although behind the United Kingdom and France, is ahead of major competitors such as Japan and Korea (OECD, 2021[23]). In terms of high-quality research output, Germany has the fourth-highest contribution (4.4%) to the top 10% of top-cited scientific publications in the world's top 10% most-cited scientific journals, behind only China (20.7%), the United States (20.5%) and the United Kingdom (5.2%).

High-quality public research organisations have supported a skilled workforce and research for innovation, underpinned by well-established knowledge-transfer mechanisms

Public research organisations and universities generate strong scientific inputs and ideas that support business innovation. Between 2001 and 2017, the share of researchers per 1 000 employed increased by 43%, from 6.6 per 1,000 to 9.9 per 1,000, the third-highest level in the world, behind only Korea (13.4, 56% increase) and Japan (10, no real change) (OECD, 2021[12]). This research basis has led to a strong output, with Germany accounting for 4.4% of the world's top 10% most-cited scientific publications and 3.7% of the world's total scientific publications, the fourth and fifth highest levels globally (OECD, 2021[24]). Leading public research organisations, such as Max Plank Society, are widely recognised for their high-quality basic research.

A long and sustained process of institutionalisation has created a differentiated institutional ecosystem for knowledge transfer. Whereas institutionalised knowledge transfer in many OECD countries has often emerged as part of special policy programmes (for example, *pôles de compétitivité* in France, established in 2004, or the "Catapult" programme in the United Kingdom, launched by the government in 2011), similar institutions in Germany – such as the Fraunhofer Society or industrial co-operative research institutions (*Arbeitgemeinschaft industrieller Forschungsvereinigunge*n) – have evolved

over many decades. Thanks to the system's strong linkages with German industry, these knowledge-transfer institutions have evolved in such a way that their output and orientation has been naturally beneficial to German competitiveness, whereas initiatives in other countries are often more top-down and government-directed. In addition to the well-known knowledge-transfer institutions, several thematical programmes are also available to support industrial and business commercialisation of science research in a range of areas, from energy and biotechnology to construction. At the same time, open technology programmes, such as ZIM, have strengthened inter-firm collaboration in different areas of market-oriented and high-risk innovation.

Germany has a well-functioning higher education system, with mature and institutionalised public-private co-ordination and co-operation supplying skills suited to the needs of the innovation system. The Humboldtian university model, which has historically emphasised research, knowledge generation and intellectual inquiry, together with the country's well-regarded technical universities, which focus on engineering and applied sciences, have contributed to Germany's rich supply of well-educated labour-market entrants. Tertiary-level attainment is high, with 1.6% of 25-64 year-olds (eighth-highest level worldwide) and 2.1% of individuals under 35 (third-highest level) graduating from a doctoral or equivalent programme (OECD, 2021[25]). Thanks to the close collaboration between industry and academia, Germany's educational institutions have ensured that the skills of individuals entering the industrial sectors are suited to innovation and practical application. Germany also has a very well-developed and widely respected vocational education training (VET) system, with a strong dual component integrating learning in schools and workplace training. The VET system has extensive coverage. In 2019, 50.7% of adults aged 25 to 64 years old (the third-highest share in the OECD) and 43.8% of 25-34 year-olds (second-highest) had received a vocational upper-secondary or post-secondary qualification in Germany. The VET system has played an important role in supporting the workforce's capacities to absorb innovation.

Germany has a well-established and decentralised policy framework for innovation, supported by a rich policy mix

At the federal level, innovation and research are steered by BMWK and the Ministry of Education and Research (BMBF). As of 2021, there were 14 federal ministries. BMWK and BMBF have the most important roles for innovation, in co-operation with other federal ministries (such as health, transport and the environment) in areas where innovation intersects with other policy areas. Implementation is generally delegated to agencies, such as the Federal Institute of Material Research and Testing (*Bundesanstalt für Materialforschung und -prüfung*) and the National Metrology Institute (*Physikalisch-Technische Bundesanstalt*). BMBF focuses on policy areas that are implemented through higher education and publicly funded research institutions. BMWK generally focuses on areas where innovation policy and applied research can support the business sector, as well as environmentally sustainable industrial development.

A consistent theme in the BMWK approach to innovation policy is the importance of "technology openness" – a sector-agnostic approach to supporting innovation. As part of its broad "Transfer initiative", BMWK reformulated its technology-neutral approach in the 2021 "From Idea to Market Success" funding programmes, which emphasise a bottom-up selection of innovation and technology investment, particularly for the country's SMEs (BMWi, 2021[26]). The "open technology" approach has been a highly successful hallmark of German innovation policy for many years. It is underpinned by the understanding that a degree of non-directionality allows policy to support both technology push and pull, stimulating innovation from both the demand and supply sides. The suitability of a technologically neutral approach to address transitional challenges may require adjustments to advance transitions. For example, the networking and co-ordination dimensions of the digital and sustainability transitions, and efforts by the government to build more resilience in the STI system, may require more co-ordination and guidance from government. The Federal Government does have several more directional tools for stimulating demand and creating markets. One approach is public procurement, which demonstrates that a co-ordinated effort by the federal and state (Länder) governments can stimulate innovation at the firm level. Public

procurement – particularly "innovative procurement" – are policy levers in the Federal Government's "INNO-KOM" transfer programme.

The government has designed robust strategies to help the German innovation system respond to future transformation opportunities and challenges. To co-ordinate some of the technology- and sector-specific strategic plans, it also developed a High-Tech Strategy (HTS), whose fourth edition was issued in 2020. A monitoring and consulting body, the High-Tech Forum, comprising members from industry, science and civil society, supports the implementation of the HTS. Several more granular strategic documents underpin the HTS, including for many frontier areas of science and innovation, such as the Artificial Intelligence Strategy (2018-20), the Autonomous and Connected Driving Strategy (2015) and the National Hydrogen Strategy (2020). These strategies reflect the importance of developing domestically key enabling technologies that will ensure Germany's future competitiveness and socio-economic resilience. Although most also emphasise creating framework conditions for innovation, they offer few direct inducements or incentives for undertaking innovation activities. The Federal Agency for Disruptive Innovation (SPRIND) is creating – like the Defense Advanced Research Projects Agency in the United States – spaces for innovators where they can take risks and think radically different.

Federal financing of R&D is administered by several ministries, with BMBF, BMWK and the Federal Ministry of Defence (BMVg) the largest contributors. In each ministry, federal funding is distributed either through project-based financing for R&D – directly through the targeted development of specific technologies or indirectly through support for the diffusion of certain technologies – or through institutional funding. The largest share (58.4%) comes from BMBF, because its budget covers federal institutional funding for public research agencies (around 45% of total federal R&D financing). Beyond direct institutional financing, BMBF also funds thematic research in areas ranging from health and environmental sustainability to material science and technologies, such as AI, microelectronics, high-performance computing, quantum technologies and photonics, production technologies and batteries. BMWK is the second-largest federal funding body (22.8%), with resources primarily allocated to project-based programmes, including ZIM and some thematic programmes in areas such as digitalisation, the automotive sector, energy, aviation and transport. BMVg is the third-largest R&D-funding federal institution, allocating its resources primarily to large defence R&D projects and procurement.

The Federal Government's direct financing of R&D is a cornerstone of German innovation policy. GOVERD is the third-highest in the world at EUR 17.4 billion, and the second-highest (after Korea) relative to GDP (0.44%) (OECD, 2021[12]). Most direct government funding of firm-level innovation is administered through grants for R&D projects from major federal programmes, as well as state-level R&D programmes. Programmes such as ZIM, INNO-KOM and IGF are important drivers of technology transfer between research and the country's SMEs, and are crucial to ensuring that the private sector is able to absorb innovative ideas and technologies. In 2020, the Federal Government also expanded its use of indirect financing for R&D with the introduction of the Forschungszulage, which grants a 25% tax credit to SMEs on their in-house R&D personnel costs and a 15% credit on their extramural R&D costs for research contractors located in the European Economic Area. The thematic focus of government R&D financing is generally tied to strategic policy documents, such as the HTS. The government has also introduced several thematic finance and policy instruments in support of innovation, such as the "Kopa 35c" programme, which finances sustainable innovation in the automotive sector, and the Industrie 4.0 strategy, which supports the digital transformation of manufacturing.

The government has numerous policy programmes that support start-ups in Germany, and developing venture capital (VC) markets for high-potential entrepreneurship is a policy priority. Through programmes such as the *High-Tech Gründer Fonds* (Venture Capital for High-Tech Founders), EXIST and INVEST, the Federal Government has developed a relatively robust policy-support framework for start-up growth in Germany. In 2021 it also launched the Future Fund (Zukunftsfonds), a EUR 10 billion equity fund managed by KfW bank, which will support start-ups in the growth phase. Nevertheless, despite the importance of VC for innovative start-ups, financing levels remain low compared to other

technologically advanced economies, such as the United States and the United Kingdom. In the absence of sufficiently developed domestic VC markets, many high-tech German start-ups have sought growth finance from foreign (mainly US) investors.

