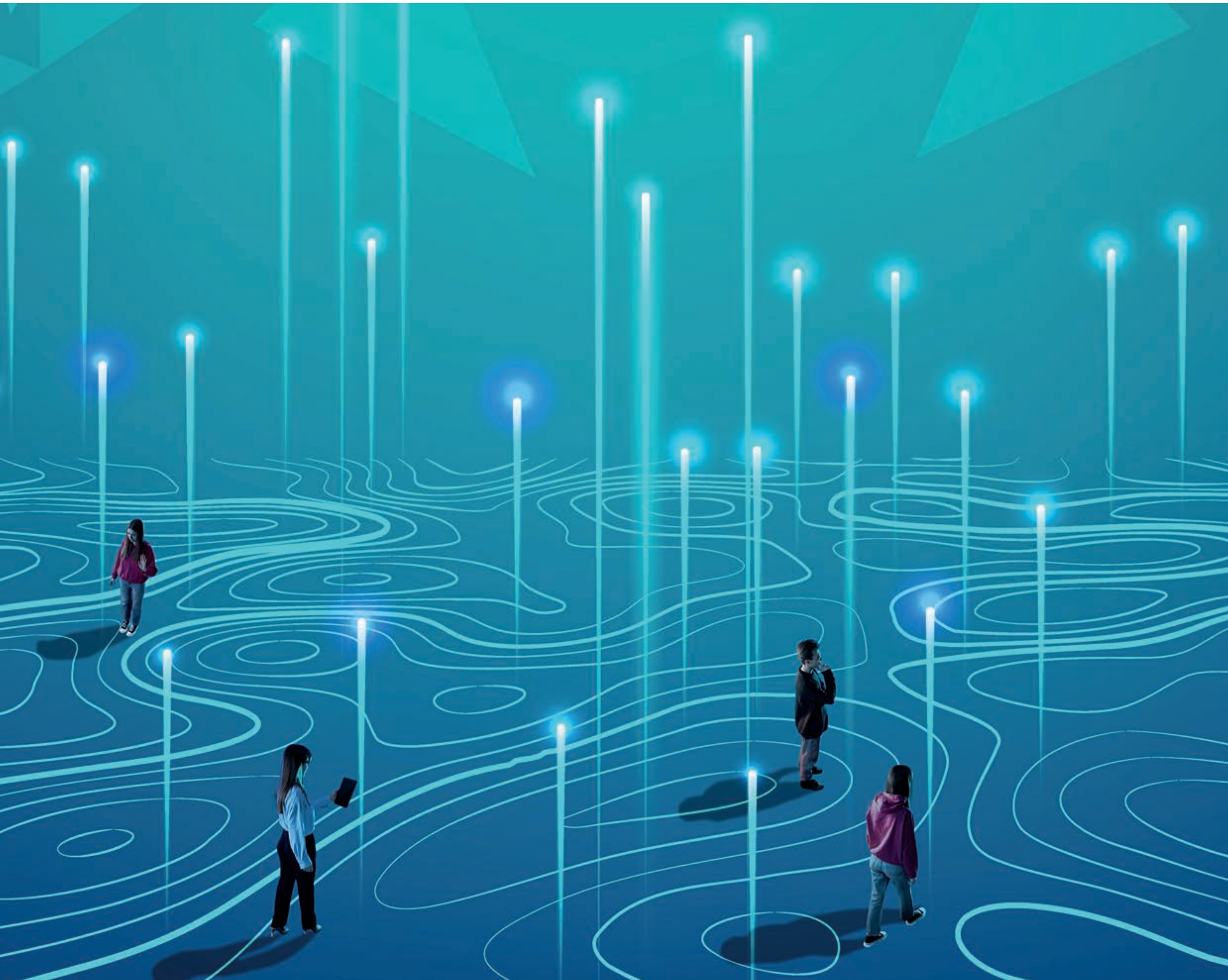
OECD Science, Technology and Innovation Outlook 2025

Driving Change in a Shifting Landscape



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DRIVING CHANGE IN A SHIFTING LANDSCAPE

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BETTER POLICIES FOR BETTER LIVES

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Foreword

The *OECD Science, Technology and Innovation Outlook 2025* reviews key trends in science, technology and innovation (STI) policy in OECD countries and major partner economies. This edition comes at a time of accelerating technological change, intensifying geopolitical tensions and urgent demands for transformative responses to economic and societal challenges.

The Outlook shows the importance of improving the effectiveness and efficiency of STI policies as they aim to tackle broad goals and multiple priorities in a context of growing resource constraints. STI policies should leverage synergies among goals, deploying complementary policy measures, promoting cross-government cooperation, and fostering public-private funding models.

A central theme of this edition is how countries can reconfigure scientific cooperation in an increasingly fragmented geopolitical landscape, ensuring the openness that drives scientific advances while simultaneously protecting economic security concerns. Another is how science systems themselves must adapt – with new institutional arrangements, skills and incentives, if they are to contribute effectively to transformative change through more multi-disciplinary approaches.

The Outlook also explores the growing convergence of technologies such as artificial intelligence, biotechnology and quantum computing, which are reshaping innovation processes and demand novel types of policy support. It highlights the potential of more granular approaches that better appreciate industrial structures and assess the impact of policy interventions to mobilise diverse actors around shared missions. It also shows how governments can strengthen their capacity for foresight, policy experimentation and strategic intelligence to remain agile in the face of uncertainty.

Taken together, these insights underline that STI policy is at a turning point. The ability of governments to mobilise science, technology and innovation for transformative change, while navigating geopolitical pressures and rapid technological shifts, will be decisive in shaping the future.

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Abbreviations and acronyms

AI	Artificial intelligence
BCI	Brain-computer interface
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CLACSO	Latin American Council for Social Sciences
CPC	Co-operative patent classification
CSTP	Committee for Scientific and Technological Policy
EEG	Electroencephalogram
EII	Energy-intensive industry
EO	Earth observation
EU	European Union
EUR	Euro
FAIR	Findable, Accessible, Interoperable and Reusable
FTA	Forward-looking technology assessment
GDP	Gross domestic product
GERI	Global Ecosystem Research Infrastructure
GUF	General university funds
IP	Intellectual property
ISIC	International Standard Industrial Classification
JST	Japan Science and Technology
LLM	Large language model
LMIC	Low- and middle-income country
M&A	Mergers and acquisitions
METI	Ministry of Economy, Trade and Industry (Japan)
MOIP	Mission-oriented innovation policy
NASA	National Aeronautics and Space Administration (United States)

NSF	National Science Foundation
ODISSEI	Open Data Infrastructure for Social Science and Economic Innovations
PIL	Policy innovation lab
PPP	Purchasing power parity
PRO	Public research organisation
R&D	Research and development
R&I	Research and innovation
RCT	Randomised control trial
RDD	Research, development and deployment
RDI	Research, development and innovation
ReICO	Research and Innovation Careers Observatory
RI	Research infrastructure
RTA	Revealed technological advantage
SDG	Sustainable Development Goal
SME	Small and medium-sized enterprise
SSH	Social sciences and humanities
STEM	Science, technology, engineering and mathematics
STI	Science, technology and innovation
STIP	Science, Technology and Innovation Policy (Database)
TA	Technology assessment
TiVA	Trade in Value Added
TRL	Technology-readiness level
TRUST	Trusted Research Using Safeguards and Transparency
USD	United States dollar
VC	Venture capital

Executive summary

Driving Change in a Shifting Landscape

Global challenges, rising economic security concerns, and disruptive emerging and converging technologies signify a new context for STI policy. Ensuring that STI policy remains fit-for-purpose in this new and rapidly changing environment requires fundamental structural reforms that can improve the effectiveness and efficiency of policy interventions, as well as continued attention to enhancing the evidence base. The *OECD Science, Technology and Innovation Outlook 2025* analyses the shifting landscape and its implications for STI systems, providing recommendations across seven chapters that lay out STI policy reforms needed to drive ambitious change.

Leveraging policy complementarities to boost efficiency

Ambitious policy agendas, together with growing resource constraints, highlight the importance of enhancing STI policy efficiencies. With annual government allocations for R&D falling by 1.9% in 2024 in the OECD area, STI policies need to intentionally leverage synergies and mitigate trade-offs between different policy priorities so that STI support to national competitiveness, for example, can also contribute to sustainability transitions. Governments also need to balance and exploit synergies between their direct and indirect (e.g., tax incentives) support measures for R&D, since both can help accelerate transformative change in complementary ways. Co-ordination between STI and non-STI policy areas should also be strengthened.

Making research security proportionate, precise and shaped with partners

Rising geopolitical tensions and strategic competition in emerging technologies are contributing to a growing securitisation of STI that is reconfiguring international STI collaborations. Public research systems are increasingly affected as governments seek to simultaneously: *promote* advanced capabilities and strategic autonomy in critical technology fields; *protect* sensitive knowledge through research security measures; and *project* national interests through selective partnerships and science diplomacy. Protecting sensitive research or academic collaborations can be done in ways that do not compromise research quality, undermine innovation and fragment co-operation on shared global challenges. To do so, research security policies must be *proportionate*, *precise* and developed in close *partnership* with scientists, businesses and other parts of government.

Broadening benefits through enhanced diffusion

Innovation activities typically cluster among leading firms, sectors, and regions due to economies of scale and knowledge spillovers. Such clustering can lead to concentration of economic and societal benefits in limited geographic areas. To broaden the impact, STI policies need to place greater emphasis on policies and investments to promote diffusion and to translate innovations into economy-wide productivity gains and societal benefits. Widening participation in innovation is a key lever for expanding its benefits, since it can enhance both the quality and societal relevance of technological development. Frontier-oriented STI policies should also consider how diffusion and adoption policies can be integrated into development efforts pushing at the technological boundary.

Adapting public science systems

Structural reforms are also needed to enable national science system to better respond to the changing policy context and enhance their contributions to major societal challenges. Key to such reforms is enabling and valuing multidisciplinary research that can generate solutions to complex socio-economic challenges that cut across disciplines and sectors. Reforms are also needed to develop a variety of transparent career-paths that recognise and enable mobility between academia and other sectors. Research infrastructures need more flexible support and governance mechanisms to enable them to operate together to address shared goals and promote transformative change. Academic research also needs to embrace greater direct engagement with society through improved communication measures and citizen science programmes. To ensure these structural reforms take root, performance assessment and incentive structures need to better recognise the variety of contributions to, and outputs from, science that are necessary to promote innovation. At the same time, governments should continue to ensure the freedom and autonomy of research, advance open science, and promote public trust in science.

Harnessing technology convergence

Promoting multi-disciplinary and cross-sectoral research becomes even more important as the convergence of technologies drives forward innovation. Four important technology areas – synthetic biology, neurotechnology, quantum technologies and earth observation from space – illustrate these processes. For example, artificial intelligence is enabling protein design to create molecules with novel properties with the potential to enable personalised therapies, while its convergence with immersive technologies offers opportunities to treat mental illness. Convergence is a process of integration involving different disciplines and communities. Governments can enhance convergence by supporting “convergence spaces”, which are physical, digital and technological infrastructures and platforms that can foster deep forms of interdisciplinary research, engineering and innovation.

Adopting an ecosystems approach

Adopting an industrial ecosystem perspective that goes beyond sectoral boundaries to consider both upstream and downstream industries can contribute to designing more effective industrial policies. It can also help governments to identify the full range of relevant stakeholders, including firms, start-ups, workers, investors, suppliers and trade partners, to design policies that better reflect the true complexity of the industrial landscape. Using the approach, however, entails developing a robust data infrastructure that brings together granular data from multiple sources to capture the ecosystem’s complexity.

Boosting policy agility through strategic intelligence and experimentation

To drive change in a shifting landscape, STI policymaking must be increasingly anticipatory and agile under conditions of high uncertainty. Practices such as strategic foresight, technology assessment, and policy evaluation can provide timely insights through anticipatory and real-time evidence production, while policy experimentation can enable testing of new ideas and critical evaluation of policy impacts. Together, these approaches support evidence-based policymaking and boost policy agility. Fostering their use among policymakers requires embedding them in national programmes and frameworks, increasing flexibility and adaptability within bureaucratic structures, and investing in training programmes for public sector officials. Ensuring there is a clear pathway for scaling up interventions that prove successful or phase down those that fail is also key.

Through these reforms, STI systems can help drive ambitious change

These policy reforms will strengthen national innovation systems, helping them drive change that responds to the shifting policy landscape and tackles future challenges.

1 Mobilising science, technology and innovation policies for transformative change

Science, technology and innovation (STI) plays a prominent role in promoting greater economic competitiveness, resilience and security, and sustainability. To realise their potential, STI systems need to be reformed to generate and deploy relevant knowledge, technologies and innovation at an unprecedented pace and scale. This chapter proposes five key actions STI policymakers can take: promote a policy agenda that contributes to broad transformative change; balance direct and indirect support to research and development; strengthen co-ordination between STI policies and non-STI areas; mobilise public funding to crowd-in private finance; and promote transformative change that goes beyond "business-as-usual" outcomes. The chapter emphasises the need for governments to experiment with and adopt innovative policy mechanisms and tools, and to better appreciate and leverage innovation dynamics to accelerate transformative change.

Key messages

- Global challenges are placing increasing pressure on governments, firms and society more broadly to rethink how our economies and societies can better operate. There is a growing need for transformative change that promotes economic competitiveness, resilience and security, and sustainability transitions.
- Science, technology and innovation (STI) systems are expected to play a prominent role in advancing transformative change. They **need to be reformed to generate and deploy relevant knowledge, technologies and innovations at an unprecedented pace and scale,** under conditions of uncertainty and complexity. Many of these reforms are already well-known within the STI policy community yet pose significant implementation challenges.
- Governments should consider a range of policy actions when reforming their STI policy mix to better contribute to transformative change agendas. First, **STI policy agendas should intentionally leverage synergies and mitigate trade-offs between a range of policy priorities** that contribute to broad transformative change. For example, policy support for national competitiveness can also contribute to resilience and security as well as sustainability transitions, if designed appropriately.
- Second, **policymakers should strike an appropriate balance and exploit synergies between direct and indirect support measures for research and development (R&D) to promote transformative change**. While direct measures can support more ambitious R&D and technological breakthroughs, non-directed measures encourage R&D activities with near-market potential that can help accelerate transformative change.
- Third, **governments should strengthen co-ordination between STI and non-STI policy areas** in pursuing transformative change. The fragmentation of state structures can hinder governments' ability to deliver the needed cross-cutting priorities and interventions to foster transformative change. Governments should continue to experiment with novel policy instruments, such as challenge-based funding and mission-oriented innovation policies, to bring together multiple actors to co-create and collaborate across innovation chains on transformative pathways.
- Fourth, **governments should mobilise public funding to crowd-in private finance** for transformative change. Several capital market failures discourage the allocation of private investment into technologies that promote transformative change. Governments should continue to experiment with instruments like blended finance to deploy public financial resources to leverage or attract private capital.
- Finally, **governments should seek to promote transformative change rather than "business-as-usual" outcomes**. To help steward fundamental, radical and possibly rapid changes, they must appreciate and embrace the nature of transformative change and how it differs from and relates to incremental change. STI policymakers should identify "leverage points" for interventions that can trigger and accelerate the sorts of system-wide changes needed for transformations.
- These five policy actions cover issues that have preoccupied STI policymakers in one form or another for several decades and in this sense are not unique to the pursuit of transformative change. However, the urgent need for transformative change means reforms like these should be implemented quickly if STI is to remain relevant and contribute to future economic and societal advancement.

Introduction

Growing geopolitical tensions, the accelerating climate crisis, biodiversity loss, rising inequality and rapid technological change: these and other challenges are placing increasing pressure on governments, firms and society more broadly to rethink how our economies and societies can better operate for the greater good. There is growing recognition of the need for transformative change, in which STI is expected to play a prominent role. To fulfil this promise, however, STI systems need to be reformed to generate and deploy relevant knowledge, technologies and innovation at an unprecedented pace and scale. This needs to be done in conjunction with reforms in other systems, including energy, health, agriculture and industrial production, where success will also depend on a range of framework conditions, including finance, skills and regulations.

Many of the necessary reforms are well-known within the STI policy community yet pose significant implementation challenges. In response, the OECD Committee for Scientific and Technological Policy has developed the Agenda for Transformative Science, Technology and Innovation Policy to provide high-level guidance to policymakers on their STI policy reforms (OECD, 2024[1]).[1] While the Transformative Agenda's framework can be applied to any transformative goals, it highlights three that capture many contemporary STI policy concerns:

Promoting economic competitiveness that is fair and inclusive. Many OECD Member countries' STI policies place renewed emphasis on productivity growth and international competitiveness. At the same time, income inequality has a sizeable and statistically significant impact on growth and is a key strategic consideration for economic development and societal outcomes.

Fostering resilience and security against risks and uncertainties posed by the growing emergence of systemic threats. Abrupt shocks, such as the COVID-19 pandemic, demonstrate the importance of resilience to anticipate, absorb, recover from and adapt to disruptive change. On the security side, rising strategic competition between countries in critical technologies and resources that underpin economic competitiveness and national security have led governments to increasingly pursue greater strategic autonomy.

Advancing sustainability transitions that mitigate and adapt to a legacy of unsustainable development from climate change, pollution and biodiversity loss. Advancing sustainability calls for accelerated transitions in specific industries, technologies, and established models of production and consumption.

Sustainability transitions have been a prominent feature in most national STI strategies for the last decade, though there are signs this may now be changing. The evolving geopolitical context has brought growing attention to national security through means of strategic autonomy and technological sovereignty (see Chapter 2), while economic competitiveness is again emerging as the pre-eminent concern of research and innovation policy. Since most OECD Member countries are interested in pursuing these goals simultaneously, this chapter considers whether they imply trade-offs or can be complementary and synergistic. It proposes that STI policy can support the transformative change needed to achieve a range of goals by intentionally leveraging synergies and mitigating trade-offs between them.

Much of the chapter focuses on the funding and financing of STI, a core concern for policymakers. Transformative change calls for greater directionality in STI systems, including in their allocation of resources. The chapter therefore explores data on R&D funding and governments' research priorities. It also considers the policy instruments governments use to direct R&D expenditures towards the chosen priorities. These measures are part of a broader policy portfolio that also provides non-directed support, e.g. through R&D tax incentives to firms. Governments face challenges to balance this portfolio and promote synergies between different measures, particularly under conditions of uncertainty and complexity that demand agility and diversity. The chapter describes a simple schema for mapping policy portfolios along the innovation chain and according to their degree of directedness. It also highlights examples of selected policy innovations by several governments to foster more responsive R&D, more breakthrough research and innovation, and more integrated policy support across the innovation chain.

The chapter also considers measures to better co-ordinate STI policy with non-STI policy areas to promote transformative change. The fragmentation of state structures can hinder governments' ability to deliver the sorts of cross-cutting priorities and interventions that are needed. Cross-government co-ordination is especially important, since market and structural conditions, such as regulations and standards, should be aligned to facilitate technology diffusion and phase-out, while the substantial scope of investments needed to facilitate transformations will necessitate buy-in from across government to co-invest in and co-manage coherent portfolios of activities. The chapter outlines how governments are experimenting with novel policy instruments, such as challenge-based funding and mission-oriented innovation policies (MOIPs), to bring together multiple actors, including from different policy domains, to co-create and collaborate across innovation chains on transformative pathways.

Since firms account for around two-thirds of R&D expenditures across the OECD and the private sector is the main source of R&D funding, they have an important role to play in promoting transformative change through STI. However, several capital market failures discourage the allocation of private investment to technologies that promote transformative change. Governments can use risk-mitigation tools to help firms cross "valleys of death" at various stages of the innovation chain. These include "blended finance", with a view to deploying public financial resources to leverage or attract private capital. The chapter argues that governments should continue to experiment with such tools, which have the potential to direct STI finance and help scale-up private investments in research, development and innovation (RDI) and innovation to promote transformative change.

All these issues are broad and long-standing and have preoccupied STI policymakers in one form or another for several decades. In this sense, they are not unique to the pursuit of transformative change. However, since transformative change refers to a radical and permanent qualitative shift in current socio-economic systems, new policy approaches to steward fundamental, radical and possibly rapid changes are needed. As a starting point, an appreciation of the nature of transformative change – and how it differs from and relates to incremental change – is essential. This chapter proposes that governments map and target multiple innovation system feedback cycles in their policy interventions to accelerate transformative change.

The chapter is structured around five proposed policy "actions" that cover these issues:

- Action 1: Promote a policy agenda that contributes to broad transformative change.
- Action 2: Direct R&D funding for transformations in combination with non-directed measures.
- Action 3: Strengthen co-ordination with non-STI policy areas on transformative change.
- Action 4: Mobilise public funding to crowd-in private finance for transformative change.
- Action 5: Promote transformative change rather than "business-as-usual" outcomes.

This chapter offers a brief overview of each action and provides selected examples of countries' policies, particularly where these involve innovative approaches that offer lessons to other policymakers.

Action 1: Promote a policy agenda that contributes to broad transformative change

Transformative change calls for ambitious levels of STI investment over a long period

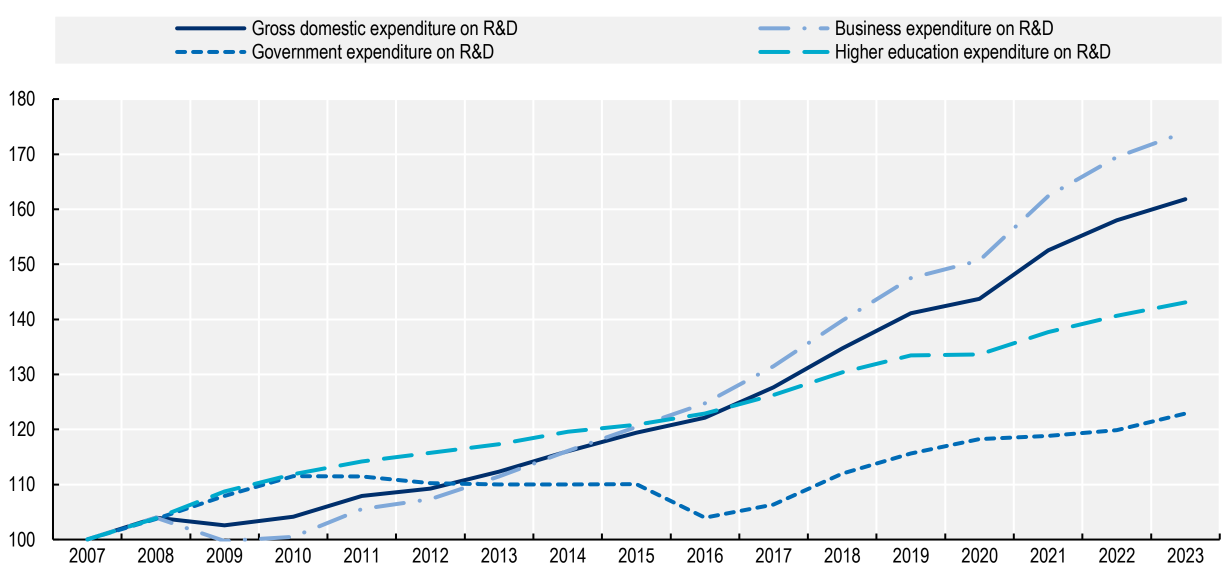
R&D investment is a key driver of growth and a core concern in STI policy. Transformative change calls for ambitious levels of investment over a long period, covering all parts of the innovation chain, from exploratory fundamental research to the deployment and diffusion of tested technologies. These investments are distributed among a variety of different actors within public research and innovation systems as well as private industry. As such, they include public funding for STI from research and innovation ministries and agencies, as well as from sectoral ministries and agencies in areas like energy, transport, agriculture and health. They also cover private financing for STI.

There has been a recent slowdown in R&D expenditure growth in the OECD

While R&D expenditures have increased markedly over the last two decades, there are concerns that debt burdens and inflationary pressures will lead to a slowdown in this growth or even an absolute decline. Recent policy uncertainty and economic activity indicators also signal the potential for rising levels of inflation and a softening of global growth (OECD, 2025[2]). The latest year for which internationally comparable OECD data on R&D expenditures are available is 2023, showing a 2.4% increase in inflation-adjusted terms on the previous year in the OECD, down from 3.6% in 2022. This growth was again driven by the business sector (Figure 1.1), which experienced a 2.7% increase from 2022 to 2023, compared to 2.5% for R&D performed in government sector institutes and 1.7% in the higher education sector. The business sector accordingly accounted for 73.6% of total gross domestic expenditure on R&D (GERD) in the OECD in 2023, up from 66% in 2010. Among the largest spending countries, the share of business-performed R&D increased in the People's Republic of China (hereafter "China") from 60% in 2000 to 77.7% in 2023, which is close to the proportion in the United States (78.4%) and higher than that of the EU27 (66.0%).

Figure 1.1. R&D trends by performing sectors in OECD countries, 2007-2023

2007=100



Source: OECD (2025), *Main Science and Technology Indicators Database*, http://oe.cd/msti (accessed in March 2025).

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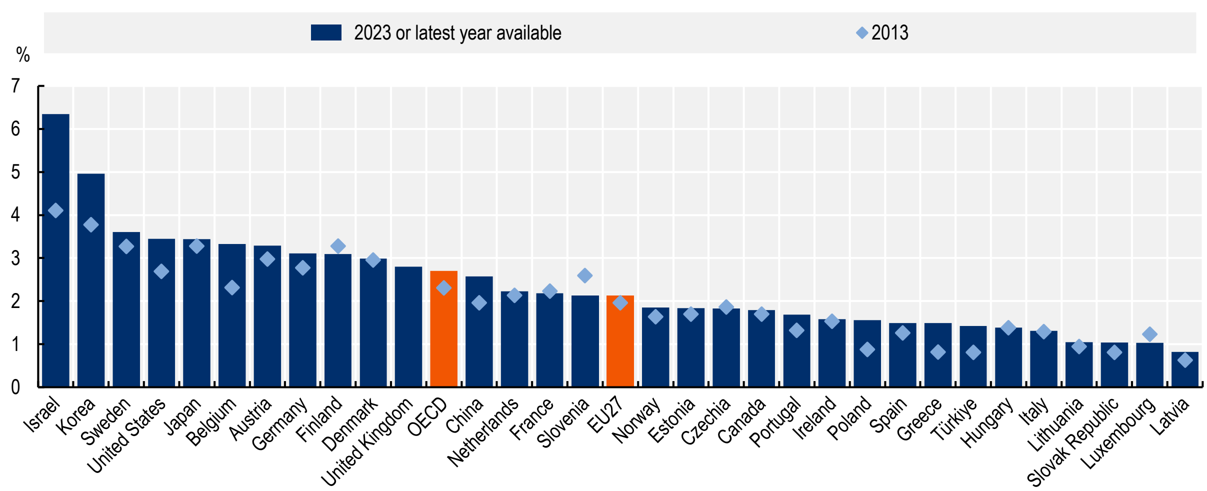
Within the OECD, Israel (6.3%) and Korea (5%) continued to display the highest levels of R&D intensity as a percentage of gross domestic product (GDP) in 2023 (Figure 1.2). R&D intensity in the OECD climbed from 2.3% in 2013 to 2.7% of GDP in 2023. Growth in inflation-adjusted R&D expenditure in the OECD was distributed across several countries but with notable differences among them. In the United States, it stood at 1.7% and in the European Union (EU) at 1.6% in 2023. The European Union's largest economies slowed the area's overall growth: Germany's R&D rose by 0.8%, while France's fell by 0.5%. In contrast, R&D expenditure in Poland and Spain increased by over 8%. R&D growth in Japan (2.7%) and Korea (3.7%) exceeded the OECD average. At 8.7%, growth in R&D expenditure in China in 2023 surpassed that of the OECD (OECD, 2025[3]).[2]

Figure 1.2. R&D intensities, selected economies, 2013-2023

As a percentage of GDP



Note: 2023 data correspond to 2022 for the United Kingdom and 2024 for Canada.
Source: OECD (2025), *Main Science and Technology Indicators Database*, http://oe.cd/msti (accessed in March 2025).

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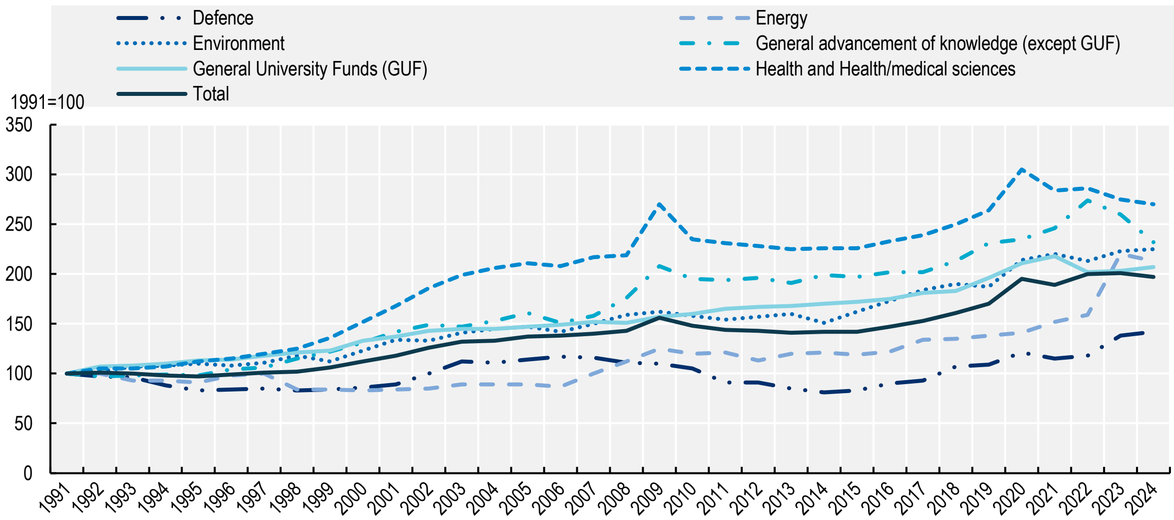
What policy goals are governments prioritising in their R&D expenditures?

Since there are always more ideas and prospective projects to fund than there are available resources, setting research priorities and selecting R&D performers have long been recognised as key policy concerns (see, for example, Weinberg (1963[4])). Furthermore, significant proportions of government-funded R&D target specific economic and societal goals, which are subject to priority-setting processes.

Data on government budget allocations for R&D can be usefully broken down to provide insights on the areas being funded by the public sector (Figure 1.3). Data for the OECD show that support has grown most strongly for health objectives (reflecting changing societal expectations on healthy living and ageing) and general advancement of knowledge (reflecting a relative retreat by governments to set research objectives) over the last few decades. However, R&D investments targeting health-related objectives have declined steadily between 2020 and 2024. After reaching USD 97.4 billion in constant purchasing power parities (PPP) in 2020 – at the height of the COVID-19 pandemic – investments fell to USD 86.3 billion in 2024, a decline of 11.5%. By contrast, support for energy R&D (USD 31.9 billion in constant PPP in 2024) and defence R&D (USD 111.17 billion constant PPP in 2024) increased sharply over the same 2020-24 period, by 51% and 17%, respectively, reflecting policy goals to reduce greenhouse gas emissions and enhance national security. There is some variety across OECD Member countries on the relative weight of these areas in their R&D budget portfolios, as shown in Figure 1.4. These reflect, in part, different institutional set-ups and R&D funding arrangements across countries, as well as their sectoral specialisation.

Figure 1.3. Trends and broad spending categories of government R&D budgets, OECD, 1991-2024

1991 = 100



Note: GUF: general university funds; GBARD: government budget allocations for R&D.
Source: OECD calculations based on OECD (2025), *Main Science and Technology Indicators Database*, https://oe.cd/msti (accessed on 17 October 2025).

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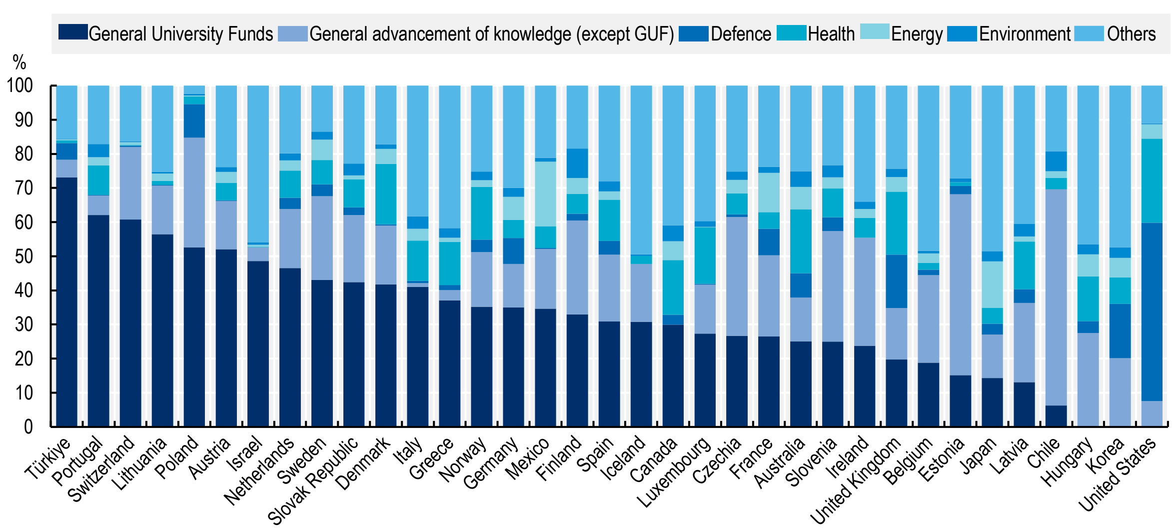
Figure 1.4. R&D budget by broad spending categories, selected economies, 2024

As a percentage of total government budget allocations for R&D



Notes: GUF: general university funds. Public GUF refer to the R&D funding share from the general grant that universities receive from the central (federal) Ministry of Education or corresponding provincial (state) or local (municipal) authorities in support of their overall research/teaching activities. General advancement of knowledge (financed from sources other than GUF) is R&D funding from general grants that cannot be attributed to an objective and are financed by sources other than GUF. 2024 data corresponds to 2023 for Chile, Israel, Korea United Kingdom and 2022 for Canada.
Source: OECD calculations based on OECD (2025), *Research and Development Statistics*, https://www.oecd.org/en/data/datasets/research-and-development-statistics.html (accessed on 17 October 2025).

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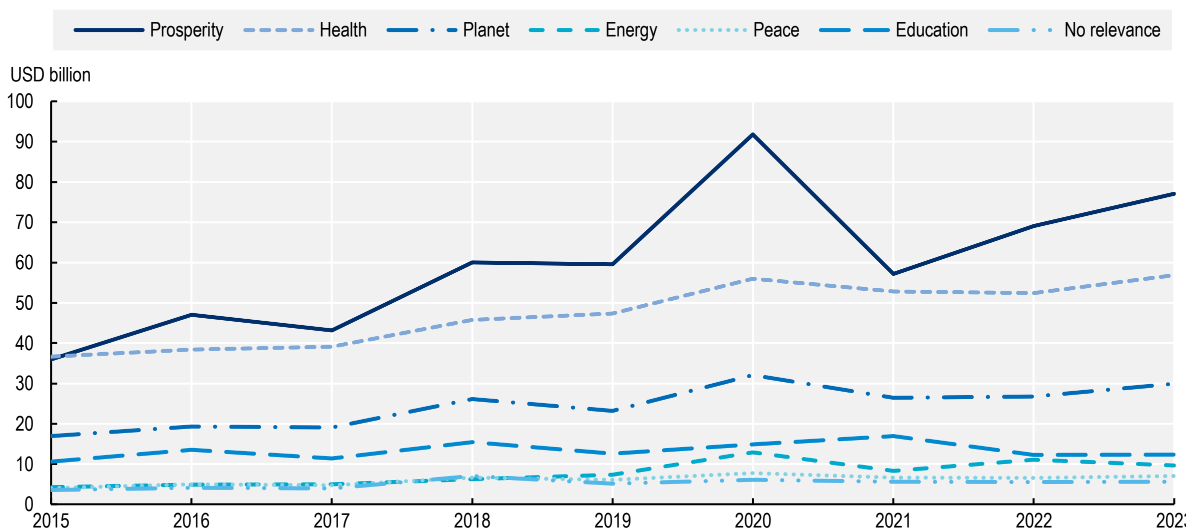
Insights on the directionality of public R&D funding can also be gleaned from analysis of the administrative data of research and innovation funding bodies. Focusing on societal goals, an analysis of R&D project funding data in the OECD *Fundstat database* (version: 2024, May 2025) (Aristodemou et al., forthcoming[5])[3] shows that public R&D funding grew across all major goals from 2015 to 2023 (Figure 1.5). Among the societal goals categories used in the analysis, "Prosperity" accounted for the largest amount of R&D funding in 2023, followed by "Health" and "Planet". In terms of growth over the 2015-2023 period, "Energy" grew 2.3 times, "Prosperity" 2.1 times, "Planet" 1.8 times, "Peace" 1.7 times and "Health" 1.6 times. "Education" saw the lowest growth, at 1.2 times. These patterns highlight that much of government R&D remains focused on promoting economic competitiveness, and that although support to sustainability transitions has risen in recent years, it remains modest in comparison.

Figure 1.5. Estimates of R&D funding to societal goals, 2015-2023

R&D funding awards for 19 OECD countries and EC-EU programmes



Notes: The OECD *Fundstat database* includes R&D project-level data from 19 OECD countries (Australia, Austria, Belgium, Canada, Czechia, Estonia, Finland, France, Germany, Japan, Ireland, Latvia, Lithuania, Norway, Portugal, Sweden, Switzerland, the United Kingdom and the United States) and the European Commission programmes. For 2021, the data for these 19 countries represent approximately 51% of the total government budget allocations for R&D, excluding general university funds, for these countries as reported in the OECD *Main Science and Technology Indicators Database*. Sustainable Development Goal (SDG) categories are mutually exclusive with fractional allocations using the SDG classifier on R&D project descriptions (Aristodemou et al., forthcoming[5]). The SDG (https://sdgs.un.org/goals) categories are defined as follows: Prosperity includes SDG 8, SDG 9, SDG 10 and SDG 11; Health includes SDG 1, SDG 2, SDG and SDG 5; Planet includes SDG 6, SDG 13, SDG 14 and SDG 15; Energy comprises SDG 7; Peace covers SDG 16 and SDG 17; Education corresponds to SDG 4 more closely resembling scholarship-driven research as opposed to research on education; and No relevance projects are without identifiable alignment to any specific SDG. R&D funding award data reflect authorisation rather than actual commitments or expenditure. The prominent peak in 2020 largely results from increased R&D funding related to the COVID-19 pandemic response, along with the inclusion of Japan's Green Innovation Fund in the database.
Source: OECD analysis of the OECD *Fundstat database* (v. 2024) (accessed in May 2025).

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Tensions and synergies in pursuing a range of priorities

While there are strong synergies and interdependencies between the priorities of economic competitiveness, security and sustainability, insular efforts to advance specific goals may compromise others. Some of the relationships between these policy goals are universal while others may be specific to a particular geographic context or sector Table 1.1 provides a comprehensive, albeit likely incomplete, overview of some of the synergies and tensions between sustainability and other policy priorities related to economic competitiveness, inclusive development, and national security and resilience.

Table 1.1. Synergies and tensions between diverse science, technology and innovation policy priorities

	Sustainability-competitiveness	Sustainability-inclusive development	Sustainability-security and resilience
Synergies	**Sustainability transitions lower long-term costs:** Maintaining an emissions or resource-intensive status quo may be more expensive than transitioning to a low-carbon system. **Green innovation drives economic growth:** When embedded into cross-government policy, green technologies and practices can drive growth, job creation and exports. **Early transitions foster first-mover advantages:** Investing early in emerging green markets can allow countries to foster long-term competitiveness and international influence. **Regulation spurs innovation and efficiency:** Streamlining regulation and harmonising standards is important for efficient markets and can accelerate clean technology deployment. **Phase-out policies remove market distortions:** Discontinuing fossil fuel subsidies and market distortions fosters competition, improves fiscal sustainability and stimulates green innovation. **Transitions drive industrial modernisation:** Environmental regulations prompt firms to improve operational efficiency, driving industrial modernisation, productivity and resilience.	**Public engagement enables context-specific solutions:** Engaging diverse communities in science, technology and innovation (STI) ensures that solutions are tailored to local needs and empowers broader benefits of STI. **Leveraging traditional knowledge makes low-carbon pathways more robust:** Local knowledge systems offer culturally relevant low-emission alternatives to complement or replace high-tech solutions and enhance sustainability. **Capacity building advances broad participation and sustainable growth:** Skills accumulation and lifelong learning, particularly among underserved groups, enables broad participation in the green economy and contributes to productivity and innovation. **Policy for sustainability can drive broader participation and development:** Sustainability-focused STI policies can dismantle structural barriers to participation, create green jobs in underserved areas, and improve access to clean air and public services. **Inclusion accelerates sustainability transitions:** Reducing inequality supports sustainable growth by expanding demand for clean solutions and cultivating public trust and consensus.	**Sustainability addresses risks and enhances resilience:** Climate action and sustainable systems strengthen resilience and reduce security threats posed by, for example, extreme weather. **Security threats can create windows of opportunity for transition:** Climate change is framed as a "threat multiplier", strengthening its relevance to national security and creating opportunities to accelerate sustainability transitions. **Technological sovereignty and sustainability share R&D priorities:** Key technologies for strategic autonomy (e.g. semiconductors, etc.) are also essential for sustainability. **Domestic capacity supports sustainable growth and security:** Strengthening domestic capacity in key global value chains (e.g. critical minerals) enhances security and supply chain resilience while supporting long-term sustainability. **Balanced international partnerships advance sustainability and geo-economic interests:** Promotion and projection policies can accelerate the development and diffusion of technologies that are key to global sustainability and security.
Tensions	**Fiscal pressures favour short-term gains over long-term sustainability:** Limited budgets often push policymakers to prioritise quick economic returns, supporting the optimisation of existing high-emission industries or less harmful industries rather than investing in transformative green alternatives. **Greening key industries faces major barriers:** Many carbon-intensive sectors like steel and cement are central to national competitiveness but lack competitive green alternatives. **Transitions can cause economic disruption:** The productivity and competitiveness of some firms may decline during transitions. Regions and sectors dependent on fossil-based industries may also face economic disruption and decline.	**Transitions can distribute costs and benefits inequitably:** Climate mitigation policies can impose high costs through the phase-out of local industries or short-term price increases, which may disproportionately impact some regions and workers. **Some transition pathways can undermine local livelihoods and human security:** Some low-carbon industries or practices may compromise basic development pathways, including local livelihoods, land rights, food systems or energy access. **Perceived injustice undermines policy support:** If climate policies are viewed as regressive or unfair, they risk triggering public backlash, eroding social cohesion and stalling action. **There may be short-term trade-offs**	**Sustainability transitions can exacerbate security risks:** Phase-out efforts reduce strategic vulnerabilities while introducing short-term risk, e.g. energy security. Global value chains are also subject to foreign influence and disruption. **Industrial protectionism can undermine sustainability goals and multilateralism:** Defensive trade policies (e.g. protection of green industries) may shield national interests but risk triggering retaliation, reducing global collaboration, and stalling green technology deployment and transitions. **Emerging threats and crises can undermine or postpone sustainability goals:** During crises, national security often overrides long-term climate or environmental goals, especially when

	Sectors exposed to international trade may not be able to compete: Increased production costs from regulation and technology adoption may cause firms to relocate. There is also a risk of carbon leakage from countries with weak climate policies.	**between poverty reduction and environmental constraints:** Immediate economic benefits of polluting activities can conflict with long-term environmental goals, posing difficult choices between development and decarbonisation.	sustainable alternatives lack viability or scalability. **Defence and climate priorities may compete for financial allocations:** National defence spending can draw funding away from climate mitigation and adaptation efforts.