The decentralised governance of Germany's innovation ecosystem has a number of advantages. First, the high level of decentralisation and regional autonomy helps focus policy interventions on local socio-economic needs, including at the industry level. In practice, this allows regional policy makers to tailor innovation policy (or indeed other policy inducements for innovation, such as tax incentives) to local business and industry needs, as the Länder are free to make localised fiscal interventions (including through income taxes) to create inducements for innovation at the sub-national level. In addition, education policy (including for universities) is devolved to the Länder. Similarly, public research organisations and universities enjoy a high level of autonomy, and are free to set their own research priorities independent of government directives. This has helped create linkages between public research organisations, local government and industry, and is an example of successful bottom-up innovation activities.

The high degree of regional autonomy in the STI system help policy makers design and implement more effective STI policy. Greater regional autonomy enables policy makers to focus on regional competitiveness issues, respond with more agility to local policy interventions, and better target the actors and sectors they will support. German policy makers must fully exploit these clear regional-level advantages, while at the same time developing a more co-ordinated and coherent national approach towards horizontal innovation challenges, such as the sustainability and digital transformations.

Germany's federated system of governance also creates challenges for the STI system. The high degree of autonomy enjoyed by regional actors in the STI system means that attention is given to local priorities, which can hinder both the implementation of federal government-level objectives, and the coherence of cross-country and cross-government ambitions. Moreover, fragmented approaches to digitalisation – including data sharing, technology transfer at the university level and within the education system more broadly – can make it more difficult to create more suitable conditions for innovation.

Germany has one of the world's most advanced and well-respected quality and certification systems (or "quality infrastructure"), which has supported international competitiveness. The country has a strong tradition of addressing issues of standardisation, certification and regulation from the perspective of creating competition-neutral instruments that support the public good. The prominence of German manufacturing – and the innovation that powers it – means that its regulatory standards have become internationalised, as German industry is intricately woven into global value chains and has high market shares in several manufacturing sectors (particularly automobiles and machinery). This ability to shape the regulatory environment and standards beyond its borders is a key strength of German industry. Indeed, being a "rule-maker" rather than a "rule-taker" can underpin Germany's innovation leadership ambition. This position, however, is challenged by its lack of international leadership in some key areas central to future economic competitiveness, notably digital and advanced technology fields such as AI, robotics, batteries and quantum computing.

Given the export-oriented nature of the German economy, innovation policy has an important international component. Germany engages closely with the European Union in several areas of innovation policy. International co-operation tends to have a higher level of directionality, particularly in supporting key enabling technologies (such as semiconductors, hydrogen and batteries) and data infrastructure. In such cases, a critical mass of technological competency at the supra-national level would have benefits for all EU Member States, both from an innovation perspective and potentially within the context of ongoing debates on technological sovereignty. The direction of innovation within the German business sector, which is highly integrated into numerous global value chains, also has systemic implications for the European Union. The German Federal Government has been working to establish an Important Project of Common European Interest on Next Generation Cloud Infrastructure and Services (IPCEI-CIS) at the EU level, having committed EUR 750 million to the project (BMWi, 2021[27]). At the same

time, EU-level co-operation reflects difficulties in adopting a more directional approach at the national level in many of the same fields, with a risk that authorities may fall foul of EU state-aid rules. Moreover, quality infrastructure has an implicitly international component as it supports free trade, which is vital to Germany's export-oriented economy.

Despite clear strengths, Germany's innovation system has several structural weaknesses

Given the significant public support measures for SMEs in innovation, as well as the size and industrial composition of the German economy, the contribution of SMEs, start-ups and young firms to innovation is lower than it could be. As in all other leading R&D-investing countries, large firms represent the bulk of Germany's BERD. However, the relative decline in the *Mittelstand*'s contribution to innovation activities in previous decades is a concern. It began in the late 1990s, but has accelerated since the 2008-09 Global Financial Crisis, with the volume of innovation expenditure by SMEs in 2019 accounting for just 29% of that invested by the country's large firms, compared with 73% in 1995. The government is aware of this challenge and is particularly intent on improving the access of SMEs to research institutions. The BMWK's "From Idea to Market Success" programme aims to counter this trend.

Expanding the engagement in innovation of SMEs and start-ups will strengthen inclusivity. Since SMEs account for 99% of the country's firms and 56% of total employment, an increasing divergence between SMEs and large firms would result in a growing concentration of productivity gains within a relatively small section of the working population (Destatis, 2020[28]). While many of Germany's innovation programmes do accept applications from first-time innovators, knowledge-transfer initiatives have historically been oriented towards firms that already perform innovation activities. Many smaller firms, including start-ups, have therefore been ineligible for publicly backed research and innovation support. It is encouraging that an increasing number of participating firms in government-backed innovation programmes are first-time applicants, although the cumbersome processes involved in applying for support may nevertheless lower the reach of these programmes.

Young firms contribute very little to innovation in Germany. Firms that have been active for less than five years represent a very small fraction of total R&D and innovation expenditure in the German enterprise sector. This may partly reflect the low share of start-ups in the business population, with Germany's share of firms that have been active for two years or less the second-lowest in the OECD (OECD, 2021[29]). Furthermore, innovative entrepreneurship has been weak for many years, albeit more dynamic in recent years. Germany does not have same level of new – often disruptive – innovative firms as other countries, such as the United States and the United Kingdom. In 2020 and within the group of European Union (EU27) countries and the United Kingdom, for example, Germany accounted for 14% of investment in AI start-ups, after the United Kingdom (55%). Linkages between AI firms and SMEs or larger firms in industry is also low, and diffusion of AI in firms for activities such as data analytics, natural-language processing, image recognition and automation remains at an early stage. These dynamics may affect the German economy's innovative capacities, to the extent that existing firms cannot reinvent themselves or adapt to a changing economic environment.

Germany's innovation system needs to opt more for disruptive and radical innovations as the success of the current incremental innovation model will not secure leadership in the future. The major paradigm shifts under way in the global economy of sustainable development and digitalisation require investing in more disruptive and radical innovations for future leadership. These investments are riskier than more incremental innovations and are less obvious in a context where the current innovation model is still highly successful in securing revenues to respective industries. This is illustrated by the continued export success of German cars. Particularly for *Mittelstand* and young firms pushing for disruptive and radical innovations will not be straightforward, with access to human capital and knowledge providers in research institutions being critical. The Federal Government's decision to establish SPRIND

in 2021 demonstrates a growing policy appreciation of the need to support breakthrough and disruptive innovation, acknowledging requires a different – more risk-tolerant and ambitious – approach to STI policy support.

Challenges in financing start-ups and innovation create risks that high-potential firms will flee and others will miss out on innovation opportunities. The German VC market remains small in both international comparison and relative to the economy's size. One of the main challenges to financing innovation in Germany is the ability of firms to access growth and late-stage capital, where investment needs are generally higher. The lack of such funds has led high-potential German start-ups to turn to foreign capital markets to launch initial public offerings or obtain later-stage venture financing. The lack of institutional investment hinders the development of this type of financing in Germany. German pension funds, insurance companies and public financing organisations provide very little risk capital, yet are among the only sources of finance that could provide the levels of capital necessary to scale the most promising innovators.

The German economy in general, and its innovation system in particular, suffer from a gender imbalance. Women remain a minority in management positions. According to the latest OECD data, only 13% of German technology start-ups in 2015 were led by women, which is likely to have an impact on the future competitiveness of the German economy, as well as inclusivity (OECD, 2020[8]). Women's participation in innovation and innovative entrepreneurship may be hindered by the same factors that hinder women's full-time employment more generally, notably the high tax burden on second earners and the insufficient supply of full-day childcare and full-day schooling (Yashiro and Lehmann, 2018[30]). The under-representation of women in innovative activities is also partly a result of the large proportion of BERD undertaken in industries where the inclusion of women has historically been low, also owing to the gender gap in STEM studies: in 2018, two out of three tertiary STEM graduates were men, perpetuating female under-representation in key sectors. It is therefore necessary to improve women's inclusion in STEM – as well as future innovators' skills – to meet the needs of increasingly data- and digital-driven innovation (OECD, 2020[8]).

Germany is confronted with skill shortages in several fields that are critical to innovation, including the provision of more cross-disciplinary training. The 2020 skilled labour monitor (*Fachkräftemonitoring*) of the Federal Ministry for Labour and Social Affairs found that labour bottlenecks are most pronounced in occupations that require a high degree of ICT skills, as well as in health care professions, skilled trades, and occupations related to mechatronics and automation technology (BMAS, 2021[31]). Germany does have a good supply of STEM skills from an international perspective, although it may not be sufficient to meet the growing needs of its industrial sectors (OECD, 2021[32]). Skill shortages are most acute in high-skilled occupations, with more than 7 in 10 experiencing shortages of highly skilled personnel, one of the highest rates in the OECD (OECD, 2021[33]). Beside technical skills, soft and social science skills are also important to advance transformative changes in the economy (for example, service-related innovations are a key vector of the digital economy, with a focus on mobility services rather than car purchases). The historical orientation of the German labour force is clear when observing the specialisations of tertiary graduates in the domestic labour market. For example, Germany has the joint-lowest share of social science graduates (24%) in the EU labour force, but the joint-highest share of engineering graduates (25%) (Paunov, Planes-Satorra and Moriguchi, 2017[34]). Promoting more cross-disciplinary training for engineering and social science graduates could enhance their future contributions to the economy.