This chapter unpacks some of the connections between sustainability transitions and economic competitiveness and inclusion (Chapter 2 discusses connections with security). The chapter first outlines synergies and trade-offs then discusses them in reference to specific policy interventions from a selection of countries to provide examples of how such synergies are leveraged, trade-offs are mitigated or where goals may be in dissonance. In this regard, the analysis considers a selection of the latest STI policy announcements and budgets from four countries – Australia, Canada, Korea and the United Kingdom – as well as from the European Union, as outlined in Table 1.2. These countries were chosen primarily for their global geographical spread.

Table 1.2. Examples of science, technology and innovation policy priorities

Review of recent policy announcements in four OECD countries and the European Union

Country	Scope and summary description of the policy announcements and budgets examined
Australia	The review of Australia's science, technology and innovation (STI) policy objectives analysed several strategy documents, including highlights from the 2024/25 Federal Budget, the 2024 National Science Statement, the 2024 Science and Research Priorities, and the 2024-2028 Corporate Plan for the Department of Industry and Science. Common themes include amplifying the economic security generated by the resources sector; enhancing adaptability, resilience and national security; protecting and restoring the national environment and transitioning to net zero. While the inclusion of under-represented and marginalised communities is emphasised via objectives related to regional development, engagement with Aboriginal and Torres Strait Islander communities, and breaking down systemic barriers for under-represented demographics, connections made to sustainability and, in particular, security and resilience, are relatively less apparent.
Canada	Analysis of Canada's current STI policy objectives targeted a review of the 2024/25 Department Plan for the Ministry of Industry, Science and Economic Development and the 2024/25 Federal Budget. Both include a prominent focus on economic competitiveness and the translation of innovation into improved outcomes for the public and future generations, which implies an indirect link to sustainability transitions. Many of the objectives are agnostic to addressing societal challenges, with much focus placed on enhancing domestic capacity in strategic technological areas like artificial intelligence, quantum science, space exploration and cybersecurity. Where multiple policy goals are pursued, it is often in relation to improving the sustainability and security of industry.
European Union	The EU Competitiveness Compass (European Commission, 2025[6]) is the European Commission's recent response to the 2024 Draghi Report (Draghi, 2024[7]). The strategy outlines three high-level priorities – closing the innovation gap, a joint roadmap for decarbonisation and competitiveness, and reducing excessive dependencies and increasing security – and five enabling conditions, among which sustainability transitions are often framed in terms of economic competitiveness and national security. Comparatively, inclusion is much less prominent or integrated with other policy goals. It is also referenced indirectly in terms of, for example, reskilling and upskilling initiatives aimed to support all Europeans.
Korea	The review of Korean STI policy objectives looked at the summary of Budget 2025; the 2025 Budget and Workplan for the Ministry of Science and ICT; the 5th Energy Technology Development Plan (2024); and the 5th Environmental Technology, Industry and Workforce Development Plan (2024). Across the strategy documents, significant attention is given to improving Korea's leadership and technology sovereignty in critical technology areas, including artificial intelligence, semiconductors, advanced biotechnology and quantum technology. Economic growth and achieving international competitiveness are significant drivers behind much of the policy. While less attention is afforded to sustainable and inclusive development in these overarching strategies, values of inclusiveness, sustainability and responsibility are embedded in many of the more granular policy supports for strategic technologies through the focus placed on responsible development, gender balance and the inclusion of civil society. These policy issues are also addressed via targeted strategies, including the Green New Deal and its associated net zero STI programmes and the Comprehensive Plan for Addressing Social Issues through Science and Technology (2023-2027).
United Kingdom	Analysis of the United Kingdom's STI policy objectives is based on the national 2024 Budget and the Science and Technology Framework, which was originally published in March 2023 and updated in April 2025 to reflect the priorities of the current government. The Science and Technology Framework outlines ten policy levers, includeing support for the development and deployment of critical technologies, including advanced connectivity technologies, artificial intelligence, engineering biology, quantum technologies and semiconductors. Other policy levers also emphasise, for example, investing in research and development to benefit society as a whole, building a workforce for the future economy, leveraging public procurement to deliver economic growth and social value, enabling international relationships to tackle global challenges, and embedding a pro-innovation culture in the

	public sector. Innovation is also a pillar of the 2024 Budget's growth mission, where the focus is on increasing productivity and improving public life. STI is a key enabler of several other pillars, many of which will also require policymakers to balance trade-offs between different policy goals. This includes efforts to maintain free and open trade while advancing sustainable, secure and resilient growth or delivering a net zero transition that drives economic growth and clean energy leadership while protecting consumers and energy security.

Synergies and tensions between sustainability and economic competitiveness?

Evidence suggests that climate action and economic development strategies are mutually reinforcing. Over the next decade, ambitious targets and policies to reduce greenhouse gas emissions could result in a net gain to global GDP (OECD/UNDP, 2025[8]). Without government intervention, industry-led STI activities tend to focus on optimising the profitability and efficiency of established solutions rather than the emergence of new alternatives (Garsous, Bourny and Smith, 2023[9]; OECD, 2025[10]). However, challenging fiscal positions may require governments to direct support towards priority areas to balance short-term growth and long-term sustainable development (OECD, 2025[2]).

The scale-up of industries and technologies that are less destructive or carbon-intensive, like the use of natural gas and liquefied natural gas as bridge fuels, can provide interim solutions. However, they can also slow or draw resources away from more sustainable alternatives (Meadowcroft, 2011[11]). Australia recognises this reality in its Future Gas Strategy, which is pragmatic about the necessity of gas-powered generation for electricity grid security and reliability while identifying the commercialisation of net zero alternatives as a means to reduce demand (Australian Government, 2024[12]).

In addition, the greening of some industries will be more difficult. This could be the case where low-carbon solutions are far from commercial or competitive, where production or deployment infrastructure requires substantial upfront investment, or where significant disruption of industrial operations would damage economic competitiveness. Many countries provide public funding or incentivise private financing for carbon capture, utilisation and storage (CCUS) technologies and infrastructures, including Canada's tax credit for CCUS (Government of Canada, 2024[13]) and Korea's Carbon Capture and Utilisation (CCU) Demonstration Support Center and supports for businesses to apply CCU technologies (Government of Korea, 2024[14]). The United Kingdom also has plans to leverage GBP 8 billion of private investment in CCUS infrastructure (HM House of Commons, 2024[15]).

Several governments are also taking steps to streamline bureaucracy or harmonise regulation to advance sustainability transitions and contribute to economic growth. For instance, Australia, Canada and the European Union have introduced initiatives to cut red tape and accelerate approval processes for clean growth projects (Commonwealth of Australia, 2024[16]; Government of Canada, 2024[13]; European Commission, 2025[6]).

Analysis of the synergies and trade-offs between policy priorities (Table 1.1), paired with policy examples from the countries analysed (Table 1.2), yields a range of policy options available for the design of integrated STI approaches needed to optimise or navigate interdependencies between different goals. These are outlined in Table 1.3 and Table 1.4 and organised loosely according to different phases of transformation and corresponding intervention points (Ghosh et al., 2020[17]; Kanger, Sovacool and Noorkõiv, 2020[18]).

Table 1.3. Policy options to support competitive sustainability transitions

Entry point	Science, technology and innovation (STI) policy considerations – competitive transitions
Developing and scaling sustainable alternatives	Provide targeted support across all stages of the innovation process to generate and commercialise clean technologies in areas of strategic importance or comparative domestic advantage. Expand sustainable economic opportunities by developing lead markets, transforming sustainability challenges into industrial opportunities, and crowding in private investment.

	Promote trade flows through foreign direct investment and exports with appropriate screening mechanisms to cultivate domestic capacity in strategic sustainability areas and prevent technology leakage. Adopt a balanced approach to international co-operation that supports the advancement of sustainability transitions and science diplomacy while growing the national economy.
Discontinuing and replacing established systems	Gradually downscale public support for environmentally harmful technologies and practices (e.g. R&D funding, subsidies, tax deductions). This can reduce fiscal burdens and accelerate shifts in energy markets and sustainability outcomes over the long term. Integrate market-based policies like carbon pricing, tax exemptions, procurement, adoption subsidies and innovation policies to help correct market failures, foster clean innovation and lower the cost of sustainable alternatives. Improve the supply of skilled labour; invest in technology demonstration, manufacturing and diffusion infrastructure; and create policy certainty to attract and retain investment into sustainable industries and technologies. Reform market structures and regulation to improve market efficiency and support the scale-up of emerging STI-based solutions or industries. Encourage the development of product and green financing standards to derisk investment into clean technologies, increase market confidence, facilitate cross-border diffusion and mitigate greenwashing.
Addressing the broader repercussions of transition	Complement STI and net zero policies with targeted support for affected industries, workers, regions and firms to mitigate transition risks and widening inequalities that are likely to negatively impact competitiveness. Safeguard access to critical technologies and materials and prevent new dependencies that may undermine national competitiveness. This can be done by cultivating strategic supply chain partnerships, diversifying sources, investing in recycling and substitution R&D, and promoting international co-operation. Design policies for sustainable regional development that address the repercussions of transitions, support laggard firms, and create new industries and employment.
Facilitating multi-system transitions across sectors and geographic borders	Strengthen connections between critical sectors and emerging areas to facilitate the development of clusters, knowledge spillovers and the flow of emerging solutions into relevant secondary industries and other regions. Engage in international negotiations and agreements that support collective commitments to sustainability transitions and prevent carbon leakage. Cultivate balanced international collaboration with trusted partners to facilitate cross-border flows of data, expertise and technology to accelerate sustainability transitions and strengthen national economic growth.

Note: In several instances, there is notable overlap or alignment between policy considerations for stewarding fair and competitive sustainability transitions.
Source: Adapted from Kangar, Sovacool and Noorkõiv (2020[18]); Ghosh et al. (2020[17]); Kivimaa and Rogge (2024[19]).

Synergies and tensions between sustainability and inclusive development?

Technology-driven development often co-exists with, or may reinforce, absolute and relative poverty (Chataway, Hanlin and Kaplinsky, 2014[20]). Without appropriate distributive or inclusion measures, contemporary innovation pathways can exclude large segments of the global population as both producers and beneficiaries of change (Planes-Satorra and Paunov, 2017[21]). Inequality is correlated with slower growth and constrained innovation and can impair sustainable development by limiting demand for less competitive net zero solutions (Mazarr, 2022[22]; Ostry, Berg and Tsangarides, 2014[23]). This is a central focus of some of the initiatives outlined in the STI strategy documents.

For instance, Canada is making efforts to improve data on the national clean technology industry to better understand and address the needs of under-represented groups (ISED, 2025[24]). The United Kingdom has embedded sustainability and inclusive development into the Innovation Accelerator programme, which supports the development of innovation clusters to advance the development of greener technologies and helps to address regional income and productivity disparities (DSIT, 2024[25]; UKRI, 2025[26]). Recent evaluations of the EU Bioeconomy Strategy have revealed uneven distribution of activities across EU regions (BioRural, 2024[27]; European Commission, 2022[28]). This has spurred efforts to update the strategy to take advantage of the growth potential of the expanding bioeconomy while reducing reliance on fossil fuels and improving economic outcomes for rural areas.

Embedding inclusion and fairness as key considerations within sustainability initiatives is necessary to facilitate fair transitions.[4] However, engagement is largely absent as a topic addressed at the strategic level in the country examples examined, apart from the Canadian and Australian strategy documents, which make mention of indigenous consultations. For example, Canada has allocated CAD 800 million to support indigenous-led environmental conservation efforts (Government of Canada, 2024[13]). The Australian government commits to drawing on the expertise of Aboriginal and Torres Strait Islander communities to mitigate climate change and the transition to net zero (Australian Government, 2024[29]).[5]

In addition, action may be necessary to balance potential conflicts between sustainable and inclusive development.[6] Many of the strategy documents reference national supports for communities and workers affected by sustainability transitions, which emphasises the necessity of connectivity and coherence between STI and other policy domains. This is further discussed below. More generally, policies focused on skills accumulation and lifelong learning may also contribute to productivity increases.[7] Chapter 3 discusses these and other related issues extensively.

Table 1.4. Policy options to support fair sustainability transitions

Entry point	Science, technology and innovation (STI) policy considerations – fair transitions
Developing and scaling sustainable alternatives	Support the design and adoption of context-specific and effective sustainability solutions through direct engagement with affected and marginalised communities. Integrate insights from indigenous and local communities into the development of STI-based solutions and policy. Support the development of community-based grassroots initiatives to complement and align technology-based innovation with local needs. Improve data collection on under-represented groups to target STI policies towards addressing regional income and productivity disparities and support equitable access to the benefits of sustainability transitions. Work with relevant policy domains to broaden accessibility and the uptake of sustainability solutions. This might include expanding infrastructure development to underserved communities or developing market-based policy instruments to support adoption.
Discontinuing and replacing established systems	Use education, outreach and public participation in STI and STI policy development to cultivate ownership over societal issues, empower informed decisions, and support iterative processes of learning and behaviour change. Pivot established networks to improve the representation of emerging industries and under-represented communities. Ensure that policy like carbon trading and pollution taxes do not disproportionately disadvantage marginalised communities. Regulate data access and ownership to advance the self-determination, empowerment and innovation opportunities of marginalised and under-represented populations. Contribute to international efforts to harmonise emerging technology standards and regulation to facilitate broad diffusion and reduce costs through economies of scale. Ensure that sustainability-focused market and regulation reforms do not widen inequalities or contribute to the vulnerability of marginalised communities.
Addressing the broader repercussions of transition	Develop strategic intelligence mechanisms to anticipate and mitigate or adapt to emerging issues or challenges posed by sustainability transitions. Co-ordinate national policies to support workers and communities affected by sustainability transitions and ensure coherence across STI, labour, social and regional development policies. Invest in education and training to support fair economic development and equip people, including marginalised groups, with the skills needed to participate in emerging sustainable industries. Design STI policy using integrated, equity-centred approaches to mitigate trade-offs and create a mutually reinforcing cycle between inclusion and climate action. Target foreign aid to support emerging economies that will be negatively impacted by shifting trade patterns e.g. declining demand for coal and fossil fuels.
Facilitating multi-system transitions	Engage in international negotiations and agreements that promote responsible and ethical technology development and deployment and support the protection of human rights in the pursuit of sustainability transitions. Provide support to emerging economies to ensure sustainability development can be pursued without sacrificing affordability or

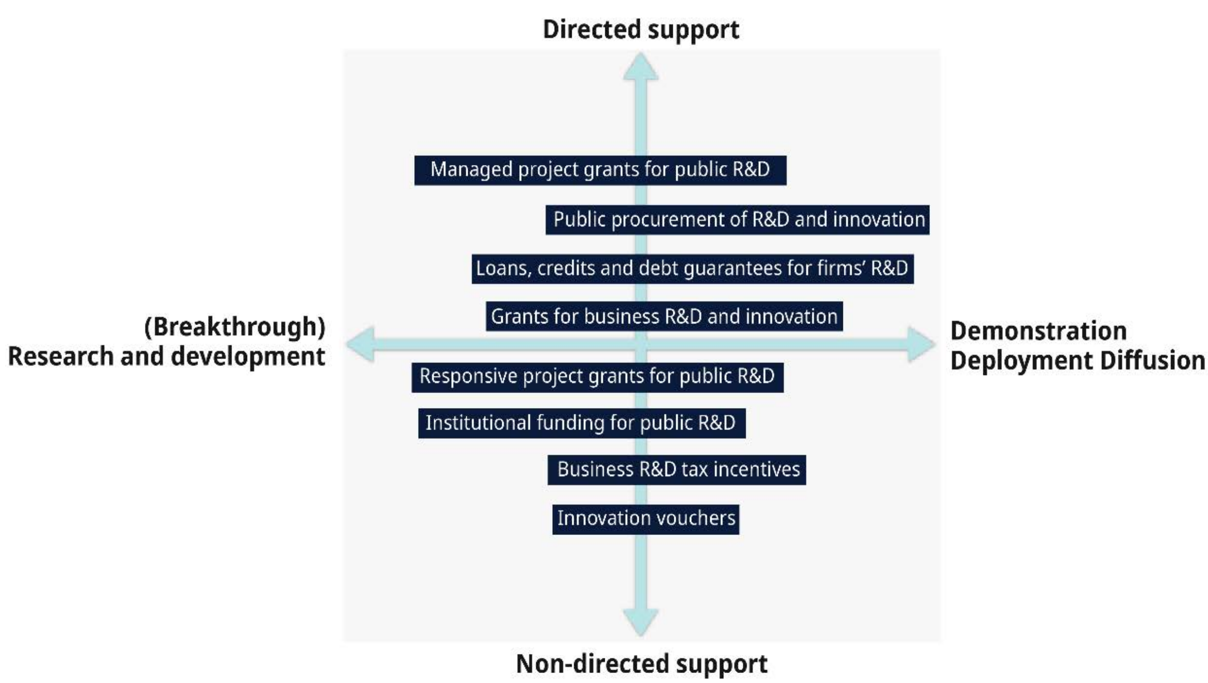
across sectors and geographic borders	economic growth. Official development assistance and technology transfer can allow emerging economies to bypass unsustainable technologies and systems in favour of cleaner alternatives.

Note: In several instances, there is notable overlap or alignment between policy considerations for stewarding fair and competitive sustainability transitions.
Source: Adapted from Kanger, Sovacool and Noorkõiv (2020[18]); Ghosh et al. (2020[17]); Kivimaa and Rogge (2024[19]).

Action 2: Direct R&D funding for transformations in combination with non-directed measures

Governments use a range of funding instruments to support RDI, many of which can be used to promote activities across a wide range of the innovation chain (Figure 1.6). Nevertheless, some funding instruments are preferred over others to promote either (breakthrough) R&D or demonstration, deployment and diffusion of technologies. Both are essential, since a mix of knowledge, innovation, and novel and existing technologies is needed to promote transformative change.[8] The challenge for governments is to strike an appropriate balance, which will vary depending on, for example, a technology's maturity and the domestic capabilities of firms and universities to develop and adopt related novel science and technologies.

Figure 1.6. Mix of selected policy instruments for public funding of research, development and innovation



Notes: R&D: research and development. This figure shows a selection of R&D and innovation funding instruments used by governments and their typical range. A more comprehensive taxonomy developed by the EC-OECD *STIP Compass database* can be found at: https://stip.oecd.org/stip.

Another important STI policy debate concerns striking an appropriate balance between directed and non-directed support to RDI activities performed in both the public and private sectors. As shown in Figure 1.3, much government support for R&D is non-directed and serves general economic development and the advancement of knowledge. In the public sector, non-directed support typically takes the form of institutional “core” funding for universities (including GUF) and public research institutes; and “responsive” R&D grants where researchers propose research projects “bottom-up” for funding. This contrasts with “managed” R&D programme project grant calls, where funding bodies define, with varying degrees of precision, the areas of research they will fund. These “top-down” calls are co-designed with the research community and support a mix of R&D: typically, basic research in universities and some public research institutes and applied research and experimental development in public research institutes dedicated to supporting firms’ technological upgrading.

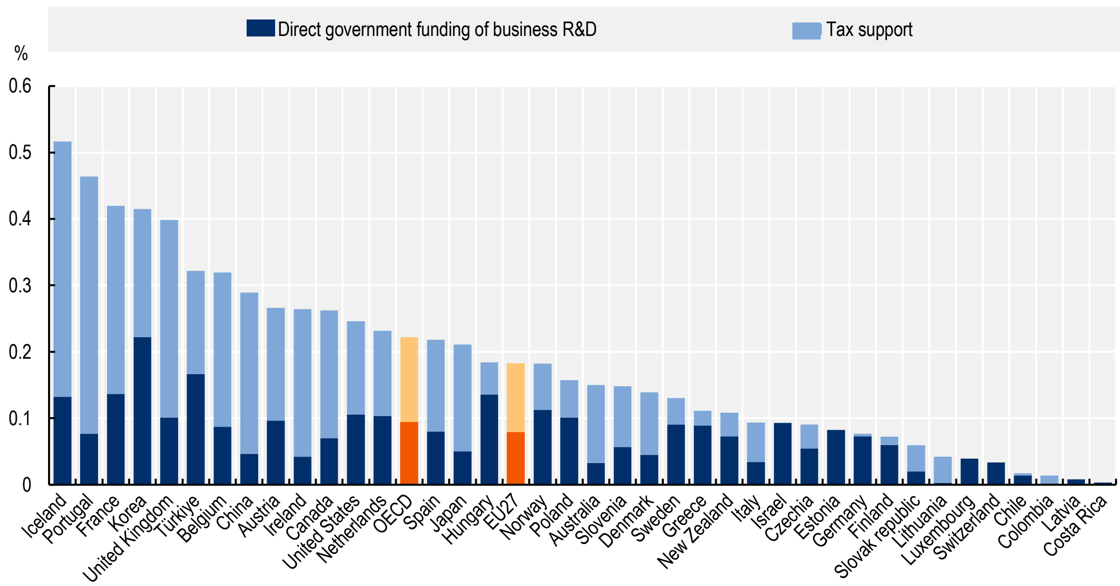
There is a natural tension between promoting scientific research that is explicitly oriented towards solving practical challenges and encouraging a broad-based development of scientific capabilities that might ultimately contribute to such goals. This is because research for nominally different purposes can help to achieve transformative goals in unexpected ways. For instance, analysis of low-carbon and other environmental management patents indicates that core scientific disciplines like chemistry and physics, together with material sciences and biology, are among the most heavily cited sources of scientific knowledge relevant for new inventions by inventors and examiners. The wide-ranging nature of these scientific influences underscores the challenge of pinpointing a single dominant field driving low-carbon innovation. This suggests that policymakers should avoid a crude classification of scientific domains as relevant for tackling specific transformative goals (OECD, 2025[30]). It is also often the case that significant breakthroughs emerge from the accumulation and combination of decades of curiosity-driven research across various fields. This was shown most recently in the rapid development of COVID-19 vaccines,[9] demonstrating how long-term investments in R&D contribute to societal resilience (see Chapter 4).

Similar tensions play out in debates around public support to private sector R&D. Not only do governments vary in the level of support they offer businesses to encourage them to perform R&D and innovate, they also vary in the policy instrument portfolio they use (Figure 1.7).[10] Among directed funding instruments, governments offer grants, loans, credits and debt guarantees to support businesses in their RDI activities and use public procurement to promote firms’ innovation and technological upgrading. Among non-directed instruments are business R&D tax incentives and innovation vouchers (Figure 1.6).

There has been considerable change in the business R&D support policy mix over the last two decades, with a near-universal shift from directed support instruments to a greater reliance on indirect R&D tax incentives. In 2022, 32 of the 38 OECD Member countries gave preferential tax treatment to business R&D expenditures. R&D tax incentives represented around 56% of total government support for business R&D in 2022, compared to 35% in 2006 (Figure 1.8).

Figure 1.7. Direct government funding and government tax support for business R&D, 2023

As a percentage of GDP



Notes: For Austria, Bulgaria, Chile, China, Germany, Ireland, Luxembourg, OECD average, Portugal, the Slovak Republic, South Africa and the United Kingdom, the latest available figures of direct and tax support for business R&D refer to 2022 instead of 2023. For Australia, EU-27 area, France, New Zealand, Switzerland and the United States, figures refer to 2021. For Brazil, Colombia, Denmark and Romania, data refer to 2020. Preliminary OECD estimate of government tax relief for R&D expenditures for the OECD in 2022. For general and country-specific notes on the estimates of government tax relief for R&D expenditures, see https://stats.oecd.org/wbos/fileview2.aspx?IDFile=7bac5f9d-e557-4938-8928-dda26fb93a19. Data on government tax relief for business R&D also includes subnational tax support for Canada, Hungary and Japan.
Source: OECD (2025), *OECD Tax Incentives Database, https://oe.cd/rdtax* (accessed in April 2025).

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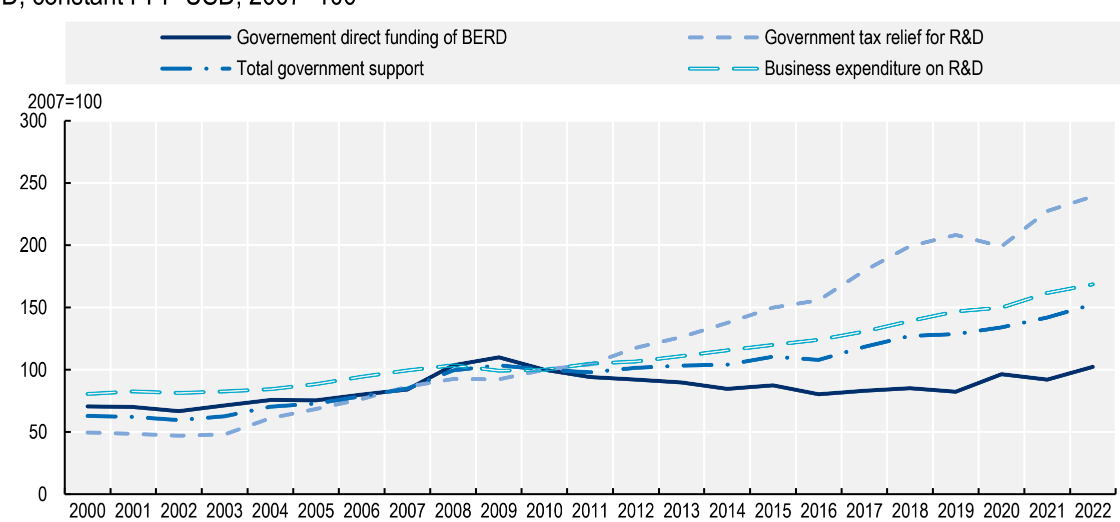
Figure 1.8. Shift in the government policy support mix for business R&D, 2000-2022

OECD, constant PPP USD, 2007=100



Notes: For general and country-specific notes on the estimates of government tax relief for R&D expenditures, see: www.oecd.org/sti/rd-tax-stats-gtard-ts-notes.pdf. Data on government tax relief for business R&D also includes subnational tax support for Canada, Hungary and Japan.
Sources: OECD (2025), *R&D Tax Incentives Database*, http://oe.cd/rdtax (accessed in April 2025); OECD (2025), *Main Science Technology Indicators Database, https://oe.cd/msti* (accessed in March 2025).

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Neutrality and reduced policy discretion of tax incentives have several desirable features when funding R&D. They are less costly to administer and, when neutrally designed and available on demand, are more easily compliant with state aid rules (OECD, 2024[31]). However, after two decades of widespread deployment, there is broad consensus that tax incentives are more suited, in principle, to encouraging R&D activities with near-market potential and the shortest payback time. By contrast, direct measures, such as grants, are more suitable for supporting longer term, high-risk R&D, and targeting specific areas that either generate public goods or have particularly high potential for spillovers. Both types of measures provide useful support, but the growing urgency to promote transformative change may point to the need for a rebalanced approach in some countries that gives greater prominence to more ambitious direct measures (González Cabral, Appelt and Hanappi, 2021[32]).[11]

Given that scientific research and technological innovation are inherently uncertain, policy support should "spread bets" on a diversity of solutions using a portfolio approach. This will help avoid technological lock-in and develop the absorptive capacities to access knowledge and technologies developed elsewhere. A portfolio approach should also balance funding support across stages of the innovation chain and promote interactions and complementarities between stages to help steward ideas from conception to application and bridge particular "valleys of death". There is no one-size-fits-all solution and the composition of these portfolios and the research areas, technologies, industries and other forms of innovation that are prioritised will depend significantly on the current context of individual countries and their desired future visions.

In the meantime, governments are experimenting with novel funding mechanisms and arrangements to promote more responsive R&D, more breakthrough research and innovation, and more integrated support across the innovation chain. These are briefly discussed below.

Innovative funding mechanisms to promote responsive R&D

Various policy innovations are emerging that aim to make funding more agile and responsive to changing conditions. Some countries have introduced funding initiatives that consider a broader set of societal considerations in their award decisions. For instance, with the Strategic Innovation Partnership programme in Sweden, the innovation agency Vinnova ranks proposals based on traditional criteria (i.e. the business case and degree of scientific excellence), and, for those that pass this initial evaluation, non-government partnerships select projects to fund that best align with their "theories of change". Under the National Research and Innovation Strategy for Smart Specialisation of the Czech Republic 2021-2027, standard RDI calls for proposals provide a "bonus" during the assessment process for projects that are relevant to the missions, which increases their probability of procuring funding.[12] The Austrian Research Promotion Agency considers the sustainability of each project in addition to the substantive and economic aspects. This includes emissions, pollution, resource and energy consumption, and socio-economic impact (e.g. effects on poverty reduction, health, education, gender, working conditions and fighting corruption).[13] Canada's Strategic Innovation Fund also includes social considerations in its funding decisions, including if a recipient commits to its 50-30 Challenge for board diversity, inclusive hiring practices, environmental practices, indigenous consultations and investment in local communities[14] (McIvor, forthcoming[33]).

Governments are also experimenting with flexible organisational structures to ensure funding agencies are better equipped to respond to emerging opportunities and challenges. For instance, some governments are using network delegation to crowd in private sector investment and take funding decisions. Under this model, governments competitively select associations, networks or consortia, who prove their connections to the STI systems to play a role in the funding process. Although the model is not entirely novel, to focus them more on transformative goals, governments are running competitions to select these types of organisations based on their co-developed visions or roadmaps for transformative change. Examples include the Netherlands' Top Consortia for Knowledge and Innovation, which provide an ongoing matchmaking role within their sectors to help develop consortia of partners to apply for funding opportunities that tackle aspects of the Dutch missions and help disseminate the results of these projects within their sectors. The government still takes the funding decisions under these arrangements. By contrast, Denmark's Innomissions programme uses a more decentralised model.[15] After issuing a call for proposals to develop roadmaps to address four mission areas, the government has delegated control to the winning consortia to issue calls for proposals, review the proposals and allocate funding, and itself performs just a state aid check of the approved projects[16] (McIvor, forthcoming[33]).

In other developments, some funding bodies are experimenting with randomisation and lotteries for taking funding decisions to test whether they can achieve more inclusive and ambitious outcomes compared to traditional allocation methods. There are variations to randomisation, including: partial randomisation, which initially vets proposals before selecting those that pass an initial set of criteria at random; weighted randomisation, which ranks proposals, with the better ranked ones awarded more "tickets" in the randomised selection; and tiering, which is similar to weighted randomisation but with less granularity in the ranking.[17] Some funding bodies are using these approaches to advance on the transformative goals. For instance, the British Academy used partial randomisation for its small research grants. It found that using partial randomisation could lead to a more ethnically and institutionally diverse cohort of award-holders.[18] The Austrian Science Fund also used partial randomisation through pilot grants, which provided seed funding for radical new and bold research ideas that have the potential to transform established scientific knowledge in all disciplines (McIvor, forthcoming[33]).

Organisational innovations to promote breakthrough R&D

Several governments are paying particular attention to the ideal organisational structures to accelerate breakthrough, or transformative, research and innovation. An increasing concern of the scientific community in recent years is that research funding processes have become too conservative and only encourage incremental advances in STI. Failure to encourage and support research on risky, "out of the box" ideas may jeopardise a country's longer term ability to compete economically and to harness science for solving national and global challenges (OECD, 2021[34]) (see Chapter 4). At the same time, there are worrisome claims that research productivity has been falling in recent decades. Multiple explanations have been offered for this phenomenon, including changes in scientific incentives that reward incremental science, the growing need for but outstanding challenges of supporting interdisciplinarity, and the declining share of public research, which tends to be more supportive of breakthrough R&D (Ciaffi, Deleidi and Di Bucchianico, 2024[35]; OECD, 2023[36]).

These concerns have led several countries to establish new public bodies to pursue focused breakthrough research and innovation, broadly inspired by, and in many cases modelled on, the United States Defense Advanced Research Projects Agency, with various degrees of adaptation. Examples include the Federal Agency for Disruptive Innovation (Germany); the Moonshot Research and Development Program (Japan); the Advanced Research and Invention Agency (United Kingdom); the High-risk, High-gain Research Programme (France); and the Advanced Research Projects Agency for Health (United States). Some of these initiatives are outlined in table 1.5 together with others that use established or open funding calls to identify high-potential projects that might be outside of current funding priorities or mandates.

Table 1.5. Selected examples of science, technology and innovation policy measures to promote funding agility and breakthroughs

Country	Policy initiative name	Description
European Union	Innovation Fund	Improves risk sharing by giving more funding in a more flexible way through a simpler selection process; open to projects from energy-intensive industries; funds dispersed in a flexible way depending on financing needs and based on predefined milestones; stacking allowed.
France	High risk high gain research programme	Detects fundamental or innovative research at a very early stage, which could generate strategic conceptual or technological breakthroughs, and offers a specific support.
Germany	Agency for Disruptive	The Agency for Disruptive Innovation (SPRIND) was established in 2019 to address a gap in flexible

	Innovation	and rapid state funding for the commercialisation of highly innovative ideas to address complex societal challenges, such as the net zero transition > stage-gated approach to funding.
Germany	Mobility Workspace 2025	Incorporates three phases of funding > individual municipal projects: phase concepts and strategies; planning, implementation and testing of mobility concepts; and transfer and adaptation of mobility concepts.
Mexico	National Strategic Program for Open Technology and Innovation	Uses an innovation funnel approach to proposal evaluation to ensure that a confidential, high-quality, relevant and agile process was used to select the most beneficial projects.
Norway	Green Platform Initiative	A platform for green renewal of the business sector through programmes and schemes that are already in place; it aims to stimulate bigger and more rapid investments from companies.
United States	ARPA-E FOAs	ARPA-E routinely uses open funding opportunity announcements (FOAs) to identify high-potential projects or high-potential, disruptive technologies and innovations that are outside of the agency's current priorities.

Source: EC-OECD *STIP Compass database, https://stip.oecd.org/stip* (accessed on 10 March 2025).

The purported need for these new research funding organisations has been justified on a number of grounds, including that larger projects are required than academic laboratories can undertake; more co-ordination is needed than occurs in academic departments or across generic research consortia; the desired innovations might be insufficiently profitable to arise through start-ups funded by venture capital or industrial R&D projects; and a mismatch exists between time frames typical of academia and traditional research funders and the immediacy of some challenges (OECD, 2024[31]). Programme managers in these initiatives typically have broad freedom to design technical initiatives and redirect resources between their portfolio of projects through a large integrated budget (OECD, 2021[34]).[19] Funding decisions can also be rapid, with organisations like Germany's Federal Agency for Disruptive Innovation being able to take some initial decisions within two weeks.[20]

Integrating funding across the innovation chain

Some countries are implementing policy initiatives that support research, development and/or demonstration activities across the entire innovation chain. Table 1.6 provides some examples. In several instances, countries have developed two-part funding programmes to support R&D and subsequent demonstration of targeted technologies, such as CCUS, e.g. Norway's CLIMIT Programme and Canada's Agricultural Clean Technology Programme.

Table 1.6. Examples of policy initiatives targeting the entire innovation chain

Country	Policy initiative name	Description
Austria	Innovation, Competitiveness and Internationalisation	The initiative encompasses a range of funding instruments from various funding sources, including the Ministry for Innovation, Mobility and Infrastructure and the Ministry for Economy, Energy and Tourism, to address various needs and innovation barriers. Funding is focused towards low-threshold support for new innovators, research and technology development within firms, support for green and transformative front runners, and the cultivation of skills required to facilitate competitiveness and transition. The Austrian Research Promotion Agency manages all funding instruments.
Canada	Agricultural Clean Technology Programme	The programme supports the transition to a low-carbon economy by fostering clean technology adoption and development in Canada's agriculture and agri-food sector through two streams: adoption and research and innovation. It supports pre-market innovation to develop transformative clean technologies in three priority areas: green energy and energy efficiency, precision agriculture, and the bioeconomy. Additionally, it supports the purchase and installation of commercially available clean technologies with environmental co-benefits.
Japan	Research, Development and Demonstration of CCUS Technology	Led by the NEDO Agency, this initiative is advancing research, development and demonstration of carbon capture, utilisation and storage (CCUS) technologies to achieve Japan's carbon neutrality goal by 2050. This includes developing monitoring technologies for safe CO_2 storage through large-scale testing and conducting surveys on related technologies, with the aim of accelerating the near-term commercialisation of CCUS by integrating CO_2 separation, capture, transportation, storage and utilisation processes.

Norway	CLIMIT Programme	This programme is focused on the research, development and demonstration of carbon capture and storage (CCS) technology. It aims to advance knowledge, competence and solutions that drive cost reductions and support the global deployment of CCS. The programme includes CCS R&D, led by the Research Council Norway, and technology demonstrations, managed by Gassnova. The initiative prioritises projects related to the European CCS value chain, large-scale CO_2 storage in the North Sea, and new CCS solutions, with strong international collaboration with the European Union and the United States.
Sweden	Industrial Life Programme	This long-term initiative provides grants for preliminary studies, research, pilot projects and investment measures aimed at reducing industrial greenhouse gas emissions and creating permanent negative emissions. It also supports strategically important efforts that contribute to the climate transition across society. The programme has supported industrial projects such as biofuels, plastic return refineries, hydrogen production, recycling facilities and battery production.

Source: EC-OECD *STIP Compass database, https://stip.oecd.org/stip* (accessed on 10 March 2025).

Individual funding authorities with more expansive mandates are also supporting solutions across the innovation system and along the innovation chain to promote transformative change. Because these organisations have such a breadth of tools at their disposal, they are uniquely situated to address more systemic challenges. In the United Kingdom, the UKRI Challenge Fund[21], for example, is addressing societal challenges through funding a range of activities, including collaborative cluster projects, R&D centres, research projects, demonstration projects, behavioural research, and other areas. While many of these agencies are funding transformative goals as part of their broader STI mandates, some funding authorities have more fundamentally incorporated these goals into how they are structured. For instance, the Netherlands Enterprise Agency has a range of instruments that support everything from proof of concept and investments in seed-stage companies to business growth and partnerships. It restructured itself around 3 thematic domains and 20 societal challenges. It then mapped out its programmes to identify how each one relates to its transformative goals to support the scale-up and phase-out of different technologies, as well as the gaps in its programme offerings. The Netherlands Enterprise Agency uses a "theory of change" to guide its investment decisions, and an annual Societal Challenge Cycle is used to update its overarching organisational strategy[22] (McIvor, forthcoming[33]).

Action 3: Strengthen co-ordination with non-science, technology and innovation policy areas on transformative change

Public funding to support scientific and technological breakthroughs as well as their diffusion must come from several parts of government, including sectoral ministries and agencies in areas like energy, transport, agriculture and health. Ministries and authorities with formal STI policy responsibilities need to help orchestrate this effort and steer public and private investments to where they are needed the most. However, multidimensional issues like inclusive economic renewal, security and resilience, and sustainability transitions cannot be achieved or even be chiefly driven by STI policies. Other policy areas with regulatory and fiscal powers have often taken the lead. Such transformations require a more systematic and agile approach to contend with issues that cut across policy boundaries and require co-ordination across subnational, national and international levels of governance.

The policy landscape in many countries is characterised by structural silos and disconnects between different policy domains, national and subnational counterparts, and different actors working at the interface between STI policy and the STI system (e.g. funding agencies). While this segmentation has enabled the management and even optimisation of different aspects of complex systems in isolation, it can be a barrier to the effective transformation of these systems to better address complex societal challenges.

Governments can deploy a range of cross-government and territorial co-ordination measures to alleviate fragmentation and better orchestrate their interventions, including shared national visions, roadmaps and missions; joint programming between research and innovation funding agencies; and strategic oversight by high-level cross-departmental committees. Some countries have also implemented structural and organisational changes, for example by merging funding agencies or ministries and territorial authorities for STI that cover different parts of the innovation chain (Halme et al., 2019[37]). Box 1.1 provides an overview of related policy measures found in the EC-OECD *STIP Compass database*.

Box 1.1. What cross-government coherence and co-ordination measures are governments taking?