Germany's demographic outlook, particularly its ageing population, presents a challenge for both its innovation system and broader socio-economic well-being. Germany's population is ageing at a faster rate than in most other OECD countries. The country's dependency ratio – which measures the number of people over the age of 67 per 100 people of working age (taken by the German government to range from 20 to 66) – is the third-highest in the OECD and set to double in the next 35 years (German Federal Statistic Service, 2021[35]). Germany's changing demographics impacts German economic

competitiveness in two important ways. First, lower levels of labour replacement (new workers replacing retiring workers) mean that labour shortages in certain areas of the economy are likely to increase (OECD, 2021[32]). Second, Germany has seen decreasing firm-entry rates at the same time as the demographic group most likely to start a business (30-50 years) has been shrinking, a trend that will accelerate in the coming years (OECD, 2020[8]). These challenges are significant, particularly in a context where start-ups can play an important role in developing the innovations necessary to remain internationally competitive in emerging technologies and digital services. If structural barriers hamper innovation, the implications for innovation at the aggregate level could be significant. The demographic context also requires offering opportunities for migrants to participate in the country's innovation system. In addition to individuals already residing in the country, this involves attracting people who possess the skills and experience demanded by Germany's innovating firms. Germany should therefore continue to ease the conditions for attracting foreign talent and facilitating start-up creation by highly skilled foreign-born professionals and scientists (see the BioNTech case below).

Mittelstand and start-ups face well-known challenges in accessing diverse research knowledge and expertise. According to the 2018 Mannheim Innovation Survey, about 38% of innovating large firms in 2018 actively engaged in collaborative research with higher education institutions or public research organisations, compared to only 17.5% of innovating SMEs; the local and regional dispersion of knowledge represented a particular constraint on collaboration (ZEW, 2018[36]). The BMWK's "Transfer initiative" was conceived specifically to increase the number of SMEs that bring a new idea to market (BMWi, 2021[37]). Research institutions also suffer from long-standing issues related to unfavourable career paths, inflexible working conditions, roadblocks to mobility and a lack of incentives for engaging with *Mittelstand* and start-up firms, minimising the potential contribution of publicly financed research institutions to economic innovation.

1.4. The German innovation system and its preparedness for future challenges

The STI system is mature and functions well, but is being challenged by structural changes

The STI system must prepare for future transformations, including by building its capacity to provide breakthrough or disruptive innovations. The German STI system has very successfully supported leadership in key sectors – automotive, chemicals and machinery – that characterised the second industrial revolution. It has provided the conditions for continuously improving innovation within those technology areas, building on technical, scientific, institutional and policy competencies. But the future is set to bring broader and more complex change, embodied by: i) advances in digital technologies that may prove disruptive to existing sectors; ii) societal demand for building environmentally sustainable futures; and iii) a global context characterised by uncertainties and increased risk of crises, as illustrated recently by the 2008-09 Global Financial Crisis and the COVID-19 pandemic. In this complex and changeable context, STI policy requires heightened agility, allowing policy makers and firms to respond to unexpected circumstances and events while maintaining the incremental innovations that have underpinned domestic competitiveness for decades.

Business innovation, research priorities and knowledge-transfer activities are heavily influenced by industry incumbents. This orientation of the STI system may impeded the emergence of disruptive and breakthrough innovation, and consequently the German economy's ability to maintain its status as a global industrial innovator. Industrial and manufacturing firms, particularly in the *Mittelstand*, have focused less on innovation activities that support technologies that support transitions (whether digital technologies and ICT, or environmental mitigation technologies), yet are particularly vulnerable to the impact of these transitions on their products and markets. The low entry of new innovative firms may further slow change in this context. A major issue with digitalisation is whether "winner-takes-most" markets characterised by

a few dominant firms will affect opportunities for *Mittelstand* firms to compete, with implications for the future innovation economy's inclusivity (Autor et al., 2020[38]).

An STI policy system that supports change will help prepare for future challenges by introducing more flexible structures and open innovation tools, as well as engaging more with civil society. Greater engagement with civil society can both improve the quality of STI policy – by harnessing a greater number of inputs – and mitigate the asymmetrical socio-economic impacts of STI policy interventions. From a policy design perspective, this could entail a broader use of strategic foresight approaches (such as the BMBF-Foresight "Vorausschau") in STI; building powerful data analytics and visualisation infrastructures at a granular level in the STI system to help design more impactful STI policies, and improve their evaluation and monitoring; and employing experimental policy tools (such as sandboxes) to facilitate implementation. Engaging with society is also important in a context where technological developments affect society, and consequently the uptake of tools resulting from those technologies (Paunov and Planes-Satorra, 2021[39]). New digital tools offer better ways of capturing societal perspectives, including through public forums. From a policy instrument perspective, using regulatory sandboxes and introducing flexibility in regulations can support experimentation, which could drive future success. Adequate tools to address barriers to breakthrough innovations, such as skill shortages and research capabilities in key enabling technologies, are also important.

Germany lags behind in the digital innovation field

Limited digital connectivity may hold back innovation. Germany has a relatively low level of digital connectivity, particularly in terms of fixed high-speed broadband networks and the penetration of high-speed long-term evolution mobile data networks. Levels of fibre-optic broadband connections are substantially below the OECD average: in 2019, 1.72% of total fixed broadband subscriptions were for fibre, compared to 8.91% on average in the OECD (OECD, 2020[8]). Only 36.9% of firms in small and rural municipalities of Germany had access to broadband with download speeds greater than 30 megabits per second, compared to 52.3% in cities (OECD, 2020[8]). The government recognises the importance of closing the connectivity divide and has undertaken a number of initiatives to support the expansion of better-quality digital infrastructure. For example, it established the Mobile Communications Infrastructure Company, which aims to close almost 5 000 "blackspots" in the country's 4G network. Although there is no agreed method for benchmarking 5G rollout, progress in Germany so far has been relatively slow. The private sector is also set to make a significant investment in the country's broadband infrastructure, with the telecommunication association BREKO estimating that some EUR 43 billion will be spent by 2026 to roll out high-quality fibre broadband (Fibre Systems, 2021[40]).

Poor connectivity has already had an impact on German firms' ability to maximise opportunities from digital technology. The slow diffusion of ICT and digital tools is a particular challenge for the innovative competitiveness of Germany's *Mittelstand*, and consequently their preparedness for a more digitally driven economy. Data already suggest that Germany has fallen behind in the uptake of certain key digital technologies. For example, the country significantly lags the OECD best performers in cloud computing, high-speed broadband and big-data analysis (OECD, 2020[8]). Low levels of advanced ICT adoption may partly explain Germany's similarly low processing of data from firms' sensors and devices compared to the best-performing nations, a crucial component of Industry 4.0 which requires investing in high-quality connectivity infrastructure. Other issues – such as outdated data regulations, concerns over cyber security, limited access to finance for corporate digitalisation programmes, limited digital sandboxes, and low levels of investment in the type of knowledge-based capital necessary to create more value from data and digital technologies – contribute to holding back the innovative potential of many German firms.

The slow diffusion of digital technologies and ICT in the public and private sectors may also stem from a lack of skills. As mentioned above, the limited supply of STEM graduates, ICT professionals and data specialists may slow the adoption of new technologies, hampering innovation (OECD, 2020[8]). For

example, employment of ICT specialists is strongly associated with firms' adoption of new ICT tools and activities supporting data-driven innovation. Neither the public nor the private sector is currently able to take full advantage of the opportunities presented by digitalisation. Government services continue to be very analogue-based compared to other OECD countries. Germany ranks twenty-sixth in the OECD Digital Government Index, denoting factors such as low digitalisation in the public sector, limited use and interoperability of data, and the limited digitalisation of government services (OECD, 2020[41]).

Germany's international competitiveness has been closely tied to its status as a world-leading innovator in key industries, but the frontier of digital innovation that drives changes across the economy lies elsewhere. In contrast to Germany, the United States, Japan, Korea and China dominate the global share of ICT patents. This is true for both general ICT patenting and more advanced applications, including important general-purpose technologies like AI and nanotechnology. In 2017, Germany accounted for 146 AI-related IP5 patent applications, compared to 1 065 applications from the United States and 1 115 from Japan. In terms of publications, only 2 of the top 50 corporations publishing on AI were from Germany in 2014-16 (OECD, 2019[42]). A similar dynamic applies to nanotechnology, which is a crucial input for the types of semiconductors necessary for the next generation of autonomous driving, as well as a range of other advanced applications: in 2017, Germany accounted for just 17 IP5 patent applications in nanotechnology, far behind the United States (140) and Japan (112). In practical terms, this means that unlike in the past, when German inventions wielded significant influence over manufacturing and industrial processes around the world, German firms will rely increasingly on innovations – and the standards that determine their use – originating beyond its borders. The divide is reflected in German digital firms' lack of global prominence compared to other leading nations in digital innovation, with only 3 firms among the top 100 digital corporations by market capitalisation headquartered in Germany, compared to 13 in China and 59 in the United States (PwC, 2021[43]).