An analysis of data from the *STIP Compass database* identified close to 400 unique cross-government coherence and co-ordination initiatives related to the transformative goals (EC-OECD, 2023[38]).* Many of the initiatives analysed target the optimisation of government operations by reducing bureaucracy, consolidating funding and activities, facilitating the co-development or co-funding of shared priorities and policy portfolios, harmonising a policymaking culture or processes in certain areas (e.g. procurement, experimentation, etc.), and making activities more responsive and flexible (e.g. programming concierge platforms, single-window funding applications, etc.).

Around 35% of the cross-government initiatives analysed include horizontal co-ordination bodies between national policy domains. Of these, the most engaged policy domains include economic affairs (37%), education (31%), environment (28%), culture (27%), energy, (27%), finance (25%) and agriculture (23%). While around a half of them issue specific recommendations to ministries to implement, a smaller proportion include the development of joint studies (18%) or the alignment of budget allocations (7%).

Around 40% of the cross-government initiatives analysed include national strategies. Many of these target objectives/challenges or themes that cut across several sectors or are universally relevant. Roughly 50% are related to climate change or environmental sustainability while over 25% target issues of socio-economic security (energy/food) and other societal challenges (health, aging population). A smaller proportion (15%) relate to inclusiveness (e.g. inequality, job insecurity). Energy is the most represented sector, included in roughly one-third of the strategies analysed. Several other sectors are also reasonably well-represented. Health and healthcare, automotive and road transport, agriculture, food, and marine and ocean are each captured in 15-20% of strategies while education, telecommunications and IT, public administration, pharmaceuticals, and electronics are each represented in 10-15%.

The presence or absence of particular follow-up mechanisms can signal the level of formalised co-ordination or concerted attention to the translation of strategies into policy action. Roughly half of the strategies analysed are introduced in parallel to periodic monitoring or evaluation mechanisms. At the same time, a smaller proportion are linked to targeted mechanisms or tools intended to support their implementation: 40% of strategies have an associated action plan, 25% have a dedicated co-ordinating or monitoring public body, 20% have dedicated budget allocations, and roughly 10% are linked to a new regulation or law. Additionally, some strategies are supplemented with complementary initiatives, such as the creation of new governance structures or bodies, policy intelligence or consultation bodies, and networks.

* Elements of the STIP Compass data taxonomy (e.g. policy themes related to green transitions, research security, and equity and inclusion) were used to identify policies aligned with the transformative goals.
Source: EC-OECD *STIP Compass database*, https://stip.oecd.org/stip (accessed on 10 March 2025).

Mission-oriented innovation policies

Among different types of STI policies with transformative ambitions, MOIPs form an internationally recognised policy approach, with distinct principles and features, and a growing body of practical and conceptual knowledge supporting their adoption (OECD, 2024[39]). They involve co-ordinated packages of policy and regulatory measures tailored to mobilising STI to address well-defined objectives related to a societal challenge, in a defined period.[23] MOIPs can span various stages of the innovation chain from research to demonstration and market deployment. They can also mix supply-push and demand-pull instruments and cut across various policy fields, sectors and disciplines. While they confront many of the traditional challenges of national innovation systems, MOIPs tend to provide longer term and more consistent funding compared to traditional research and innovation schemes, reflecting their alignment with the long-term character of broader, transformative goals (OECD, 2024[40]).

Given that missions are often nested across different levels of government, the locations from which they are co-ordinated and operated play a critical role in shaping their governance dynamics. Different centres of gravity provide different opportunities and challenges to mission governance. A recently published OECD study of about 100 missions aiming to reduce greenhouse gas emissions has found that, despite significant achievements and progress, they fall short of leveraging the complementarities of various policy and regulatory interventions to scale-up broad and ambitious solutions (OECD, 2024[40]). Most remain narrowly focused on technological innovation, led by STI authorities and reliant on innovation policy funding.

Budgets can set powerful conditions on funding that may force groups to co-operate across silos on the delivery of certain budget items. However, while many missions are supported by a rather integrated co-ordination structure, most of them are funded by different funding streams that correspond to the different instruments/activities they integrate into their portfolio, originating from different mission partners and beyond. A mission may have funding for core STI activities (development of the agenda, "orchestration" of the mission) then lack funding to support other activities from research and innovation to skills and infrastructure needed to make an impact. This fragmented funding structure has significant implications for the level of mission integration, since it hinders co-ordination and co-operation. Mission managers often find government budgets inflexible and cyclical, which makes it harder for missions to pivot. Box 1.2 outlines possible governance configurations to help make missions more transformative.

Box 1.2. Making missions more transformative

While the challenge to design and, even more, implement missions are numerous and are well-documented, the options to make them more transformative are less clear. Based on previous and ongoing OECD work, five main pathways can be envisaged:

1. **Gradual broadening and strengthening of missions** by incrementally enlisting new actors; building trust; learning and attracting higher commitments from public authorities outside the science, technology and innovation (STI) realm; and higher investments from private actors. Given the legitimacy of and resources available to STI authorities, which define in large part their convening power, these missions might not extend and deepen much further.
2. **Transfer of mission leadership from STI to sectoral authorities** who "own" the challenges. Their mandate aligns more closely to the mission objectives (e.g. net zero, circular economy) and they hold essential intervention tools, resources and legal powers to realise them. STI authorities would need to ensure innovation remains a priority in the strategic agendas of these sector-led missions.

3. **Ownership of missions by centre-of-government bodies** such as a prime minister's office or a powerful "transition" committee that can enforce a whole-of-government approach to realise the mission. In practice, this pathway has been challenged by a tendency for approaches to remain innovation-driven and a lack of buy-in from participating ministries. A carefully designed combination of carrots and sticks will be necessary to prevent departments from drawing on mission budgets without fully embracing objectives.
4. **Smaller scale regional or local missions may be better equipped to define collective agendas** and integrate different interventions while leveraging the benefits of place-based innovation and various forms of proximity (e.g. geographic, cultural). These "micro-missions" would still need to be articulated with bigger (national, global) transformative agendas to contribute meaningfully to grand challenges.
5. **Dedicated mission agencies could be developed to "co-ordinate mission operations** from the ground floor" and report to participating ministries. Once entrusted with one or several missions, these agencies should enjoy significant autonomy to protect activities from political short-term interference. They would also require a large portfolio of instruments or the possibility to co-operate with other agencies.

The one thing these pathways all have in common is adapting leadership structures and fostering co-ordination and collaboration beyond STI authorities to unlock missions' transformative potential. The choice between these pathways will depend on the trajectory of each mission, but also on underpinning national or regional institutional specificities.

Source: Adapted from OECD (2024[40]).

To help alleviate some of these challenges, separate funding authorities are issuing joint calls, which allows them to co-ordinate with a broader selection of funding instruments to support more activities across the innovation chain or the innovation system. In this model, the funding pots remain separated by authority. For instance, in Norway, the PILOT-E scheme[24] funds business innovation from concept to market through a collaborative approach between five funding agencies that take a co-ordinated funding decision based on the programmes they have available and the technology readiness level of the proposal. Similar flexibility is provided by Ireland's Impact 2030 Steering Group[25], which launches joint calls across the five largest STI funding departments. The funders then determine which instruments are best suited for supporting the different proposals[26] (McIvor, forthcoming[33]).

Some governments are using central pots of funding to support activities from across government in a manner that transcends traditional ministerial structures and authorities. France's Acceleration Strategies for Innovation[27] has a central budget managed directly by a dedicated agency under the Prime Minister's Office. They fund a broad portfolio of activities under various government agencies, without influence by their supervisory ministries, which cover a range of activities, including R&D, technology transfer, technology demonstration, infrastructure investment, and skills formation. Chile is taking a similar approach through its Sustainable Productive Development Program, which also combines investment and STI measures under the one programme. Ministers decide on a theme to focus on each year[28] (McIvor, forthcoming[33]).

The ability to end a programme's or project's funding is an important aspect of agility but is often hard to achieve in practice within standard governance structures. Many MOIPs have built in either formal review processes within the life cycle of the project or taken stage-gated approaches to funding, where over a specified interval they reduce the number of projects and increase the amount of funding, e.g. Korea's Alchemist programme, which funds six projects in the first year, three in the second and just one over five years (McIvor, forthcoming[33]).

Missions often grant key roles in the development of the strategic agenda and in implementation to incumbents within the sector(s) where the mission is located. These actors have resources and capabilities as well as infrastructure and networks that make their participation “unavoidable” in any change initiative. However, they also have vested interests in the currently established system that they may be tempted to preserve by advocating for incremental improvements rather than transformational change through alternative, more exploratory, solutions.[29] Balancing the participation of incumbents in governance is therefore a key challenge for many missions, especially for ecosystem-based missions that rely on a high level of delegation of several governance functions (not least the development of the strategic agenda and the mobilisation and co-ordination of stakeholders) to ecosystem actors. Policymakers should be wary of becoming limited in their reach to established players within existing policy ecosystems, who already identify and know how to navigate this ecosystem. This calls for an important role for the state as a “moderator” to ensure a balanced and inclusive approach in the development and implementation of the mission’s strategic agenda to avoid mission capture (OECD, 2024[41]).

Action 4: Mobilise public funding to crowd-in private finance for transformative change

In recent years, there has been a growing focus among policymakers and funders to promote innovative financing mechanisms that can crowd in new sources of private financing for climate, clean energy, biodiversity and other sustainability challenges. According to the 2024 Financing for Sustainable Development report (United Nations Department of Economic and Social Affairs, 2024[42]), financing the SDGs requires trillions of dollars per year. Access to finance remains a critical obstacle, however, as shortfalls in funding constrain many countries’ ability to put forward and deliver ambitious climate commitments. The private financing gap is most evident in the energy sector, where, according to the International Energy Agency, 85% of the required investments in non-fossil fuel-based energy will need to come from private sources (IEA, 2019[43]).

Several capital market failures discourage the allocation of private investment into technologies that promote transformative change.[30] For example, there are often long-standing alternatives to low-carbon technologies, while deep technology solutions are well-known for being more intensive with timelines for development that do not align with private sector investment requirements. For emerging markets and developing economies, financing the implementation of their current climate plans remains particularly challenging in a context of high public debts and insufficient international support for climate finance (OECD/UNDP, 2025[8]). Achieving the SDGs will require co-operation between developed and developing economies where most of the impacts of the global challenges like climate change and global health are occurring. At COP29, for example, developed countries agreed to a plan in which developed countries committed to providing USD 300 billion annually by 2035 to assist poorer countries in combating climate change. This amount falls short of the USD 1.3 trillion annually that many developing countries believe is necessary to address climate challenges adequately (Bhattacharya et al., 2024[44]; CORDAID, 2024[45]).

Channelling STI financing for the SDGs requires more and new partnerships with multilateral development banks, charities and private foundations, and official development assistance, but also with private investors, pension funds and financial actors operating at the local level. Yet to direct STI financing for the SDGs at scale, a transformation in private investment and financing is needed. Governments can play critically important roles in promoting private investment in sustainability transitions through a range of economic and regulatory instruments. These are underpinned by a range of public policy goals, e.g. climate policies, industrial policies, energy security policies, and improving economic resilience and reducing dependence on global value chains.[31] Many of these instruments target innovation and technology, even if they do not directly subsidise the costs of firm investments in R&D, by affecting the broader financial eco-system for innovation.

Towards blended finance?

Mobilising private capital rests primarily on managing risk. When public capital is used to mobilise private or commercial capital, it normally means to provide an investment situation in which risk and returns have found a balance that is acceptable to those investors. This will also depend on the project itself and to what extent the financial solution offered provides an acceptable risk-return profile in each case. Among the innovative approaches to crowd in private finance is "blended finance", which has mainly been used in development finance (OECD, 2018[46]). With its focus on deploying public financial resources with the view to leverage or attract private capital, blended finance has contributed large resources for investments in developing countries. It is an approach for combining financial instruments in ways that allow participants in the blending to respect their respective mandates and risk-return preferences within an agreed-upon contractual structure.

Approaches like blended finance, which initially emerged as an innovative tool in the development community to crowd in private financing for sustainability projects in developing countries (Samans, 2016[47]), are gaining traction in the STI policy field as a way to combine public and private finance across the innovation chain (Miedzinski et al., 2020[48]; OECD, 2022[49]).

Research on blended finance has shown that different settings or investment purposes typically lead to different combinations of instruments, such as grants, debt, guarantees, funds or facilities and others, to be structured according to the investment situation to achieve a best possible fit of partners and instruments (Kwon et al., 2021[50]). Table 1.7 outlines some of the main instruments and their definitions, which can be clustered into four groups:

1. *Grants and technical assistance* originate from either public funding or philanthropic capital without any expectation of positive returns. Actors leveraging on these instruments are typically the ones initiating the transactions, and grants blended in the mix will play the catalytic role.
2. *Outcome funding, impact bonds and impact-linked finance* stand out from the rest in that they connect impact with financial rewards.
3. *Various debt and equity instruments*, like market-rate, concessional or subordinated debt, normally take higher risk expecting higher returns than debt finance.[32] Hence, debt may be used in the later stages of a project's development.[33]
4. *First loss and guarantees* do not normally seek returns but are deployed to provide derisking and attract additional capital. They are typically used in later stages of a development when scaling is needed and when there is a track-record of performance at hand.

These clusters of instruments often co-exist in single overarching policy initiatives, some of which are briefly outlined in Table 1.8.

Table 1.7. Definitions of selected blended finance concepts and instruments

Instruments	Definitions
Guarantee	A risk mitigation instrument that promises to repay all or some of the invested amount to the investor in the case of default.
First-loss	A risk mitigation instrument in which a donor or other entity agrees to be the first to take losses.
Outcome funding	An umbrella term for transactions that pay upon accomplishment of results rather than efforts to accomplish those results. Instruments including impact-linked finance or impact bonds are subtypes.
Concessional finance	Repayable capital offered on terms substantially more generous than generally available commercial terms. The concessionality is achieved either though rates below those available on the market or grace periods.
Subordinated debt	Subordinated debt, also called mezzanine finance, has many of the characteristics of both debt and equity. A subordinated creditor agrees to rank after senior creditors but before ordinary shareholders in the event of liquidation.
Impact-linked finance	An approach to linking financial rewards for market-based organisations to the achievements of positive social outcomes, often used as a means of aligning positive impact with economic viability.
Impact bond	Impact bonds use investor capital to cover working capital required for a provider to set up and deliver a service.

Table 1.8. Selected policy initiatives supporting private finance for sustainability and growth

Country	Policy name	Description	Yearly budget range (EUR)
Australia	Clean Energy Innovation Fund	The fund supports the development of innovative clean energy technologies and businesses by providing debt and/or equity financing. It focuses on technologies and businesses that have moved beyond the research and development stage and need seed or growth capital to advance to the next level. It is jointly managed by the Australian Renewable Energy Agency and the Clean Energy Finance Corporation.	n/a
Austria	Seed Financing Programme Deep Tech and Innovative Solution	This programme provides funding for high- and mid-tech start-ups, addressing the long-standing lack of early-stage venture capital by, as of 2024, offering up to EUR 300 000 in pre-seed funding and up to EUR 1 million in seed financing, particularly in ICT, life sciences, nanotechnology and green tech.	20-50 million
Canada	Canada Growth Fund	The initiative is designed to attract private capital to build Canada's clean economy by mitigating investment risks in low-carbon projects, technologies, businesses and supply chains. The fund's assets are managed by the Public Sector Pension Investment Board. Its CAD 15 billion budget was announced in 2022, and its aims are to reduce emissions, accelerate the deployment of key technologies like low-carbon hydrogen and carbon capture, and scale-up companies that drive clean growth and job creation.	+500 million
European Union	Innovation Fund	The fund supports high-TRL low-carbon technologies through market pilots and demonstrators. It offers flexible funding and risk-sharing for projects and supports projects in energy-intensive industries, carbon capture and storage, renewable energy, and energy storage, aiming for significant emissions reductions across Europe. It focuses on fostering clean energy investments, creating local jobs and reinforcing Europe's technological leadership in the global market.	+500 million
France	Ecotech Fund	The fund focuses on minority equity and quasi-equity investments in innovative, unlisted small and medium-sized enterprises, primarily based in France. It supports businesses in sectors such as carbon-free renewable energy, green chemistry, the circular economy, smart grids and future vehicle technologies. Its goal is to accelerate the growth of sustainable innovations and strengthen France's position in the green economy. It is managed by Bpifrance Investissement, backed by EUR 150 million from the Future Investments Programmes and implemented by the French Agency for Econological Transition.	150 million
Lithuania	Co-Investment Funds	This initiative encompasses a set of co-funding programmes, including the Co-investment Fund for Transport and Communications, the Business Angels Co-Investment Fund, and the Co-Investment Fund RDI. Its aim is to strengthen the country's venture capital market by improving access to capital for high-growth companies, especially those with limited financing options. The focus is on mobility services and sustainable transport technologies.	1-5 million
Norway	Nysnø Climate Investments	This fund, fully owned by the government and managed by the Ministry of Trade, Industry and Fisheries, invests in companies that develop profitable and smart solutions to the challenges of climate change. The aim is to contribute to reducing greenhouse gas emissions through investments in unlisted firms that may bring new technology to the market.	50-100 million

Source: EC-OECD *STIP Compass database, https://stip.oecd.org/stip* (accessed on 10 March 2025).

At the same time, the ability of public finance to crowd-in private finance for sustainability transitions should not be overestimated. Many regulations and incentives that are hard-wired in global capital and financial markets continue to direct private finance towards profitable ventures that may not always promote sustainability. The financing of STI activities targeting the SDGs faces familiar obstacles, such as market failures in the private financing of RDI, as well as economic and technology risks.[34] A particular challenge to financing the SDGs is that several of them involve mobilising STI for the preservation and production of "common pool resources", such as biodiversity, global health and sustainable oceans. Private firms have fewer incentives to provide such public goods; they also have an incentive to maximise the use and exploitation of common goods.

New funding models for STI involving public and private actors offer a mechanism to increase STI funding to support the provision of global public goods. These funding models include blended finance involving multilateral international development banks, philanthropies and institutional investors such as pension funds. Sustainability bonds issued by governments and corporations can potentially scale-up private financing if issues of transparency, monitoring and accountability can be effectively addressed. STI-for-debt swaps, which function like climate-for-debt swaps, could also be used to encourage developing countries to invest in STI capacity building.

Action 5: Promote transformative change rather than "business-as-usual" outcomes

In promoting transformative change, STI policy measures should be directed at specific actions that help achieve transformations rather than "business-as-usual" outcomes. Many of the necessary reforms are familiar to the STI policy community, and promoting transformative change often coincides with achieving reforms to address long-standing challenges in STI systems.[35] Barriers remain, however, for example in bridging aspirational strategy with the development and implementation of concrete policy interventions and in scaling-up and institutionalising corresponding policy innovations.

Change versus stability

A starting question is the concrete differences between incremental (adaptation) and transformative change, as well as how or if these two processes are related. Transformative change refers to "a radical permanent qualitative change in the subject being transformed, so that the subject when transformed has very different properties and behaves or operates in a different way" (HM Treasury, 2022, p. 122[51]); and "a major change in the structure of the economy brought about by deliberate policy efforts aimed at supporting specific long-term environmental, social, economic or other goals, or in response to climate change and other relevant long-term trends" (New Zealand Ministry of Business, Innovation and Employment, 2023, p. 1[52]). By contrast, incremental change is predominantly focused on preserving integrity and stability. Small-scale, localised and short-term adjustments are made to cope with change or challenges. These changes enable an evolution that allows maintaining fundamental structures and functions of the system (Schumer et al., 2022[53]).[36]

Are the two processes related? It has been postulated that the aggregation of many incremental interventions can push a system towards a threshold or tipping point that, when breached, triggers a self-perpetuating process of deep and rapid change (Lenton et al., 2022[54]; Mey, Mangalagiu and Lilliestam, 2024[55]). This non-linear process can be attributed to various feedback dynamics common to innovation processes (Allen and Malekpour, 2023[56]; OECD, 2025[57]) (Box 1.3). The resulting transformation is generally faster, more intense or extensive than expected and can result in "tipping cascades" that impact other systems (Milkoreit, 2022[58]; Spaiser et al., 2024[59]). It proceeds through a combination of complex, dynamic and non-linear pathways, often following S-shaped curve dynamics where the pace of change ramps up and tapers off depending on the phase (Loorbach, Frantzeskaki and Avelino, 2017[60]; Meadowcroft, 2021[61]; Victor, Geels and Sharpe, 2019[62]). The result can be the reconfiguration of component parts of the system, including the pattern of interactions between them, and resulting outcomes (HM Treasury, 2022[51]).[37]

Box 1.3. Selected feedback dynamics common to innovation processes

- **Economies of scale:** Supply-side cost reductions occur as production increases and becomes more efficient and fixed costs are spread over larger volumes. This can yield a virtuous cycle where lower costs encourage adoption, leading to the scale-up of production and further cost reductions.
- **Learning-by-doing:** As experience accumulates, improvements in performance and cost occur, often in parallel to economies of scale. This can yield a virtuous cycle where greater adoption provides more opportunities for learning, improving quality and competitiveness, and spurring further adoption.
- **Network and co-ordination effects:** As adoption grows, utility may also increase for particular types of innovation. For example, this type of feedback dynamic is typically observed for platform technologies (e.g. blockchain, artificial intelligence), interoperable systems (e.g. electric vehicle charging networks, Internet of Things devices) and knowledge communities (e.g. open-source software). When a critical mass of adoption is reached, a bandwagon effect can occur and tip the market in favour of the emerging technology. Indirect network effects can also occur as complementary goods increase in quality or become more abundant (see system build-out).
- **Adaptive expectations:** Technological feedback is reinforced via political, institutional and cultural dynamics. Increased uptake reduces uncertainty and strengthens the confidence of users, investors and other actors. Legitimacy and credibility spur expectations, norms and new institutions like industry associations, standards bodies, educational curricula and user communities, which enable further adoption and investment and may motivate divestment from or discontinuation of the status quo (see destabilisation and phase-out).
- **System build-out:** Complementary innovations (e.g. products, infrastructures, business models, etc.) can help to address technical challenges and enhance the utility of the core technology. However, established technologies also often have deeply embedded complements that can become liabilities or stranded assets as transitions progress.
- **Destabilisation and phase-out:** Once a tipping point is reached, reinforcing feedback dynamics can accelerate the phase-out of established systems through declining sales and economies of scale, erosion of network advantages, increasing costs and reduced competitiveness. When incumbent firms anticipate declining profitability or stricter regulation, they may divest or innovate, which contributes to the cycle.