Beyond strictly digital sectors, Germany's position as a global leader in manufacturing will come under pressure as value added derives increasingly from products' digital component. Germany's automotive sector is a strong innovation performer, accounting for some 43% of global patents in "electrical digital-data processing". The digitalisation of the automotive sector will have implications for German manufacturers in several other areas, including the valorisation of digitally embedded services in products, the acceleration of innovation cycles, the opportunity for greater collaboration in digital innovation and firm-level investment in digital solutions to reorganise internal processes. In the German automotive sector in particular, core value added may shift to digital components as the importance of internal combustion engines – a key source of value added in the sector – wanes.

The digital transition will have uneven distributional effects. According to the latest projections of the Federal Ministry for Labour and Social Affairs, approximately 5.3 million jobs will disappear in the next 20 years (until 2040), while 3.6 million new jobs will be created (BMAS, 2021[31]). While accounting for a broader range of issues beyond digitalisation, these findings are in line with OECD observations on the impact of technological transformations on the labour market. For example, Germany is likely to see significant labour displacement due to automation, compounding labour-market and demographic challenges. A 2018 OECD analysis estimated that a large number of jobs across the OECD could be displaced due to automation (Nedelkoska and Quintini, 2018[44]). At the same time, the increasingly digital and knowledge-intensive nature of German firms may aggravate the existing regional divide in terms of productivity, investment and infrastructure quality, especially if there is limited public investment to address some of these issues. Ensuring that displaced workers are equipped with the necessary skills to remain in the labour market, and considering digital technologies (such as high-quality internet connections) as a public good that is necessary to ensure firms' competitiveness, will be a key challenge for policy makers in the years ahead.

The impact of COVID-19 also highlighted the need for a better digital infrastructure. As workers were required to operate from home owing to pandemic-related restrictions, and businesses sought ways to keep lines of communication and collaboration open, the importance of digitalisation to the future of work

became increasingly obvious. Deficiencies in the digital infrastructure (such as inadequate bandwidth to support video conferencing or cloud-based collaborative working), as well as skill-related issues, highlighted the different levels of preparedness of different actors across the German economy. The crisis also underscored the importance – and potential – of advanced real-time reporting, which made it possible to integrate detailed and frequent updates on the public health situation into policy making, although this was somewhat impeded by the limited digitalisation of different actors within the public administration.

The sustainability transition affects the core of Germany's innovation strengths and provides an opportunity for leadership

Meeting Germany's reduction targets as part of the Paris Agreement will require fundamental changes within German industry. The example of Germany's automotive industry is particularly edifying in terms of the innovation challenges facing the country's economy and future competitiveness. On the one hand, demand for internal combustion vehicles should continue to fall owing to changing mobility habits and the international shift toward decarbonisation, although the transport sector will remain a major source of carbon emissions in Germany. The country's high-value vehicle exports will likely face lower demand at a time when high-priced product strategies – such as those pursued by the country's automotive manufacturers – are becoming increasingly vulnerable to disruptive innovation.

The automotive sector is a clear example of the interconnectedness of technological competencies for sustainable transitions and key sectors of the German economy. For example, the share of electric vehicles in global car sales continues to grow every year as electric vehicles become more advanced and more cost-competitive against vehicles equipped with internal combustion engines. EU legislation to ban the sale of new internal combustion engines from 2035 may accelerate this trend, an indication that climate-related legislation will fundamentally change consumer preferences in the years ahead. Beyond the automotive sector, STI will contribute to a range of technological solutions to environmental challenges, such as carbon storage and capture, a greater contribution of clean energy to the electricity mix and improved energy efficiency. In the absence of stringent carbon pricing – and given that the government has maintained a number of industrial energy subsidies – German industry has so far not faced significant financial pressure to undertake transformational change, but these pressures are likely to grow in the years ahead.

Just as with the digital transformation, decarbonisation can have an uneven distributional effect, which could aggravate existing inequalities if left unaddressed. Policy makers need to think about distributional implications. For example, coal mining is concentrated in a small number of regions such as Lausitz and Rheinland, which have higher levels of unemployment and lower levels of entrepreneurship relative to the national average (OECD, 2020[8]). The phasing out of coal as part of the country's energy mix is therefore likely to create unequal labour displacement, with a risk of increasing inter-regional inequality. The indirect consequences of decarbonisation – for example, in the automotive sector – are therefore likely to affect the German labour market far more profoundly.

Improving sustainability and supporting decarbonisation are also economic opportunities. Germany has already shown that it can use innovation to create new products and markets supporting decarbonisation. For example, the development of feed-in tariffs as part of its Renewable Energy Sources Act – a cost-based pricing mechanism for electricity production that creates incentives for private investment in renewable sources – shows that public policy, when underpinned by STI, can advance structural transformation. These successes, combined with Germany's innovative potential, augur well for the country's ability to meet its decarbonisation targets in carbon-intensive sectors such as transport and industry. Still, political ambition and astute industrial leadership will be necessary to exploit these opportunities. With an ageing public infrastructure in need of significant investment, the government has an opportunity to target subsidies, investment and public procurement to support the creation of new markets underpinning sustainability and decarbonisation.

Germany's Energy Transition Strategy (Energiewende) outlined a committed plan for transitioning to renewable energy. The strategy, which became official policy after the nuclear accident of Fukushima in 2010, included shutting down Germany's nuclear power plants. It also emphasised the role of innovation in energy technologies, the need for smart energy policies and the export opportunities for climate technologies. It also formulated ambitious targets for a number of sub-aspects, such as reducing carbon emissions. Recent innovation indicators show an increase in R&D spending and the number of patents for energy- and mobility-related innovations compared to other environmental technologies (Walz et al., 2019[45]; Gehrke, Ingwersen and Schasse, 2019[46]). However, the strategy has been more cautious about supporting disruptive innovation strategies that would require new consumption patterns to achieve targets. The challenge here is also global. While technological solutions (such as carbon capture and storage, or the use of hydrogen in industrial processes) are gaining in technological feasibility, several more years will elapse before they can be scaled more widely and become competitive. In the context of Russia's war against Ukraine and the ensuing impetus to German energy diversification, a greater contribution of renewables to total energy consumption will require accelerated innovation, combined with greater levels of investment and policy support. Going forward, the question is whether Germany has the right innovation-policy mix to encourage both the diffusion of available low-carbon technologies and the development of breakthrough technologies.

The shocks of COVID-19 and Russia's war in Ukraine have highlighted structural issues in the German STI system

Strong external demand for Germany's manufactured goods in the decade prior to the COVID-19 pandemic helped underpin a decade-long economic expansion. In the last pre-pandemic year (2019), exports reached USD 1.4 trillion, making Germany the third-largest exporter in the world, behind only the United States and China. While European markets continue to account for the majority of German exports, rising demand from China and the United States for German automobiles and electrical components over the past decade has considerably heightened their importance for German firms. Not only has Germany so far mitigated some of the more drastic labour displacement effects seen in other manufacturing nations, but the spillover into the wider economy remains significant, with 1.2 jobs created for every person employed in manufacturing (Legler et al., 2009[47]).

The shocks caused by the COVID-19 pandemic and Russia's war against Ukraine have highlighted structural vulnerabilities in Germany's export-oriented economy. While these events are very different, both shed light on vulnerabilities in global supply chains, including i) the economy's reliance on trade for both inputs (of intermediary goods and raw materials, including energy) and outputs; ii) the need for the STI system to be resilient and responsive to future shocks, including to the value chains upon which it relies and to which it contributes; and iii) the need for agility in policy design, to avoid damages to innovation and the economy in periods of crisis.

Interruptions to the supply of key intermediary goods for the German economy have particular implications for the country's STI system and the private sector it supports. As border closures disrupted the flow of goods, Germany industries faced a number of shortages, refocusing policy attention on issues of technological and production sovereignty. China's continued "zero-COVID" policy into 2022 has perpetuated these disruptions, with implications for German output. It is precisely owing to supply-chain disruptions that German GDP growth dropped so dramatically. Demand generally remained strong throughout the pandemic, but the fragility of the global supply chains – from raw materials and energy to high-tech intermediate components – meant that industry could not produce the output required.

The crisis also highlighted the importance of having innovative and technological reserves to bolster socio-economic resilience. This was starkly demonstrated by the success of the German biotechnology company BioNTech, in collaboration with the American pharmaceutical company Pfizer, in developing the first COVID-19 vaccine approved for use by a stringent regulatory authority. Germany's

pharmaceutical sector is a major investor in R&D, and (as with other areas of the economy) its motivations are understandably commercial. The experience illustrates the importance of building and maintaining technological and innovative capacities in a range of areas, which can be activated in times of crisis or in the face of complex challenges. The contribution of STI to addressing the COVID-19 challenge may be a harbinger of its potential contribution to other complex areas where science and innovation intersect with socio-economic challenges, and where supporting innovative competencies in a range of areas can underpin domestic resilience.

Agile policy making during the COVID-19 pandemic helped the German economy and society emerge relatively unscathed. Quick and well-designed policy interventions saved German lives and mitigated the pandemic's impact on businesses. Sizable public intervention, supported by expansionary fiscal policy throughout 2020, helped protect jobs and firms. A discretionary stimulus package amounting to 4.5% of GDP supported loans, guarantees, grants and equity injections to maintain firm liquidity, preventing the unnecessary market exit of viable firms and long-standing economic scarring. Nevertheless, the challenges outlined above are indicative of several structural issues facing the German economy and its innovation system.

1.5. Recommendations

Context for the policy recommendations

The policy recommendations provided here focus on strengthening the current STI system and preparing for its future. Complex transformative processes, such as digitalisation and the societal push for environmental sustainability, will lead to significant changes for Germany's key manufactured and industrial goods and markets. Given the rich and well-functioning German innovation-policy system, the recommendations focus on the framework conditions for innovation, governance of STI policy, demand-side policies for innovation and policy agility. The rich diversity of policy instruments in support of innovation at the federal and state levels remains essential to future success and must be maintained.

The policy recommendations reflect Germany's ambition of global leadership and are therefore set at a high level for Germany's innovation ecosystem and policies. In the context of the sustainability and digital transformations, Germany's innovation ecosystem must promote high-impact and more disruptive innovation lead. Among the key challenges it considers is how the STI system can engage in breakthrough innovation activities, including to ensure that SMEs are equipped with the skills and technical capacities to engage in cutting-edge technological research, and that this research can be scaled and commercialised. The review also expounds the importance of promoting key enabling technologies.

The review focuses on applied R&D rather than basic research. While questions around the conduct of basic research fall outside the scope of this review, they nevertheless remain essential to the functioning and future competitiveness of the German STI system. The high level of government and business expenditure in these areas is welcome. It is clearly a source of strength for Germany's innovation system, and the review recommends maintaining this strong commitment.

Recommendation 1: Develop a shared vision "Germany 2030 and 2050"

Overview and detailed recommendations:

Most transformational challenges posed by the transition to sustainability and digitalisation challenge Germany's existing innovation governance system. This has resulted in important experiments, notably within the strategy for research and innovation (R&I) (see Chapter 5), to devise new governance arrangements for STI. This recommendation foresees the establishment of a whole-of-system "forum" to steer Germany' STI system towards specific goals and ambitions described in a strategic vision. The proposal offers a time-bound and collaboratively developed vision for Germany. For its implementation, this recommendation complements Recommendation 2 on the creation of a public-private laboratory for innovation policy experimentation.

R1.1 **The government should create a cross-ministerial, federal-state, cross-institutional and cross-sectoral forum to steer the process of developing a shared vision founded on identified key priority areas for action**. The purpose of this forum would be to ensure broad engagement in policy making and identification of priorities, both to promote the type of horizontality and multidisciplinary approaches implicit in the challenges posed by transitions, and to secure the social and political legitimacy of the proposed actions. The forum would also provide an environment where all areas of policy (such as digital policy, social policy, education, environmental and health policies) can be discussed as they interact with STI. Although these issues fall outside traditional STI policy portfolios, they invariably affect the effectiveness of policy interventions.

R1.2 **The forum should develop pathways for innovation to realise the desired vision for Germany in 2030 and 2050, as well as define approaches to deal with future risks and inclusivity issues in orienting innovation policies.** All countries will face important socio-economic transitions resulting from the digital transformation and the ambition to develop environmentally sustainable development pathways, as well as the increased risks – including health threats (such as the COVID-19 pandemic), geopolitical conflicts and climate change – arising from the interconnectedness of the global economy. Defining a shared vision can underpin steadier and more and strategic action, rather than addressing challenges in an ad hoc and reactive manner. The debate on inclusivity should also address the question of potential trade-offs of innovation excellence and inclusivity, and how to best approach these challenges.

R1.3 **The vision and its forum must be recognised as central at the highest level of government, as well as by key industry stakeholders and society, to effectively promote an agenda of change in the STI system**. The forum should receive high-level political support to allow it to engage government ministries and institutions at both the federal and state levels, as well as STI stakeholders more broadly.

R1.4 **Effective implementation requires establishing a public-private budgeted strategic plan for the realisation of the "Germany 2030 and 2050" vision. The plan should focus on key thematic areas for action and the monitoring of progress made at different stages. Core themes will be achieving the digital and environmental sustainability transitions, and the role of innovation and STI more generally in that regard.** Other related topics include preparedness for future disruptions (e.g. supply-chain preparedness), key enabling technologies, the industrial transformation and diversity in the innovation system (gender, age, ethnicity and socio-economic background). More granular topics could be developed, depending on which key priorities are identified for the "Germany 2030 and 2050" vision.

R1.5 **Importantly, implementation defined along key missions should not be top-down, but rather bottom-up and market-driven.** Bottom-up approaches can help accelerate implementing pathways for realising the "Germany 2030 and 2050" vision. Adopting actor-driven approaches, in

particular, can hasten transition efforts that "reward" lead actors in specific states, regions, sectors, cities and policy fields that undertake innovative actions for change. Market-driven dynamics are also a key aspect of the vision's implementation plan, which should identify and agree on transition pathways and partnerships with industry partners. In this manner, both government and industry commit to investments and other contributions or initiatives (such as "fossil-fuel free Sweden'", with its industry roadmaps negotiated between industry and government) that will drive transitions. The "transformation dialogue for the automotive industry" (*Transformationsdialog Automobilindustrie*") is a first attempt in this direction.

R1.6 **Important goals of the forum, and the "Germany 2030 and 2050" vision, would be to draw upon systemic capacities for STI and better co-ordination in mission-oriented approaches.** Germany has developed a number of mission-oriented approaches for STI, but they are not always sufficiently "transformative" and suffer from a lack of coherence and co-ordination among missions.

Recommendation 2: Create a public-private laboratory for innovation-policy experimentation

Overview and detailed recommendations:

The pace of technological change and the nature of the transformative challenges facing Germany's socio-economic future require more agility and experimentation in policy making. STI policy approaches require foresight strategies, co-creation of policies with civil-society actors and digital tools to inform innovation-policy approaches, such as semantic and big-data analyses to gather and interpret data relevant to the STI system. More agile STI policy could enhance the effectiveness of mission-oriented interventions, help scale the most effective policy approaches and allow recalibrating the chosen course of action more quickly. This is essential if Germany wants to take the lead in introducing new disruptive innovations and associated business models. The proposed public-private policy laboratory would introduce policy agility in key areas linked to the proposed "Germany 2030 and 2050" vision of keeping up with the global pace of change needed to lead in the transitions (see R1).

R2.1 **The laboratory should act as the forum's institutional arm (see R1) to support policy agility, increased and accelerated responsiveness, experimentation and learning, and the major changes needed to achieve the "Germany 2030 and 2050" vision**. To this end, the laboratory would have a mandate to support champions – those who engage in experiments – and promising innovations across the STI system, including public bodies undertaking regulatory experimentation (R3) and innovative public procurement (R7), as well as city initiatives and other bottom-up efforts supporting transitions. This would include promoting lead-actor mechanisms across Germany's *Länder* to experiment with core missions – such as the digitalisation of the public sector – and new approaches to innovative procurement across all levels (including municipalities). The laboratory would also have a mandate to mitigate co-ordination failures across line ministries and public institutions, industry and civil society. It would exploit regional competencies and priorities to hasten the development and scaling of the most promising regulatory and policy approaches to innovation challenges. Importantly, the laboratory would look for ways to promote responsiveness and learning from policy experiments, as well as (where needed) facilitate fundamental policy changes.

R2.2 **The laboratory would promote implementation and monitoring, and the "Germany 2030 and 2050" vision (see R1).** Concretely, it could implement a strategic foresight exercise that will produce the "Germany 2030 and 2050" vision, as well as monitor developments and co-ordination challenges that may impede the transitions. This means considering the full innovation chain, from idea generation to market introduction, driving transfers across different actors. The laboratory would also support agents of change – notably through prizes, competitions, etc. – that

help markets and different actors of the STI system to achieve the vision. For example, it would support the development and implementation of regulatory sandboxes and other forms of regulatory simplification (as detailed under R3), and could similarly support innovative public procurement (R6). It would also promote demand-side mechanisms for stimulating innovation, such as innovative procurement, and promote framework conditions conducive to innovation. Finally and importantly, the laboratory would support breakthrough innovation by promoting the activities of SPRIND and, more broadly, risk-taking entrepreneurship.

R2.3 **The laboratory would have the autonomy and means to recruit staff with different profiles through more flexible employment options, as well as to engage flexibly with innovation actors.** This would promote a greater level of industrial engagement through secondments or temporary positions, ensuring that policy making in frontier and complex areas of science and technology is underpinned by technical and entrepreneurial experience, and practical knowledge. To avoid adding further complexity to an already extensive set of STI policy actors, the laboratory would fulfil a temporary role, designed to set in motion a new agenda of change for future transitions.