Along similar lines, the OECD Agenda for Transformative Science, Technology and Innovation Policy suggests that a progressive series of incremental changes in the STI policy mix could also potentially combine into a deeper intervention that disrupts the status quo and creates system-wide change.[38] In this way, promoting transformative change may coincide with achieving multiple reforms that address long-standing challenges distributed across STI systems. Its non-linearity makes transformative change messy and unsuited to “command-and-control” notions of policy intervention. Instead, STI policy should identify “leverage points” for interventions that acknowledge positive and negative feedback dynamics, the distribution of power within systems,[39] and the necessity to sequence change to unlock potential pathways. This calls for a reappraisal and recalibration of the frameworks, tools and mechanisms currently used to develop and deploy STI policy, to embrace more reflexive, systemic and responsive processes (OECD, 2024[1]). Table 1.9 outlines policy implications and case study examples related to feedback dynamics like these. Box 1.4 details two examples where governments have taken a more systemic approach targeting multiple, interdependent feedback cycles.

Table 1.9. How science, technology and innovation policies can harness the dynamics of innovation processes

Feedback dynamics	Science, technology and innovation policy can:	Case study examples
Economies of scale	• Support early deployment and scaling through pilot and demonstration programmes, test beds and living labs, and public procurement of prototypes. • Subsidise and distribute production and scale-up costs through capital grants, production subsidies and cost-sharing schemes for infrastructure and manufacturing facilities. • Facilitate the generation of lead markets using instruments like subsidies, feed-in-tariffs, tax credits and advance market commitments. • Co-ordinate domestic buyers through demand aggregation platforms. • Leverage regional or global markets through the development of international consortia and supportive trade policy.	USA: CHIPS and Science Act (2022): The act provides direct grants and investment tax credits for building and expanding semiconductor fabrication facilities to offset high capital costs and encourage co-investment from industry. It also supports research and development (R&D) for related technology like photonics and lithography and encourages vertical integration and the formation of semiconductor manufacturing clusters.
Learning-by-doing	• Facilitate standardisation and knowledge sharing through innovation consortia and test centres, open data platforms, learning-oriented regulation, and monitoring and evaluation programmes for early technology deployment. • Support university-industry linkages, industrial clusters and ecosystem development to enable knowledge spillover, co-ordinate the emergence of new supply chains and accelerate experiential learning. • Develop targeted technical training programmes and apprenticeships to address gaps in practical expertise. • Foster user and developer communities like living labs, testbeds, sandboxes and open-source platforms that promote technology uptake and mutual learning.	Germany: Mittelstand-Digital Innovation Hubs (2021-present): The Federal Ministry for Economic Affairs and Energy's Mittelstand-Digital funding priority supports small and medium-sized enterprises (SMEs) in digital transformation, offering guidance on digitisation, artificial intelligence and cybersecurity. Its nationwide network of Mittelstand-Digital Innovation Hubs, which succeed the previous Mittelstand 4.0 Centres of Excellence, provide demonstration environments in partnership with universities, research institutes, chambers and associations. Beyond national reach, the hubs collaborate with initiatives like the European Digital Innovation Hubs to strengthen SME adoption of new technologies.
Network effects	• Reduce market fragmentation and improve interoperability and integration across users and systems through the development and harmonisation of regulation, and support for standards. • Support the development of enabling infrastructure and supply chains to enable deployment and reduce distribution costs. • Where relevant, establish platforms-as-public-goods to lower barriers to entry, allow early adopters to derive value and attract new users.	Estonia: E-Estonia initiative (2008-present): All government agencies have been mandated to use a common digital platform that uses blockchain to secure sensitive data across government databases and ensure integrity and continuity even under cyberattack. Every new public or private service that is integrated into the infrastructure improves overall situational awareness and security of the network.
Adaptive expectations	• Set clear policy mandates and send strong long-term signals through national strategies and roadmaps, grand challenges and missions, consistent multi-year targets and incentives. • Establish publicly endorsed, strategic narratives through strategic foresight, horizon scanning and technology assessment exercises. • Reduce regulatory and financial risk by streamlining permitting processes, improving the agility and responsiveness of regulation and facilitating risk-sharing through loan guarantees, insurance pools and first-loss guarantees. • Develop and promote standards and certification systems by endorsing standards development organisations, adopting certification and benchmarking guidelines, and aligning national regulation with international practice. • Embed consideration of emerging technologies or systems into curricula reform, skills development and workforce planning.	Finland: Roadmap to a Circular Economy (2016-2025): Development of the strategic plan convened a range of "change-makers" from government, industry, academia and civil society to foster a shared vision of and commitment to the circular transition. The strategy was also accompanied by an unprecedented investment in education and skills at all levels, from preschool to university, and efforts to align vocational training and workforce programmes. This helped to effectively shape new norms related to minimising food waste and sorting trash properly. Regulatory changes and pilot projects were also used to reduce uncertainty about the feasibility of circular practices.
System build-out	• Support complementary R&D and innovation (e.g. hardware and software improvements, business model experimentation, process innovations, social and community-based innovation) to enhance the utility of the core technology. • Provide real-world environments (e.g. testbeds, sandboxes, living labs) to	Canada: Strategic Innovation Fund (Stream 3) (2021-present): The programme is intended to develop a domestic, vertically integrated clean technology and battery ecosystem. It co-funds projects that catalyse clusters of SMEs,

	pilot and test integrated systems and identify challenges and gaps. • Promote collaboration between firms, researchers and users working on interrelated components through innovation clusters and tech parks, etc. • Support the deployment of first-of-a-kind systems that require the integration of multiple emerging technologies and/or co-ordination across multiple systems. • Repurpose or deal with stranded assets from the declining system.	suppliers and service providers and supports the development of regional supply chains and infrastructure. A variety of complementary innovations are supported, including: process and business model innovations, smart manufacturing and automation systems, and battery recycling and critical mineral processing.
Phase-out	• Redirect research and innovation funding away from unsustainable, inequitable and non-resilient technologies, sectors and practices and provide support for transition planning, remediation and repurposing legacy assets. • Eliminate or sunset supports for legacy systems like subsidies and public procurement rules. • Strengthen operating standards (e.g. circularity requirements, emissions caps, security standards, net zero mandates). • Enhance performance and risk monitoring by legislating the disclosure of related risks, liabilities and stranded assets; publishing performance benchmarks; and supporting independent watchdogs. • Support impacted workers, communities, consumers and small businesses in adapting through upskilling and reskilling programmes, economic diversification strategies, transition plans, etc. • Encourage firm-level anticipatory adaptation through phase-out targets and innovation grants or conditional funding to prompt diversification or transformation.	Denmark Climate Agreement for Energy and Industry (2020-2050): The policy sets a firm end-date for oil and gas extraction paired with measures to boost emerging clean industries; supports a just transition for impacted workers and regions by, for example, retraining fossil industry workers for offshore wind construction; and commits funding to repurpose legacy oil and gas infrastructure for carbon capture and storage and other emerging sustainability opportunities.

Box 1.4. Stewarding transformative change using systemic science, technology and innovation policy packages

Sweden's School Food Mission

Sweden's School Food Mission is a Vinnova pilot project intended to transform Sweden's school food system and contribute to systemic change across the broader food system. The programme has made use of various transformative policymaking approaches. System maps have been co-created with stakeholders to identify leverage points to trigger system-wide effects. Design thinking and prototyping were used to develop pilot activities in partnership with students, municipalities and food producers, among others. The initiative's governance mechanisms also enable co-ordination across various policy sectors.

The programme targets feedback dynamics in various ways. The mission has a strong culture of prototyping and iteration where over 1 500 students and 140 partners have engaged to test and evaluate open-source solutions. The programme has evolved through multiple phases involving the adjustment of activities and targets (learning-by-doing). It also exhibits a strong degree of system co-ordination and stakeholder co-ownership where roadmaps and platforms have been designed to bring actors together across silos and foster legitimacy (network effects). Societal expectations have been shaped by the mission's shared vision and co-created plans and initiatives (adaptive expectations). Finally, the mission's focus extends beyond food to develop complementary systems needed to facilitate wider transformation. This includes infrastructure (e.g. redesigned food halls), data systems, procurement tools and curriculum reform (system build-out).

Germany's National Hydrogen Strategy

Germany's National Hydrogen Strategy[40], launched in June 2020 and updated in July 2023, focuses on advancing and scaling hydrogen technologies, expanding infrastructure, and fostering partnerships to secure clean hydrogen supply. The update introduces new measures to accelerate production, import and use; facilitate integrated solutions and broader sector deployment; and support the development and integration of hydrogen ecosystems at the national and international levels.

The strategy targets feedback dynamics in various ways. Large-scale production projects, including international lighthouse initiatives, help to spread fixed costs while demand-side mechanisms like conditional contracts and procurement auctions ensure uptake (economies of scale). Several regulatory sandboxes and living labs provide real-world testing grounds to identify technical, logistic, legal and business model challenges, facilitating learning and regulatory adaptation (learning-by-doing). Linking to the European Hydrogen Backbone in addition to building up 1 800 km of domestic infrastructure connects domestic and regional production hubs, storage centres, and import terminals. The Southern Hydrogen Corridor initiative between Germany, Austria and Italy also facilitates strategic infrastructure development along transport and industrial corridors (Landini, Amante and Wacket, 2024[63]) (network effects).

In addition, the Hydrogen Acceleration Law (May 2024) helps to boost investor confidence and streamline approvals (German National Hydrogen Council, 2024[64]) and was further endorsed by the federal cabinet with over EUR 3 billion in procurement financing (2027-2036) (HyResource, n.d.[65]) (adaptive expectation). In addition to advancing electrolyser technologies and hydrogen infrastructure, supports also target the development of hydrogen refuelling infrastructure for buses, trucks and trains and pilot projects for fuel cell technologies (system build-out). Finally, construction of the Hydrogen Core Network aims to incorporate repurposed natural gas pipeline, with 60% of the network already available from repurposed natural gas pipeline (phase-out).

Sources: EC-OECD (2025), STIP Compass: International Database on Science, Technology and Innovation Policy (STIP), edition October 7, 2025, https://stip.oecd.org/moip/case-studies/43?utm= ; German Federal Ministry for Economic Affairs and Energy (2025[66]).

Conclusions

This chapter proposed five policy “actions” that governments should consider when reforming their STI policy mix to better contribute to transformative change agendas, focusing, for the most part, on funding and financing arrangements for STI. In the first action – promoting a policy agenda that contributes to broad transformative change – the chapter highlighted several STI policy options that can leverage synergies between different priorities. In this way, support to national competitiveness can also contribute to resilience and security, as well as sustainability transitions, if designed appropriately.

The chapter’s second policy action – balancing direct and indirect R&D funding for transformative change – introduced a simple schema that governments can use to map their policy interventions along two axes: 1) the innovation chain, i.e. from (breakthrough) R&D to demonstration, deployment and diffusion; and 2) the extent to which they are directed “top-down” by government and STI funding bodies. All instruments can play important roles in promoting transformative change, and a key challenge for policymakers is to strike an appropriate balance between them. There are no one-size-fits-all portfolios and an appropriate balance will depend on a country’s assets and priorities.

The chapter’s third policy action – strengthening co-ordination between STI and non-STI policy areas – aims to bridge policy silos to advance transformative change. Among popular approaches are MOIPs, which nevertheless remain constrained by a narrow focus on technological innovation and reliance on STI leadership and funding. The chapter highlighted how governments have begun to experiment with various governance solutions to overcome these limitations, including the ownership of missions by centre-of-government bodies and dedicated mission agencies.

Looking beyond co-operation across the public sector, in its fourth policy action, the chapter outlined how governments can mobilise public funding to crowd-in private finance for transformative change. Among these approaches is so-called "blended finance", which combines a range of financial measures – including grants and various debt and equity instruments – that can accommodate the risk-return preferences of different actors within an agreed contractual framework. These approaches have their limits, however, especially when the goal is to use STI to preserve or produce common pool goods. Governments should continue to experiment with instruments like sustainability bonds and STI-for-debt swaps, which have the potential to direct STI finance and help scale-up private investments in RDI to promote transformative change.

Finally, in its fifth policy action, the chapter called for greater appreciation of the nature of transformative change and how it differs from and relates to incremental change. This is an important consideration with a view to achieving more than "business-as-usual" outcomes. Transformative change is non-linear and marked by various feedback dynamics that can ramp up the pace of change and reconfigure whole systems. The chapter argued that STI policymakers should identify "leverage points" for interventions that can trigger and accelerate the sorts of system-wide changes needed for transformations.

These five policy actions clearly overlap and should be viewed systemically when formulating and implementing STI policies. The fifth policy action – appreciating the non-linear dynamics of transformative change – underpins the other policy actions proposed in the chapter and should be an essential consideration when balancing the STI policy mix. Co-ordination across government on priority agendas is also essential insofar as support to research and innovation and their diffusion is widely distributed across various ministries and agencies. Co-ordination must also extend to the private sector, given its dominant role in RDI and their commercialisation. Finally, as societies and economies face multiple challenges – and opportunities – governments must balance their STI policy support to a range of priorities, including economic competitiveness, resilience and security, and sustainability transitions. This is far from easy, but the chapter has highlighted several policy options for intentionally leveraging synergies and mitigating trade-offs between them.

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Notes

[1] The OECD Agenda for Transformative Science, Technology and Innovation Policies is a product of a meeting of the Committee for Scientific and Technological Policy at Ministerial level held in April 2024 with the theme of “Enabling sustainability transitions through science, technology and innovation: Shared challenges and transformative actions”. Ministers affirmed the need for an ambitious agenda for transformative STI policies and values-based technology governance frameworks, and provided strategic directions for the future work of the Committee for Scientific and Technological Policy. The main outcome of the meeting was the adoption of the Declaration on Transformative Science, Technology and Innovation Policies for a Sustainable and Inclusive Future (hereafter the “Declaration”). Structured around four pillars, the Declaration makes a case for transformative STI policies to accelerate sustainability transitions while embedding shared values in the governance of science and emerging technologies, reaffirming the need for international co-operation in STI to address global challenges, and focusing on making STI more inclusive and strengthening the evidence base. The Declaration is made operational by two underpinning documents welcomed by Adherents to the Declaration: the OECD Agenda for Transformative Science, Technology and Innovation Policies (OECD, 2024[1]); and the OECD Framework for the Anticipatory Governance of Emerging Technologies (OECD, 2024[71]).

[2] The United States remains the largest absolute spender on R&D in the world, spending USD 956 billion in 2023 (measured in current PPP USD, the standard method for international macroeconomic comparisons). The pace of growth in R&D spending picked up in the United States around a decade ago, leading to a widening gap with the EU27 and other leading industrial economies, such as Japan. Using the same measure, the second-largest spender is China (USD 917 billion in 2023), whose R&D expenditures surpassed those of the EU27 a decade ago and are now 62% greater. On this measure, the gap in the level of R&D expenditure between China and the United States narrowed significantly in 2023, with China’s R&D expenditure 96% of the United States’, up from 72% ten years before. However, when measured in USD at market exchange rates (an alternative measure to constant PPP USD), the gap remains much wider, with China’s R&D expenditures 49% of those of the United States in 2023, up from 42% in 2013 (OECD, 2025[3]).

[3] The OECD *Fundstat database* (version: March 2024) comprises data on government R&D project funding in 19 OECD Member countries (Australia, Austria, Belgium, Canada, Czechia, Estonia, Finland, France, Germany, Japan, Ireland, Latvia, Lithuania, Norway, Portugal, Sweden, Switzerland, the United Kingdom and the United States) and the European Union from 2010 onwards. Administrative data on government R&D project funding offer potential for international comparative analysis (OECD, 2015[73]). While such data provide a foundation for accountability, stemming from the government funding processes that generate them, these records are often inconsistent across countries, complicating cross-national analysis. Despite limitations, project-level data can provide insights into the directionality of government R&D funds, with varying levels of quality and completeness. The *Fundstat database* is an evolving database overseen by the OECD Expert Group on the Management and Analysis of R&D and Innovation Administrative Data and has been used for the analysis of directionality for artificial intelligence R&D (Yamashita et al., 2021[86]) and COVID-19 R&D (Aristodemou et al., 2023[85]).

[4] For example, efforts to improve the sustainability of regional or national electricity grids have been supplemented in some countries by growing engagement of public consumers in the energy system as prosumers (i.e. consumers and producers) and the evolution of community-scale integrated heat and power networks (IEA, 2022[74]).

[5] The EC-OECD *STIP Compass database* incorporates a thematic portal on indigenous knowledge and communities which includes information on scores of initiatives from a wide range of countries. See: https://stip.oecd.org/stip/indigenous-portal.

[6] Job losses spurred by sustainability transitions have been found to be up to 24% more costly in high-emission sectors compared to low-emission ones due to tendencies for impacted jobs to be concentrated among older workers in relatively high-paying jobs compared to educational attainment (OECD, 2025[72]). The creation of new jobs has largely benefited high-skilled workers.

[7] OECD research estimates that boosting the performance of the average OECD country to the level of the top three country performers in the area of adult skill outcomes would generate a productivity increase of 17%. This could be achieved through policy to support skills accumulation, lifelong learning and movement of labour, among other types of initiatives (OECD, 2025[2]).

[8] For example, the IEA estimates that more than a third of the emissions reductions required in 2050 to achieve net zero scenarios will come from technologies that are still in the lab (IEA, 2023[75]). In other words, unless certain pre-commercial technologies are rapidly proven and scaled up, net zero is likely out of reach. The fact that the other emissions reductions in the scenario (i.e., unrelated to those pre-commercial technologies) are very hard to achieve without substantial cost reductions and performance improvements is not deducible from this number but is a key part of achieving overall net zero. Achieving net zero, therefore, requires a mix of new R&D and demonstration activities together with the deployment and diffusion of existing technologies. Moreover, the resulting sustainability and digital transitions go beyond the adoption of new technologies and include investment in new infrastructures, the establishment of new markets, the development of new social preferences, and support for people of working age and communities in attaining new skills and opportunities as part of “just green transitions” (Causa et al., 2024[76]). Non-technological innovations, including social and process innovations, among others, will also make important contributions.

[9] Decades of investment into fundamental research on mRNA largely facilitated the expedited development and deployment of mRNA-based vaccines during the COVID-19 pandemic response (OECD, 2023[77]). Further, mRNA vaccine platforms build on established vaccine technologies and have the potential to accelerate development and manufacturing processes without compromising on safety (Litvinova et al., 2023[78]).

[10] Given the business sector’s importance for innovation, not only do governments contribute to the costs of business RDI, but also must ensure to create innovation-friendly framework conditions that incentivise companies to spend more on R&D.

[11] Only a few countries have also used tax measures to provide directionality for R&D in specific priority areas, such as green or energy-related R&D. This includes Italy, which has a higher tax credit rate for certain types of technological innovation support for the environment, and Korea, which has an enhanced tax credit rate for R&D aimed at so-called “new growth and basic technologies” (273 technologies in 14 areas, including future cars, next-generation electronic information devices, energy and environment) and “National Strategy technologies” (OECD, 2025[84]).

[12] See: https://stip.oecd.org/moip.

[13] See: https://fdoc.ffg.at/s/vdb/public/node/content/-5t5IDKMRcieVsqbCMVbCQ/6.0?a=true.

[14] See https://ised-isde.canada.ca/site/strategic-innovation-fund/en/about-program/program-guide.

[15] See https://stip.oecd.org/moip.

[16] See https://stip.oecd.org/moip.

[17] See https://academic.oup.com/rev/article/32/1/86/6780169?rss=1.