Recommendation 3: Broaden and mainstream the use of agile policy tools to support innovation efforts by SMEs, and achieve the digital and green transitions

Overview and detailed recommendations:

The Federal Government should consider mainstreaming policy tools (such as regulatory sandboxes) to maximise their potential for change, normalise the use of such methods in the context of its approach to STI and generate more data for policy evaluation. Regulatory sandboxes (*Reallabore*) refer to a limited form of regulatory waiver or flexibility that enables firms to test innovative technologies, products or services which are not yet fully compliant with the existing regulatory framework. At the same time, the government should build greater flexibility into existing areas of regulation and policy, and adopt a more risk-taking and experimental approach to policy making in a context of important transformations.

R3.1 **Reduce bureaucratic and administrative barriers affecting SMEs and start-ups.** The government should both rationalise the processes required for certain government-to-business services, as well as the administrative steps required for firms to receive STI policy-support measures (such as innovation grants). Some SMEs and start-ups will shy away from applying for support schemes because the application procedures are not easily accessible or straightforward. Where legal barriers impede the simplification and flexibility of support measures, the government should undertake a review of the changes required to streamline access conditions. Programmes such as ZIM (BMWK) and KMU-innovative (BMBF) have demonstrated good practices and the feasibility of increasing the rate of firms participating for the first time in initiatives supporting research and innovation.

R3.2 **The government should pursue a programme of digitalising government policy, services and processes.** The digitalisation of government services should proceed after the rationalisation of existing regulations and procedures. Pivoting to digital delivery would consolidate all interactions between firms – particularly SMEs and start-ups – in a single location, preferably a digital “one-stop shop”. More than digitising existing analogue processes, this requires improving them (by reducing the number of intermediary steps), and collecting and analysing data from interaction with digital services to further improve and inform policy making. The integration of new tools, such as machine learning and semantic analysis, could both improve the quality of government policy and regulation, and enable the government to take an active lead in the digital transformation of the public and private sectors.

R3.3 **Expand the use of regulatory sandboxes**. Germany's adoption of the Regulatory Sandbox Strategy (as discussed in Chapter 15 on policy agility and the corresponding R2 on the establishment of a policy laboratory) has been a decisive step in the use of regulatory sandboxes, but additional focus should be placed on the following:

- Strengthening regulatory co-operation across various federal regulators – as well as among municipal, state and federal authorities – when implementing regulatory sandboxes: this is particularly important because emerging innovative areas often cut across traditional industrial sectors, and thus the mandates of regulatory authorities and federal ministries.
- Targeting SMEs and start-ups to ensure they have access to regulatory sandboxes and that the eligibility criteria do not exclude younger or smaller firms: the government should continue to organise awareness-raising activities (such as competitions) on the opportunities and possibilities of sandboxes, with a particular focus on SMEs and citizens. Establishing regulatory sandboxes also requires avoiding possible regulatory capture by participating firms.

R3.4 **Support an easy-to-use digital one-stop-shop for STI policy engagement.** Germany currently provides the private sector with a wealth of policy instruments to support innovation, but their overall effectiveness could be increased. To this end, the public administration should consider improving communication about these instruments, which currently includes a centrally co-ordinated platform listing the instruments (*Förderfinder des Bundes)* and individual consultation activities to allow firms to find offers matching their specific needs (*Förderberatung Forschung und Innovation des Bundes)*. Complementing these services with a full-fledged digital one-stop-shop for STI policy engagement of SMEs, start-ups and individual entrepreneurs would improve access and use of the support schemes. This digital one-stop-shop should also allow any firm (both domestic and international) to easily check its eligibility for different innovation-support instruments. It would also integrate the existing consultation activities by centralising and digitising the back-office application processes for these instruments. The platform could also serve as a vessel for goal- and challenge-oriented innovation, increasing firm-level awareness of and participation in innovation programmes supporting socio-economic policy objectives.

Recommendation 4: Improve data infrastructure and data access, especially for industry

Overview and detailed recommendations:

This recommendation highlights the particular importance of data as a necessary input for all other areas of this review, from supporting greater agility in policy making and more innovative use of procurement, to processing data at the firm level to enhance research and efficiency.

Improving the coherence and interoperability of the data infrastructure for future digital innovation should be a government policy priority. Effective collaboration between research institutions and firms for purposes of innovation also depends on the presence of an accessible and well-designed data infrastructure.

From the perspective of Germany's innovation strengths and international comparative advantages, the strategic use of more industrial data for innovation should be a priority for the public and private sectors, with a focus on the innovation-intensive automotive, machinery, chemical and pharmaceutical industries. This requires top-down and framework-related approaches, complemented by policies to improve the bottom-up uptake of data-producing and data-dependent technologies at the firm level. Open innovation platforms and collaborations to exploit those data are necessary to help activate this potential.

R4.1 **The government should support a programme to improve the country's data infrastructure, and increase the public and private sectors' absorptive capacity of both infrastructure and human capital**. This programme should have a clearly defined mission, with

a strong focus on the use of data produced by the business sector and during research to support STI. The programme would be responsible for rationalising and eliminating the soft and hard infrastructure issues constraining the development of better data infrastructure and data access.

R4.2 **The government should consider the data generated by the business sector as a strategic dividend that can strengthen German innovation and competitiveness**. Having recognised the centrality of data for innovation in the Data Strategy of the Federal German Government (BKAmt, 2021[48]), Germany could exploit its position as Europe's largest economy to ensure that high-quality, interoperable and accessible industrial data become an additional strength of its innovation system and economy. From an infrastructure perspective, the GAIA-X and Important Projects of Common European Interest (IPCEI)-CIS programmes – both of which aim to support European-based cloud infrastructure services – are first steps in this direction. The same is true, to a greater extent, for the ongoing efforts to digitalise the automotive sector's value chain through initiatives such as the CATENA-X platform. While these initiatives are important, they must be scaled, the scope broadened, and the speed with which they are rolled out increased. A whole-of-industry strategy will require a coherent and systemic approach to leverage industrial data effectively for innovation, and should be pursued with the relevant actors at both the national and transnational levels.

R4.3 **To promote data-driven innovation, the German Federal Government should address barriers to SMEs' use of the data they produce and enhance SMEs' access to data produced across the economy**. Specifically, the Federal Government should support rationalising regulatory differences across the *Länder* and provide support for implementing the General Data Protection Regulation. It should increase legal certainty and, where appropriate, promote flexibility in using data for innovative processes, encouraging businesses to make the necessary intangible investments to produce, store and process data for innovative purposes. At the same time, the government should recognise the urgency of ensuring that firms are equipped with the necessary connectivity infrastructure to support data-driven innovation and production in the context of the digital transformation, including fibre-optic broadband and the 5G connections required to convey the massive volumes of data inherent to Industry 4.0 processes.

R4.4 **Promote open innovation platforms and approaches. Producing data is a necessary but insufficient condition for innovation.** To succeed in the digital era, firms must have access to data they do not produce, and be equipped with the skills and technological competencies to process and use them. In addition, while some firms may not have the internal capacity to derive value or insights from the data they do (or could) produce, other firms may be able to unlock such insights. This highlights the importance of supporting an open innovation approach – which the Federal Government has begun pursuing through its 2021 Data Strategy – and creating platforms that involve other innovation actors in producing innovations based on private-sector and industrial data. An important benefit of such open innovation platforms is that they allow more collaboration between firms as well as with PROs and universities.

Recommendation 5: Improve cross-disciplinary and cross-sectoral knowledge transfer and collaboration

Overview and detailed recommendations:

Extensive and inclusive knowledge exchange and collaboration across institutions, disciplines and sectors, as well as multidisciplinary open innovation approaches, should become cornerstones of German STI policy. Success in this area would have other positive spillover effects on inclusivity in STI, such as engaging in innovation activities a wider share of the population with skills beyond STEM. Germany's traditional innovative strengths have generally been intra-sectoral, so that knowledge is created, and technology transferred and applied, within a particular cluster and industry. In a digital world, however,

knowledge and technology transfer increasingly occurs at the intersection of digital technologies and "analogue" sectors. In addition, the type of innovation necessary to succeed in the sustainable development challenge is – and will continue to be – disruptive. This requires significant breakthroughs, which are achieved through effective knowledge transfer and industry-science collaborations, and based on open innovation approaches and industry-science collaborations across all sectors of the economy. The support for knowledge transfer and collaboration should transcend traditional innovative sectors. The success of the government's recent pilot phase of the Innovation Program for Business Models and Pioneering Solutions (IGP) programme (see Section 2 of this chapter) also demonstrated the potential of government-supported programmes to promote non-technical and multidisciplinary innovation in areas ranging from digital platform design to social impact.

R5.1 **Improve universities' engagement with industry and support research institutions in playing a leading role in the transitions required to achieve the "Germany 2030 and 2050" vision.** Part of the vision should consist in reframing the relationship between research institutions and industry, so that it supports knowledge transfer and innovation collaboration in areas of future importance, as well as an "ecosystem" approach to innovation. In this light, ensuring that innovation actors contribute to knowledge transfer and collaboration could become a formal pillar of German research organisations' responsibilities, with a training and information campaign accompanying this change. This strategy would benefit from incorporating these objectives into performance-based funding and developing a set of metrics, including qualitative measures, to improve the visibility of related programmes. The "Germany 2030 and 2050" vision could also establish a formal mechanism, encompassing the forum proposed in R1, the policy laboratory and the higher education system, to engage research institutions in Germany's transformational processes, including by contributing to environmental development objectives.

R5.2 **Encourage and facilitate the development of university proof-of-concept funds to support academic spin-offs and start-ups.** Through its direct funding of higher education R&D, the government should encourage the establishment of proof-of-concept funds within universities, which could be complemented by industrial contributions. These funds would help accelerate technology transfer commercialisation. The government should explore regulatory channels that would allow (and make it simpler for) universities to engage directly with external finance actors, such as VC firms and the banking system more broadly, as happens in Belgium, Denmark and the United Kingdom. Moreover, the government should take a long-term approach to monitoring and assessing the development of proof-of-concept programmes within higher education – a luxury that the private sector (particularly SMEs) cannot afford.

R5.3 **Reinforce incentives for academics to engage in innovation.** Policy makers and universities need to improve incentives for academics to pursue innovation activities, and address relevant barriers. Establishing clear performance evaluations that take into account knowledge transfer and collaboration at the institutional and researcher levels will be important in this regard. This entails raising entrepreneurial awareness and knowledge among students and faculty, encouraging academic staff to support students who approach them with ideas, or indeed to develop and pursue their own ideas. Academics should be encouraged to avail themselves of industry secondments. At the same time, the government and the higher education system should address financial incentives (such as equity participation and licensing revenues) or barriers to university-based start-ups.

R5.4 **Support multidisciplinary and entrepreneurship training across the entire education system to promote entrepreneurialism, as well as spin-offs and spin-ons.** Training efforts should also be inclusive and involve groups throughout society. The government should encourage under-represented groups, such as women and migrants, to engage in innovation activities, from participating in academic spin-offs to contributing to knowledge transfer and collaboration. Academic "spin-ons", which connect researchers with entrepreneurs, can be an

effective way to exploit complementary skills to drive innovation, rather than attempting to transform all researchers into savvy entrepreneurs.

R5.5 **Enhance accountability and develop a framework for performance metrics.** The government should promote the creation of a core set of knowledge-transfer metrics and consistent reporting mechanisms, conducted on an annual basis. This requires strengthening measurement at the institutional level, by establishing reporting cultures and related processes, as well as collecting more holistic metrics, including qualitative measures (e.g. pathways and examples) and new approaches to evaluate the impact of knowledge transfer.

R5.6 **Increase opportunities for open innovation and co-creation.** German SMEs could benefit from further open innovation and co-creation initiatives. These include joint innovation labs (and joint/shared infrastructure and equipment); digital innovation hubs; open innovation platforms; open fab-labs; and testing/demonstration platforms, living labs and hackathons. Co-creation and innovation labs can take the form of digital platforms and virtual laboratories allowing research and data sharing, as well as the co-design and co-creation of solutions, and their piloting and testing. This pooling of diverse competencies would significantly reduce infrastructure and research costs, and accelerate development.

Recommendation 6: Promote financial markets that are conducive to scaling up breakthrough innovations

Overview and detailed recommendations:

Although German firms generally have good access to finance, providing young and small firms with the capital needed to scale remains challenging. This reflects in part the comparative underdevelopment of the venture and growth capital markets in Germany and the European Union as a whole.

R6.1 **Revisit the legal framework for German capital-collecting institutions to encourage investment in risky innovation**. The Federal Government should consider requiring institutional funds to allocate a percentage to VC or private equity funds for innovative firms. For example, German pension funds, insurance companies and public financing organisations provide very little risk capital, even though they are among the only sources that could provide the levels of funding (including investments in private companies through VC funds and investments in listed companies) that are necessary to scale the most promising innovations. Another approach might be to facilitate employee stock-ownership plans. Overall, the German tax framework for equity ownership and awards has been largely unattractive compared to international benchmarks.

R6.2 **Expand tax incentives, especially those that allow private investors to offset capital losses against other income, or to exempt future profits when investing in the VC asset class**. Such incentives should apply to both the VC segment (pre-initial public offerings) and investment through the stock market (development and growth financing). The United Kingdom and France, for example, each have six different tax-incentives to improve the supply of private capital for VC markets.

R6.3 **The Federal Government should support the development of financial instruments at the EU level that would help scale and retain innovative firms**. The volume of finance necessary to scale some of the most promising firms is often available neither in Germany nor within the European Union, meaning that firms regularly move to countries where finance is more easily available, such as the United States or the United Kingdom. The German government should advocate the establishment of EU-level private equity development for investment in pre-public technology and digital innovators. The Federal Agency for Disruptive Innovation, SPRIND, could play a more prominent role in developing a domestic VC market for higher-risk investments.

Recommendation 7: Strengthen the use of public procurement as a driver of innovation

Overview and detailed recommendations:

The public sector has enormous potential to promote innovation through procurement, which it could also use to better support the climate and digital transitions. The market-creating aspect of public procurement can also accelerate the transition of an idea to market by shortening the time required for commercialisation. Start-ups and *Mittelstand* firms in particular will be more inclined to engage in innovation efforts, as the government represents a reliable and high-profile client. A number of barriers, ranging from the low attractiveness of careers in public procurement to its fragmented and un-coordinated approach, currently prevent Germany from fulfilling the potential of public procurement as an instrument of innovative change. As discussed at Recommendation 10, using public procurement as a driver of innovation may require engagement with EU state-aid rules.

R7.1 **Commit to innovation procurement by taking legislative action and creating co-ordinated innovation procurement programmes within public agencies at the federal, state, community and city levels.** One line of action would be to require public agencies to allocate a dedicated amount or percentage to procurement of pre-competitive innovative research. Co-ordinating the different levels of public procurement (federal, state and municipal) will mitigate any potential fragmentation arising from this targeting. These efforts can support the overall "Germany 2030 and 2050" vision if it is linked to strategic projects emphasising innovation procurement, such as in sustainability, health and digitalisation.

R7.2 **Invest in building capacity and incentives for implementing innovative public procurement.** Acting on this commitment would entail a programme focusing on (i) the formulation of innovation agendas (roadmaps/challenges), as well as preparatory tasks for the definition and launch of innovation procurement programmes; (ii) capacity-building and training of staff in charge of public procurement; and (iii) offering incentives for public agencies in charge of procurement to reward innovative procurement (including through prizes). This would benefit from the support of the proposed laboratory on experimentation (see R2 in Chapter 15).

R7.3 **Direct some of the public seed funds for technology commercialisation programmes to pre-commercial procurement programmes**. This can take the form of staged-funding programmes, in the spirit of pre-commercial procurement programmes. The purpose of this approach is to add conditionality or challenges to publicly backed seed funds.

R7.4 **Create incentives for SMEs and start-ups to engage in innovative procurement.** This involves raising awareness of procurement opportunities and rationalising administrative barriers to the participation of SMEs and start-ups, such as clauses requiring past financial statements which start-ups cannot provide. Smaller and younger firms may currently be excluded from procurement tenders, limiting the ability of high-potential firms to scale and commercialise innovative solutions. The government could also create a platform that allows public authorities to issue challenge-oriented procurement tenders, which would draw smaller, high-potential firms. Such a platform would promote stronger innovative business creation through public procurement.

Recommendation 8: Increase the involvement of civil society and key stakeholders in STI policy to achieve the transitions

Overview and detailed recommendations:

Many of the economic and technological challenges facing Germany have asymmetrical, often significant consequences, with societal impacts . The debates around ethics in the use of artificial intelligence (AI) tools and gene editing illustrate such impacts. STI policy making, therefore, should further include civil society in STI, ensuring that government policy and direction reflect the concerns and ideas of a broad

range of actors. Broader civil-society engagement would also increase the *supply* of policy ideas and provide testbeds for experimentation, including especially at the city or municipal level. Participation of diverse social groups in innovation activities will also promote wider societal involvement, aside from helping to introduce transitions. Moreover, engaging civil society and STI stakeholders in a dialogue on the best ways to design STI policy programmes targeting or impacting themcan improve diversity in participation and boost programme quality by incorporating the potential difficulties the intended beneficiaries may experience in engaging with those programmes.

R8.1 **Create citizen councils to debate innovation and innovation policy**. These councils could be formally linked to the forum proposed in R1, thereby providing structured input into STI policy making and direction. The citizen councils' discussions could centre on the same thematic agenda as the forum's. Testing policies and defining innovation challenges could also be elements of such exchanges.

R8.2 **Develop "city innovation laboratories"**. The government should consider developing of city laboratories where municipal authorities would have the autonomy to test new approaches to innovation policy. These approaches could take the form of public-private partnerships; partnerships with research institutions or start-ups; and procurement from innovative firms to address local issues linked to transitional challenges, such as electric mobility. City laboratories could provide real-world testbeds for bottom-up and entrepreneurial-driven innovation targeting a range of complex challenges, and serve as a springboard for scaling successful approaches at the state or national level. As an additional advantage, they would provide a more direct and responsive line of communication between STI policy makers at the national and local levels, which could significantly improve policy responsiveness and agility.