[18] See https://www.thebritishacademy.ac.uk/news/promising-results-from-first-year-of-innovative-grant-awarding-trial.

[19] For example, in the Japanese cross-ministerial Strategic Innovation Programme, the powerful programme directors in each programme act as chairs of their respective promotion committees and are deemed essential for the promotion and smooth operation of inter-ministerial co-ordination and science-industry co-operation. In Norway's Pilot-E, the programme manager oversees the secretariat of the steering group that gathers the three partner agencies. Another aspect of variation in these types of programmes concerns the types of individuals who manage the research portfolio. For example, Canada's National Research Council's Challenge Programmes generally use their own technical experts to manage portfolios. While they have had success in steering the research towards new ambitious areas (which is where their expertise lies), commercialisation has been more of a challenge – something they are looking at incorporating earlier on in their process. In contrast, the UK Research and Innovation Challenge Fund generally employs former industry leaders who found it more difficult to steer the research, but then have played a greater role in identifying market opportunities for teams to pursue at the commercialisation stage (OECD, 2024[41]).

[20] See www.sprind.org/en/impulses/challenges/articles/overview.

[21] See www.ukri.org/what-we-do/ukri-challenge-fund.

[22] See https://docs.google.com/document/d/19VSOwbxvtVuc67gkb_ZWWZVwaOkT3FgZp5pkPQDucLY/edit?tab=t.0.

[23] For instance, many MOIPs related to achieving net zero carbon emissions are targeted directly at the 2030 and 2050 aims of the Paris Agreement for Climate Change.

[24] See www.enova.no/pilot-e/information-in-english.

[25] See www.gov.ie/en/publication/27c78-impact-2030-irelands-new-research-and-innovation-strategy.

[26] See www.creatingourfuture.ie/2022/07/minister-harris-publishes-more-than-18000-ideas-generated-from-national-brainstorm-creating-our-future.

[27] See www.info.gouv.fr/organisation/secretariat-general-pour-l-investissement-sgpi/strategies-d-acceleration-pour-l-innovation

[28] See www.economia.gob.cl/2023/11/22/gobierno-destinara-6-mil-millones-de-pesos-para-investigacion-de-litio-y-salares.htm.

[29] The example of Sweden's Strategic Innovation Programmes (SIPs) has shown that this can result in a strong role played by powerful players in mature industries to the detriment of the transformative potential

of the missions. Each SIP is steered by an industry-dominated board, drawn from the industry, academia and the public sector, with industry generally being dominant. The final evaluation concluded that the SIPs mostly resulted in incremental innovation at the individual project level (Åström, 2021[79]).

[30] For example, in the green transition, challenges for private investors include insufficient profitability compared to investments with similar risk profiles; difficulty assessing risks owing to information asymmetries between innovators and investors; lack of awareness and uncertainty around government priorities and regulations; and challenges in meeting “internal rate of return” requirements or “return on equity” thresholds. These imperfections in capital markets limit the amount of private capital available for low-carbon technologies (Montague, Raiser and Lee, 2024[80]).

[31] Supply chain finance has emerged as a new tool to increase available internal capital in small firms, thereby encouraging investment in R&D and innovation activities. By combining the supply chain to build long-term stable trade relations, supply chain finance can also provide stable capital flow and lower financing costs for small and medium-sized enterprises. The supply chain-based financial model can provide short-term financial support for enterprises and meet their long-term funding needs.

[32] Governments have long supported the development of venture capital and private equity investments, but this support is increasingly targeted towards green transitions using a variety of models that vary in terms of the level of public ownership and direction over investment decisions (Berger, Criscuolo and Dechezleprêtre, 2025[81]).

[33] Analyses of the financing initiative reported in the *STIP Compass database* in 2023 show that some 17% of equity financing initiatives target the sustainability transition’s transformative goal. Most of these programmes support innovative start-ups and SMEs through the provision of seed and/or growth and late-stage venture capital. Transformative equity-based financing is often administered through direct public equity funds or co-investment funds. There are comparatively few fund-of-fund initiatives. Most equity financing is also focused on net zero priorities. Some programmes are broader than this and aim to support various technology areas, such as cleantech, med-tech, precision agriculture and the circular economy. Roughly 25% of the credit/loan and debt/risk-sharing initiatives captured in the *STIP Compass database* relate to sustainability transitions. Relevant credit programmes most commonly target the development of new products and processes or the upgrade of existing ones. In general, these initiatives support innovation by offering loans with subsidised rates. There is comparatively less focus on providing working capital or financing an expansion to acquire existing technologies.

[34] The obstacles and challenges to STI finance are not uniform across the different SDGs due to differences in financial and market structures, differences in the capital intensity of research and industrial activities, and structural differences in the share of public and private R&D funding. For example, obstacles to finance STI for clean energy will differ from those faced in the financing of research for global health challenges. Obstacles to finance STI for clean energy would involve a greater share of business financing from firms’ internal sources as well as from equity and capital markets, whereas obstacles to finance STI for research for global health challenges will rely more on public research funding by governments.

[35] For example, progress on a range of issues – such as strengthening various linkages in STI systems (e.g. between business and academia, between different parts of government, and between science and society), enhancing firms’ skills and organisational capabilities, and reducing precarity in research careers – will contribute to STI system reforms that hasten progress on the transformative goals. Likewise, directing STI systems towards goals like resilience and inequality can facilitate progress on these long-standing issues if transformation-friendly values are embedded in STI policymaking. Thus, the pursuit

of the transformative goals provides an opportunity to promote structural reforms that address long-standing issues in STI systems and vice versa (OECD, 2024[82]).

[36] Persistence or absorption are alternative strategies focused on maintaining the system's structure and function by mitigating risk and resisting change (Béné et al., 2012[68]).

[37] The ability of a handful of lead countries to accelerate the global adoption of electric vehicles is often held up as an example of policy effectively leveraging this kind of change process. In this instance, economies of scale allowed for the generation of a self-perpetuating, non-linear cycle of technological advancement, cost reduction and learning effects (Eker et al., 2024[67]).

[38] Public policy has its own positive and negative feedback dynamics that are also relevant for STI policymakers. According to (Edmondson, Kern and Rogge, 2019[83]), these include resource, interpretative and institutional effects, as well as socio-political, administrative and fiscal feedback.

[39] Transformative change is likely to face resistance from influential coalitions interested in maintaining the status quo, as well as disadvantaged groups concerned about the negative impacts of radical change (Blühdorn, 2019[69]; Novy, Barlow and Frankhauser, 2022[70]). Dominant stakeholders generally have vested interests in maintaining established industries, technologies and practices and are often able to influence structural conditions, e.g. regulation, or mask the full costs of the status quo. Accordingly, transformation is generally spurred by exogenous pressure, which can arise from a slow-moving trend like demographic change or a sudden shock.

[40] See www.bundeswirtschaftsministerium.de/Redaktion/EN/Dossier/hydrogen.html.

2 Reconfiguring scientific co-operation in a changing geopolitical environment

Growing geopolitical tensions and intense competition on emerging critical technologies are reshaping international co-operation in STI. Recent national STI policies and strategies reflect this shift with their increasing attention to security-related concerns. Focusing on public research systems, this chapter describes how governments are aiming to enhance national research and technological capabilities as they seek greater strategic autonomy that promotes both their economic and national security. This includes a growing policy emphasis on dual-use STI, as well as research security measures to protect against unauthorised knowledge leakage and foreign coercion. Governments have also become more strategic in their international STI linkages, including in their science diplomacy measures, with a view to projecting their national interests. The chapter highlights various risks and opportunities these policies pose and proposes that governments pursue balanced STI securitisation policies that are proportional, precise in their targeting, and based on committed partnerships with scientists and businesses, as well as across government.

Key messages

- Rising geopolitical tensions, accompanied by growing strategic competition on emerging critical technologies, are contributing to the **growing securitisation** of science, technology and innovation (STI). This includes the public research system, which is the chief focus of this chapter.
- Governments are pursuing a mix of policies that contribute to this growing securitisation. First, they are increasingly implementing **promotion policies** that orient research and development (R&D) funding towards enhancing national and economic security, covering, among other things, **dual-use initiatives** to foster mutually beneficial links between civil and defence research.
- Second, governments are using **protection policies** that introduce restrictions on sharing research findings with dual-use potential, as well as recent measures to strengthen **research security** more broadly to avoid exposing sensitive research to risks that ultimately erode safety and trust.
- Finally, they are implementing **projection policies** that provide strategic direction to international STI relations, including **science diplomacy** initiatives that support research co-operation with like-minded countries and strategic competitors.
- These policies imply some **reconfiguration of international research relations**. For example, policies that aim to promote economic and national security could involve pooling research resources with like-minded countries, while research security measures could exclude or discourage collaboration with countries that are not considered safe partners for international co-operation.
- Securitisation policies that restrict international research co-operation and mobility could have negative effects on research quality, innovation performance and economic competitiveness if **applied overzealously**. There are also risks that securitisation policies could fragment international STI linkages to such an extent that **it undermines co-operation on tackling global challenges**.
- STI securitisation measures involve different parts of government but are closely related and should be strategically oriented and co-ordinated. To improve their co-ordination and prevent over-securitisation, policymakers should adopt **governing principles** to design and implement **balanced STI securitisation policy mixes** that are **proportional** to the risks and opportunities at hand; formulated and implemented in **partnership** with scientists, businesses and across government; and **precise** and agile in their targeting.

Introduction

Scientific discovery and technological innovation occur in an interconnected global ecosystem that draws upon collective knowledge, talent, resources and infrastructure. Countries individually benefit from this international connectedness, which contributes to their competitiveness and societal well-being. Such connectedness is also critical for tackling challenges and managing risks at the global level, such as pandemic preparedness, environmental stewardship and food security, which require multilateral co-operation in STI.

Rising geopolitical tensions, accompanied by growing strategic competition on emerging critical technologies, are reshaping frameworks for international STI co-operation that have emerged over the last three decades. These tensions and competition undercut opportunities for cross-border knowledge exchange, collaborative STI projects and technology transfer, while national interests are routinely framed as trade-offs with global priorities. These developments impact everything from international research collaboration to international trade and investments in high-technology products and facilities.

The 2023 edition of the *OECD Science, Technology and Innovation Outlook* introduced the concept of "STI securitisation"[1] to discuss these trends (OECD, 2023[1]). This chapter continues along similar lines, focusing chiefly on the research aspects of STI systems and the impacts of growing securitisation on international research linkages. It consists of three main parts. The first part presents selected statistics on international scientific linkages, as measured by international research collaboration, researcher mobility and the scientific contributions of different countries to tackle global challenges, to highlight how these have evolved in recent years.

The second part of the chapter outlines the growing securitisation of STI policy, with a particular focus on newly intensive policy efforts towards achieving mastery and greater strategic autonomy in emerging science and technology in support of economic and national security objectives; the growing use of research security measures to protect against unauthorised knowledge leakage; and the increasing prominence of national interests in international science diplomacy.

These three sets of STI securitisation measures are closely related and imply an emerging reconfiguration of international research linkages. Accordingly, the third part of the chapter proposes a set of governing principles policymakers could adopt to design and implement balanced STI securitisation policy mixes that are proportional to the risks and opportunities at hand; formulated and implemented in partnership with scientists, businesses and across government; and precise and agile in their targeting.

Recent trends in international STI co-operation[2]

International STI linkages have grown strongly since the 1990s to the benefit of research, innovation and economic development. Among these linkages is international research co-operation, which benefits the quality of research which, in turn, contributes to economic competitiveness through new knowledge generation and enhanced skills development. International research co-operation also broadens the dissemination of research results, helps tackle global challenges and can contribute to intercultural understanding.

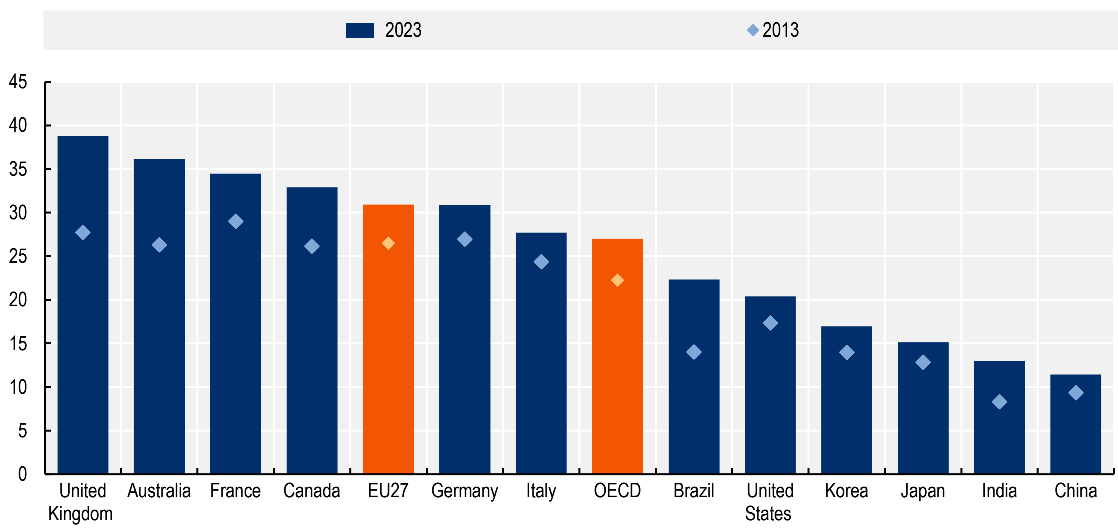
In times of heightened geopolitical tensions, it is important to understand these implications for international research linkages. This section presents selected statistics on international research collaboration, researcher mobility and different countries' scientific contributions to tackle global challenges to highlight how international research linkages have evolved in recent years.

Growth in international research collaboration has recently stalled

Collaborative research is at the core of an interconnected global research community. Data on co-authorship of scientific publications involving authors with institutional affiliations in different countries provide an indication of international scientific collaboration.[3] While only 2% of scientific papers had authors from more than one country in 1970 (Olechnicka, Ploszaj and Celinska-Janowicz, 2019[2]), the proportion was 27% of all publications in OECD countries in 2023, up from 22% in 2013 (Figure 2.1). The United Kingdom has the highest collaboration intensity within the top 15 science publishing economies, followed by Australia and France. The leading Asian economies exhibit lower than average international collaboration. Australia, Brazil, India and the United Kingdom experienced the largest proportional increase in collaboration intensity over the period 2013-2023.

Figure 2.1. International scientific collaboration intensity, selected countries, 2013 and 2023

As a percentage of domestically authored publications, based on fractional counts



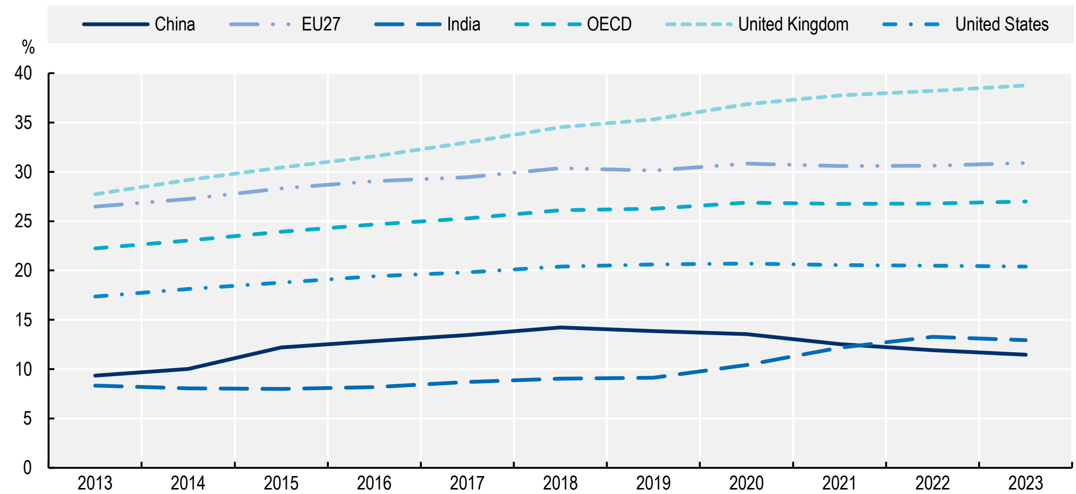
Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 1.2025, April 2025.

StatLink https://stat.link/p79m86

More recent data, however, suggest that the trend towards increasing international collaboration has lost momentum and might be partly breaking down (Figure 2.2). The external collaboration rate for the United States and the EU27 area has remained virtually unchanged since 2018, while the People's Republic of China's (hereafter "China") international collaboration intensity declined significantly between 2020 and 2023, with India surpassing it in 2021. The growing scale and advancement of China's research system mean there are more opportunities than ever to collaborate domestically with leading research groups, which could reduce incentives for international collaboration.[4] However, as Figure 2.3 shows, this decline is largely driven by a sharp fall in collaboration with the United States. It applies across most research fields and is particularly pronounced in the natural sciences and engineering, as shown in Figure 2.4. Similar data covering China's collaboration with other countries show some decline in a few fields with Japan and the United Kingdom, but continuing strengthened ties with the EU27. Despite these declines, the intensity of China's research collaboration with the United States remained considerably higher in 2023 than with these other countries.

Figure 2.2. Trends in international scientific collaboration, selected countries, 2013-2023

Percentage of scientific publications involving international collaboration, based on fractional counts

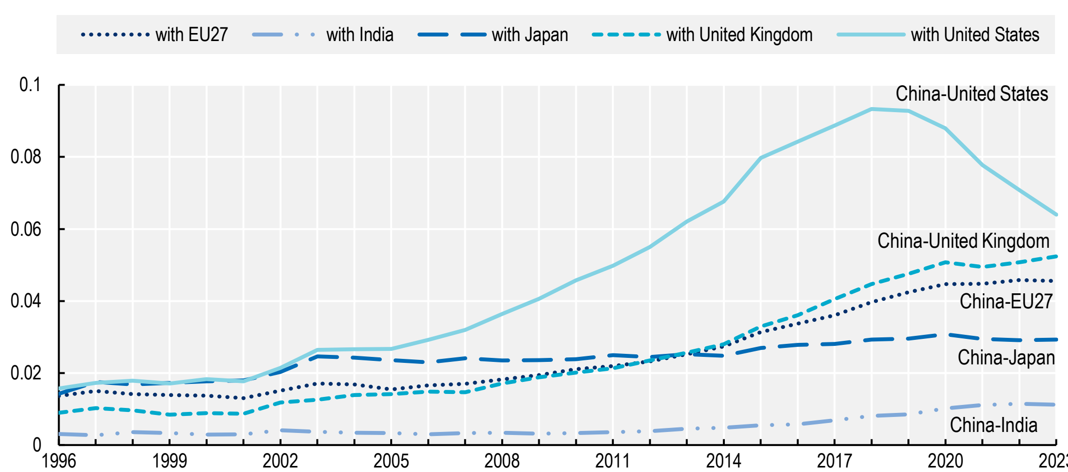


Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 1.2025, April 2025.

StatLink https://stat.link/s6u8d3

Figure 2.3. China's bilateral collaboration intensity trends in scientific publications, 1996-2023

Normalised collaboration based on whole counts

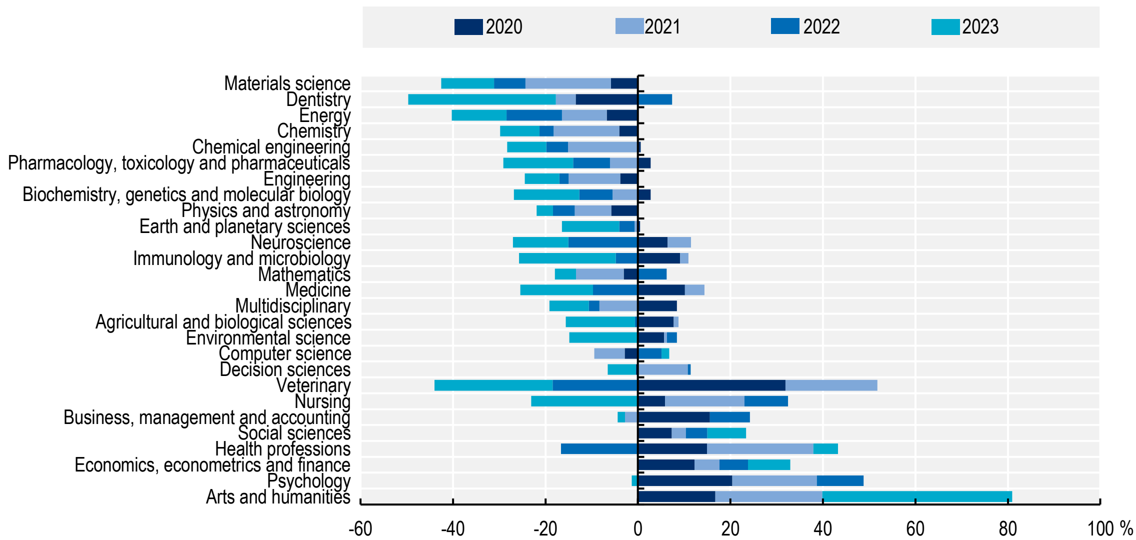


Notes: The bilateral collaboration intensity between two countries is calculated by dividing the number of scientific publications by authors with affiliations in both countries (whole counts) by the square root of the product of the publications for each of the two countries (whole counts). This indicator is, therefore, normalised for publication output. Publications refer to all citable publications, namely, articles, reviews and conference proceedings.
Source: Calculations based on Scopus Custom Data, Elsevier, Version 1.2025, April 2025.