R8.3 **Create a policy programme that allows cities or municipalities to apply for special status that grants regulatory flexibility for innovative experimentation**. Allowing local authorities to apply for special status would streamline and accelerate bottom-up innovation as they could create more responsively the conditions conducive to innovation for local firms and better utilise these innovative capacities to solve place-specific challenges. Such localised approaches could encourage the emergence of regional leaders in a range of areas, including policy agility and co-ordination, public-sector digitalisation, innovative procurement, innovation for sustainability, innovation missions, citizen science and innovation, and social innovation.

R8.4 **Use co-creation programmes for innovation at the city and regional levels.** Local co-creation could be especially useful in encouraging innovative public procurement and open innovation systems, such as living labs, regulatory testbeds, and hackathons. Sustainable mobility activities in cities are an important example of where innovation activities could benefit from local co-creation. Co-creation between the public and private sectors in particular could help de-risk innovation investment in emerging areas of technology for both parties.

R8.5 **Boost diversity in the innovation system.** Engaging a more diverse set of actors will support diversity and inclusion, but it can also help improve the quality of innovation. In the context of an ageing society, attracting and involving skilled migrants, women, minorities and individuals from disadvantaged socio-economic backgrounds in innovation training and careers will be essential to ensure the innovation system has the talent it needs to succeed. Unequal representation of women, minorities and individuals from disadvantaged socio-economic backgrounds at senior levels of management could therefore be a source of weakness for the German private sector. The need for new skills – soft as well as technical –for success in the context of the sustainable and digital transitions also means that STEM skills that predominate in corporate boardrooms and leading innovation may pose a challenge for the future and also reduce inclusivity. Women tend to be more represented in these fields than STEM fields, and therefore supporting more those innovations could both bring more women into the innovation system in

addition to improving Germany's innovative output in an area where it is comparably weaker. Widening the support for innovation could potentially also increase diversity beyond gender. Importantly, boosting about diversity needs to be also about diversity in the management and steering of innovation activities and not only about participation. Supporting citizen science and innovation activities are also important, as is involving civil society in collaborative innovation activities, that deal with issues important to civil society.

Recommendation 9: Digitalise, modernise and strategically use quality infrastructure

Overview and detailed recommendations:

Quality infrastructure – the standards and norms that shape and inform manufacturing and services – Germany's competitiveness in the manufacturing of certain goods implicitly granted it global leadership in standard-setting. In a world where output has a higher digital intensity, and a greater degree of interconnectedness exists across products, services and sectors, standard-setting is more complicated. The much faster speed of change in the current period of transitions also requires new approaches and more strategic uses of the standards and quality infrastructure.

R9.1 **Enhance digitalisation and develop state-of-the-art capabilities in both the standard-setting process and quality infrastructure**. The institutions in charge of standards and quality infrastructure have not completed their digitalisation, despite urgent needs in capacity and infrastructure investment. The digital connectivity across institutions at the federal and state levels also requires attention. Germany's advanced metrology institutions must be strengthened and modernised to deal with the complexity and interconnectedness of the new technologies they must measure, such as autonomous driving or the application of AI in the medical and pharmaceutical sectors. Developing the quality and standards infrastructure also critically depends on supporting investments in human capital, including by promoting the attractiveness of working in this field.

R9.2 **Use the quality infrastructure as a strategic instrument for innovation and competitiveness**. Germany's leadership in many areas of manufacturing and industry, combined with the high quality of the current metrology system, have conferred on its economy an implicit leadership position in standardisation. This leadership confers competitive and innovative advantages, as it orients global manufacturers towards norms set by German firms. The government should thus adopt a systemic approach to standardisation and the quality infrastructure as integral components of international innovation and competitiveness, explicitly determining their contribution to achieving the "Germany 2030 and 2050" vision.

Recommendation 10: Take a leadership role in shaping EU and global innovation policies

Overview and detailed recommendations:

The ability to effectively address many of these recommendations requires leveraging the scale of EU and international co-ordination. Beyond Germany, efforts are needed at the EU and transnational levels to ensure success, including by (i) developing competencies in key enabling technologies for more resilient value chains; (ii) exploiting efficient digital-data infrastructures (R4); (iii) developing a sufficiently large financial market to scale disruptive, high-potential innovations (R6); (iv) defining the desired standards and quality-control procedures (R9); and (v) boosting innovation to promote environmentally sustainable development. To this end, the German government needs to take active leadership in shaping innovation policies at the EU and global levels.

R10.1 **Better align domestic STI policies and the EU internal market**. As detailed in R9.1, the impact of domestic STI priorities and policies could benefit from a multiplier effect if they were

better aligned with the EU and the internal market. The example of data infrastructure is telling, with projects such as GAIA-X able to reach a larger scale than any equivalent national project, as it targets the vast array of industrial and commercial data inputs from across the EU internal market. A similar approach could be taken in other areas of STI, such as the development of specific enabling technologies, the digitalisation and strengthening of industrial supply chains, and the scaling of pre-commercial or pre-public solutions through the internal market in areas such as climate-management technologies. As advocated in R2 (policy laboratory) and R7 (innovative public procurement), Germany could take a leadership role in promoting policies that stimulate demand-side dynamics for innovative solutions at the EU level.

R10.2 **Identify potential IPCEI to support enabling technologies**. Supply shortages during the COVID-19 challenge highlighted Germany's dependence on a few global supplies. Germany could take a more direct role in garnering support for IPCEI targeting the development of certain technology fields. This could have multiple benefits for the German economy and the broader European Union, by (i) enabling the development of key technologies within the European Union and key EU partner economies, to increase supply-chain resilience; and (ii) developing key technological competencies that will be sources of competitiveness for the future.

R10.3 **Take a leadership role in promoting standards and quality-control procedures at the EU level.** Building on the items outlined in R9, and reflecting the multiplier effect of aligning domestic STI policy with EU policy and the internal market, Germany should take the leadership in promoting EU-wide standardisation and quality infrastructure to support the broader competitiveness and innovative strengths of the European Union and its Member States. This would help align the approaches taken by EU economies, and consequently strengthen the position of the internal market in the context of international and systemic competition.

R10.4 **Maximise international co-operation to navigate uncertainties and address the complexities of transitional challenges.** As with other world economies, the nature of the challenges facing the Germany economy is such that no single government or actor possesses all the answers. While there may be no panacea for the complexity of the sustainability and digital transition, there are nevertheless numerous instances where German policy makers can learn from the experiences and efforts of other countries to navigate these complex challenges, from commercialising decarbonisation technologies to digitalising the public sector within a federal state. As part of the "Germany 2030 and 2050" vision, the government should actively seek international collaboration in priority areas identified by the forum, both within the European Union and beyond.

R10.5 **Take a key role internationally in strengthening the global and national innovation ecosystem.** This involves shaping the global innovation agenda and the main targets set for key innovation agendas globally, such /as in AI and biotechnology. Another important component here is connecting effectively to global innovation efforts, attracting talent and engaging in effective collaborations to support the national innovation ecosystem.

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Endnotes

[1] These indicators are taken from the OECD How's Life? (2020) report and cover the following areas: household adjusted disposable income, household median wealth, housing affordability, employment rate, life expectancy, student skills in science, life satisfaction, homicide rate, time off, social interactions and voter turnout.

[2] In many of these areas, Germany has more than twice the total level of capital stock than the second-ranked country. This high level of investment is indicative of globally leading levels of knowledge and productive capacity. All values are given for the latest year available, ranging from 2016 to 2019.

[3] While patents do not give an indication of market readiness or demand for innovative output and are therefore an incomplete measurement of the innovation system's performance, they nevertheless provide an important – and internationally comparable – indication of innovation intensity.

[4] IP5 patent families are patents filed in at least two offices worldwide, including one of the five largest IP offices: the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the United States Patent and Trademark Office (USPTO), and the China National Intellectual Property Administration (CNIPA).

[5] A triadic patent family is defined as a set of patents registered in various countries (i.e. patent offices) to protect the same invention. Triadic patent families are a set of patents filed at three of these major patent offices: the European Patent Office (EPO), the Japan Patent Office (JPO) and the United States Patent and Trademark Office (USPTO). Triadic patent family counts are attributed to the country of residence of the inventor and to the date when the patent was first registered. This indicator is measured as a number.

[6] There exists no fixed definition for "hidden champions" in terms of employee numbers, and some have over 1 000 employees. However, according to the findings of a recent paper, the vast majority have fewer than 250 employees (Rammer and Spielkamp, 2019[19]).

[7] Firms such as Grammer (which specialises in seating and vehicle components), Marquardt Group (electronic and electromechanical switching systems) and Rosenberger Group (high-frequency and high-voltage connectors) are global leaders in their fields, demonstrating the breadth of expertise present in German SMEs (Handelsblatt, 2019[49]).