StatLink https://stat.link/ma4gbo

Figure 2.4. Changes in collaboration between China and the United States, 2019-2023

Percentage change in year relative to 2019 baseline



Notes: Collaboration between China and the United States is defined by the number of co-authored publications between both countries (whole counts). Publications refer to all citable publications, that is articles, reviews and conference proceedings. The graph shows the changes in collaborations for each year versus the previous year, as a percentage of 2019 collaborations.
Source: Calculations based on Scopus Custom Data, Elsevier, Version 1.2025, April 2025.

StatLink https://stat.link/0bekdo

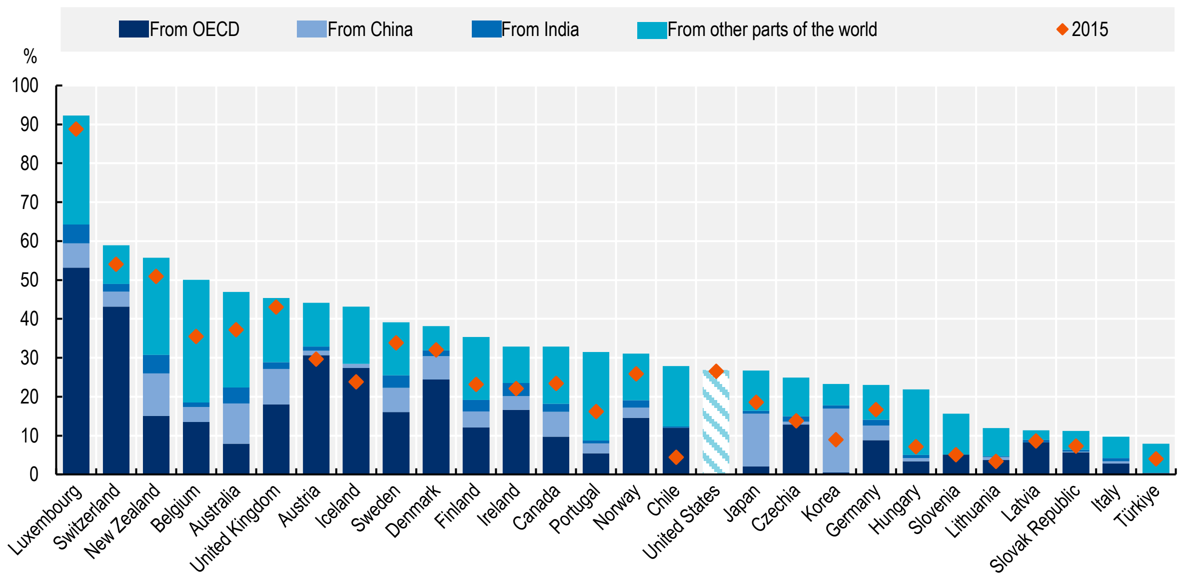
OECD science systems depend on a ready supply of internationally mobile researchers

International scientific mobility has also grown in recent decades and the research workforce of several major research performers in OECD countries is heavily dependent on foreign-born doctoral and postdoctoral researchers. In the United States, for example, some 45% of workers in science and engineering occupations at the doctorate level in 2021 were foreign-born, with the highest shares among computer and mathematical scientists. More than half of foreign-born workers in the United States in 2021 whose highest degree is in a science and engineering field were from Asia. The leading birthplaces were India (29%) and China (13%) (US National Science Foundation, 2024[3]).

Early-career researchers conduct much of the research carried out in OECD Member countries' laboratories. Although internationally comparative statistics are difficult to come by,[5] many of these researchers are internationally mobile. They go abroad to enhance their qualifications, access world-class research facilities and improve their career prospects.[6] The OECD's education statistics show that Australia, Austria, Belgium, Luxembourg, New Zealand, Switzerland and the United Kingdom have particularly high shares of international doctoral student graduates – at least 40% of their total number – as their universities attract global talent through scholarships, research opportunities and strong academic networks (Figure 2.5). Moreover, these proportions grew markedly between 2015 and 2022, with the exception of Luxembourg, the United Kingdom and the United States, where they have remained the same. In some countries, the high proportion of international doctoral students also reflects declining interest in pursuing a PhD among domestic students (OECD, 2025[4]). In France, for instance, factors such as long periods of study, uncertain career prospects and more attractive opportunities in the private sector are reported to have made doctoral studies less appealing for national candidates.[7]

Figure 2.5. Share of mobile PhD graduates, selected countries, 2015 and 2022

As a percentage of total PhD graduates



Note: Mobile doctoral students correspond to students in PhD programmes (ISCED level 8) enrolled in a country different from the one where they obtained their previous qualification, including homecoming nationals. Internationally harmonised data for the United States are unavailable.
Source: OECD *Education Statistics Database* Education access, participation, and progression | OECD (accessed on 18 July 2025).

StatLink https://stat.link/vx9p7z

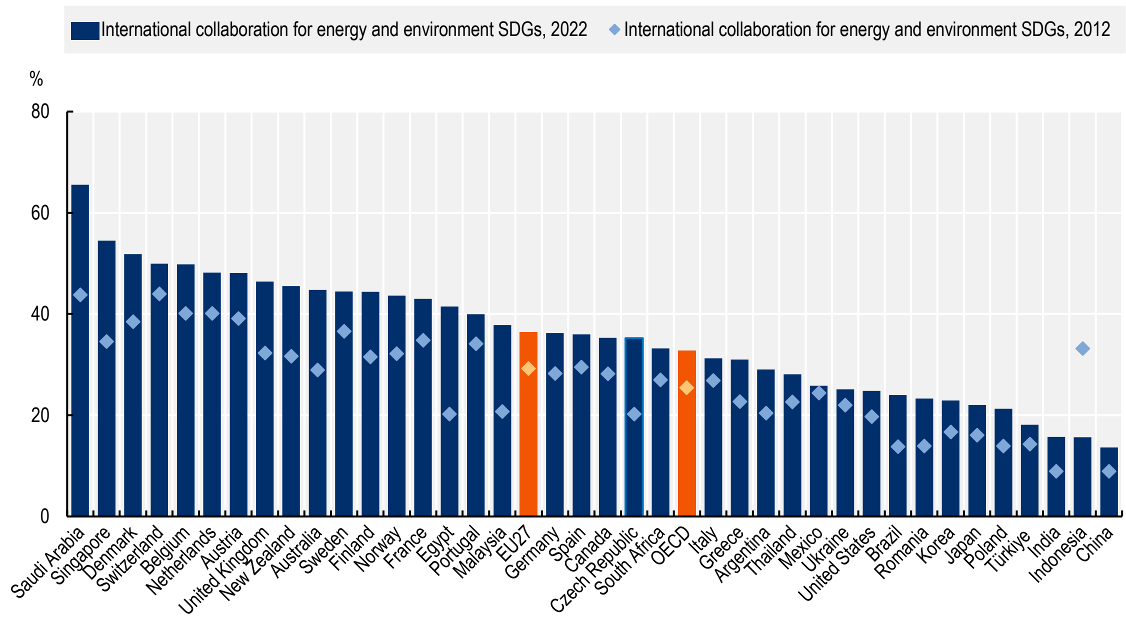
As Figure 2.5 shows, significant proportions of these mobile doctoral graduates are from China, particularly in English-speaking countries (internationally harmonised data for the United States are unavailable), and in neighbouring Japan and Korea. Restrictions on international mobility as part of growing securitisation measures could weaken this important source of researchers and oblige countries to look elsewhere to attract global talent.

OECD countries need to tap into widely distributed knowledge to tackle global challenges

International scientific collaboration is particularly important in research relevant to energy security and environmental sustainability. Compared to all other areas of science, sustainability and energy-relevant research is more collaborative. Furthermore, this international collaboration has increased over time in virtually all countries (Figure 2.6). At the same time, there have been major changes in the contribution of the largest global economies to energy- and environment-relevant research output. The United States and the European Union have seen large declines in the share of relevant publications while China's share has increased rapidly and India has also seen a steady increase (Figure 2.7). This implies a reduction in the overall relative contribution of OECD countries to scientific output in this area, over and above the general scientific publication shift that has been taking place (OECD, 2025[5]).[8] It also highlights the importance of international openness and exchanges that allow OECD countries to tap into this more widely distributed knowledge.[9].

Figure 2.6. International collaboration intensity in energy and environment SDG-relevant scientific output, select countries, 2012 and 2022

As a percentage of domestically authored documents, fractional counts

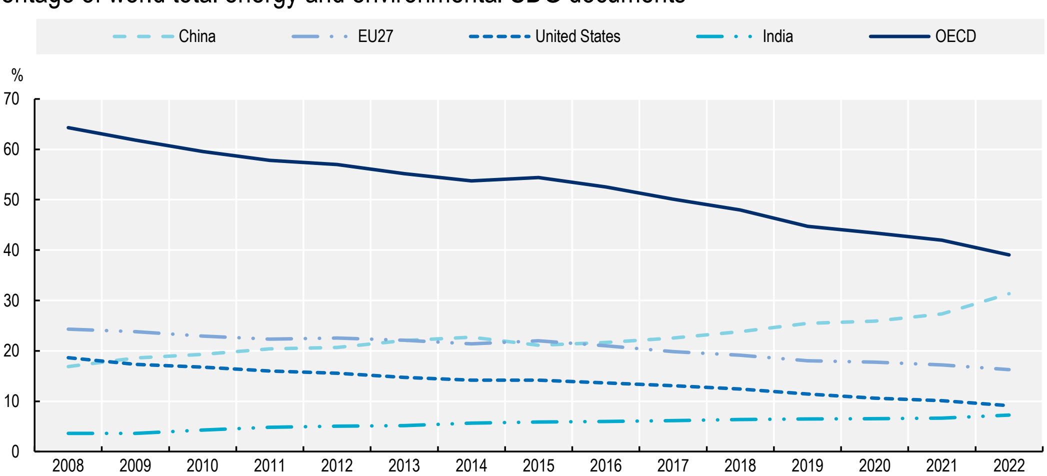


Notes: SDG: Sustainable Development Goal. International collaboration refers to publications co-authored among institutions in different countries. Estimates are computed for each country by counting documents for which the set of listed affiliations includes at least one address within the country and one outside. Single-authored documents with multiple affiliations in different countries count as institutional international collaboration. A publication is tagged as relevant to environmental sustainability and energy if it has the highest aggregated probability for the SDGs under the "Planet" umbrella (6, 12, 13, 15 and 7).
Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 1.2024.

StatLink https://stat.link/b2vmrt

Figure 2.7. Trends for main contributors to energy and environmental SDG scientific publications, 2008-2022

As a percentage of world total energy and environmental SDG documents



Notes: SDG: Sustainable Development Goal. A publication is tagged as relevant to environmental sustainability and energy if it has the highest aggregated probability for the SDGs under the "Planet" umbrella (6, 12, 13, 15 and 7).
Source: OECD calculations based on OECD SDG classifier (OECD, 2025[6]) and Scopus Custom Data, Elsevier, Version 1.2024.

StatLink https://stat.link/e1w8ud

The growing securitisation of science, technology and innovation

Concepts such as “strategic autonomy” and “technology sovereignty” have emerged as increasingly prominent frames for STI policy (Edler et al., 2023[7]; OECD, 2023[1]).[10] This orientation extends beyond technology to cover research as well: for example, growing concerns over safeguarding national and economic security and protecting freedom of enquiry have led many OECD countries to develop guidelines and checklists to increase awareness of and provide guidance to the academic community on research security and integrity. Individual countries are also moving towards more selective international knowledge sharing, enhancing co-operation with countries that have similar values and political interests, particularly in STI areas with national security implications.

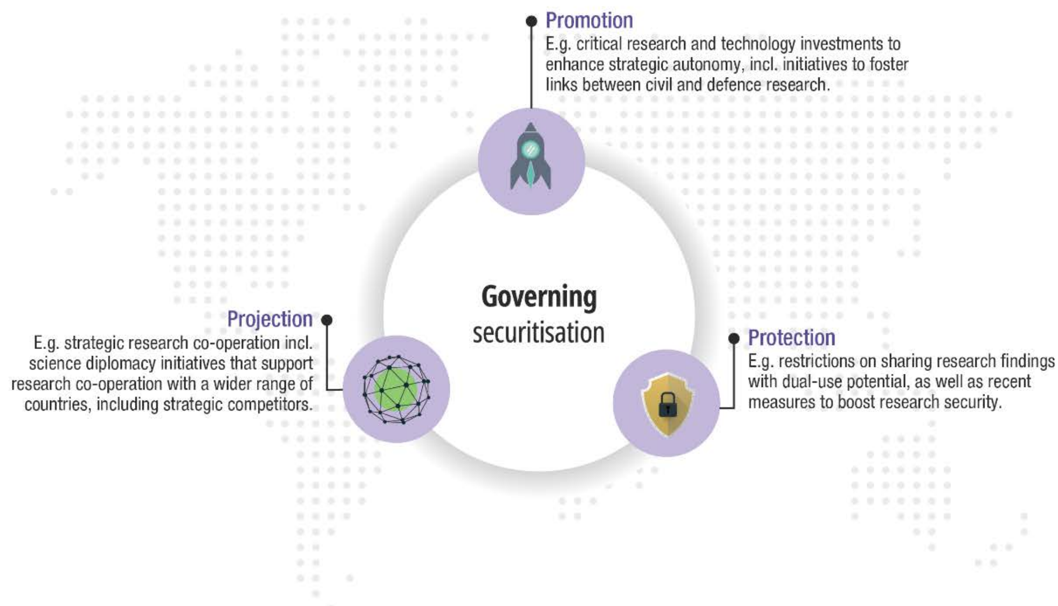
The 2023 *OECD Science, Technology and Innovation Outlook* discussed at some length the growing securitisation of STI policy.[11] It introduced a three-part framework – promotion, protection and projection policies – to map the policy responses of China, the European Union and the United States to growing geopolitical tensions and increasingly intense technological competition (OECD, 2023[1]). This framework has its origins in the policy analysis literature (see, for example Helwig, Sinkkonen and Sinkkonen (2021[8]); March and Schieferdecker (2021[9]); Goodman and Robert (2021[10])) and has recently been adopted by policymakers in the European Union, which used it to structure the European Union’s Economic Security Strategy (European Commission, 2023[11]), and by the Japanese government, which used it to articulate its economic security policies (METI, 2024[12]). Both policies are further described below. The framework’s advantage lies in the comprehensive picture it provides of the securitisation landscape that policymakers can use to design and deliver more joined-up and aligned policies across a range of areas.

This chapter uses this three-part framework to consider STI policy developments that focus predominantly on the research system (Figure2.8):[12]

1. *Promotion* policies, including directed R&D funding and broader industrial policies to enhance national and economic security, covering, among other things, dual-use initiatives to foster mutually beneficial links between civil and defence research.
2. *Protection* policies, including restrictions on sharing research findings with dual-use potential and recent measures to strengthen research security more broadly.
3. *Projection* policies, including international strategic research co-operation that further advances protection and promotion, as well as science diplomacy initiatives that support research co-operation with a wider range of countries, including strategic competitors.

Each of these is discussed in more detail below.

Figure 2.8. Three-part science, technology and innovation securitisation policy framework



Note: The chapter's focus is mostly "upstream" on research

Leveraging the civil research system to enhance economic and national security

Technological leadership has long underpinned the economic prosperity and security of OECD countries, and with geopolitical tensions on the rise, governments are prioritising technological mastery and strategic autonomy as part of their broader national and economic security policies (OECD, 2023[1]). The first type of STI securitisation policy intervention therefore concerns the *promotion* of critical research and technology capabilities, for example through directed R&D funding that serves economic and national security needs.

Along these lines, recent years have seen a proliferation of national strategies targeting the development of a few critical technologies, where countries primarily aspire to capture their economic benefits. For example, quantum science and technology promises to reshape computing, communication and problem-solving in fundamentally new ways (OECD, 2025[13]), and around the world, governments, leading research institutes and some of the best-known technology companies are investing billions of dollars in quantum research (Box 2.1).

Box 2.1. National quantum policies and strategies

Quantum technologies have become a matter of geopolitical contention, echoing dynamics seen in other dual-use emerging technologies such as artificial intelligence and semiconductors. Their civilian and defence uses make quantum technologies dual-use. Over 30 countries have formulated substantial policies in support of developing quantum technologies, and among them, 14 OECD countries have adopted comprehensive strategies and committed substantial public investments to quantum research and development.

Defence establishments have been pivotal in developing quantum technology policy. The "quantum race", therefore, is not merely a pursuit of technological supremacy but a crucial dimension on global security and power. At the same time, economic imperatives have complemented security concerns in driving quantum strategy development, particularly with reference to classical computing's physical limitations.

Apprehensions about dependency on external actors for critical components have led to explicit mandates to develop domestic supply chains, protect intellectual property and cultivate in-house expertise. The aspiration to capture the transformational potential of quantum technologies underpins strategic efforts to foster diverse innovation ecosystems. These efforts blend top-down leadership (such as national-level funding initiatives and roadmaps) with bottom-up ecosystem-building (through incubators, consortia and test beds). Strategies are often accompanied by substantial investments in research institutes, infrastructure and interdisciplinary hubs.

Source: OECD (Forthcoming[14]).

Enhancing economic and national security is increasingly a main objective of science, technology and innovation policy

Governments are also embarking on more ambitious forms of holistic industrial policy (Dechezlepretre, Diaz and Lalanne, 2025[15])[13] in which STI policy plays a prominent part. These policies increasingly target ecosystems that transcend traditional industrial sectors and knowledge domains (see Chapter 6).[14] However, what clearly distinguishes the most recent initiatives from those of just a few years ago is their securitisation perspective and inclusion of strategic autonomy as a key consideration. While different aspects of security – including energy, health and food security – have received growing attention, enhancing national security is increasingly entwined with economic security as a main STI policy objective. Box 2.2 outlines the European Union's recent related measures, which are largely framed by the 2023 European Economic Security Strategy.[15]

Box 2.2. The European Economic Security Strategy

Published in 2023, the European Economic Security Strategy (European Commission, 2023[11]) aims to provide a framework for robust assessment and management of risks to economic security at the European Union (EU), national and business level at a time when these risks are both evolving rapidly and merging with national security concerns. It cites as a prime example of risk the speed with which critical new technologies are emerging and blurring the boundaries between civil and defence applications.

The European Economic Security Strategy uses the "3Ps" framework to propose a raft of policies that include promotion measures that foster the research and industrial base in strategic areas such as advanced semiconductors, quantum computing, biotechnology, net zero industries, clean energy or critical raw materials; protection measures to prevent the leakage of sensitive emerging technologies, as well as other dual-use items, to destinations of concern that operate civil-military fusion strategies; and projection measures (referred to as "partnering") with countries who share common concerns on economic security and by investing in sustainable development and secure links throughout the world through the European Union's Global Gateway initiative.

The risks related to technology security and technology leakage are being assessed based on a list of strategic technologies critical for economic security. At the same time – and reflecting the duality of perspectives on dual-use as an issue of concern for protection and promotion – a recent white paper outlined options to enhance targeted support for research and development (R&D) of dual-use technologies (European Commission, 2024[16]). This acknowledges that technologies used in the context of security and defence capabilities increasingly originate in the civilian domain, where private sector investments are higher, indirect costs lower and R&D cycles faster.

Taking up this theme, the Draghi Report on the future of European competitiveness asserts that dual-use programmes are insufficiently developed in the European Union,[1] despite their potential to enhance collaboration between civilian and defence sectors, drive deep technical innovation that also addresses military needs, and mitigate risk by leveraging common technologies across different end uses (European Commission, 2024[17]). The Niinistö Report on strengthening Europe's civilian and military preparedness and readiness, also published in 2024, highlights the need for Europe to better harness the much faster civil innovation cycles for technologies with dual-use potential to maintain its competitiveness and enhance military capabilities (European Commission, 2024[18]). Both reports compare EU expenditures on defence R&D unfavourably to similar investments by the United States.

In March 2025, the European Commission published a new white paper, *European Defence Readiness 2030*, which declares that technology will be the main feature of competition in the new geopolitical environment. It proposes new ecosystems and value chains for cutting-edge technologies, like artificial intelligence and quantum computing, to feed into both civilian and military applications. It highlights the blurred distinction between civil and defence research, particularly in the realm of "deep tech", and affirms that relevant civil research results should play a crucial role in developing cutting-edge military capabilities (European Commission, 2025[19]).[2]

In July 2025, the European Commission published initial proposals for its tenth Multiannual Framework Programme (2028-2034), which for the first time embraces a "dual-use-by-design model" across much of its entirety (European Commission, 2025[20]).[3] One of its priorities is the reduction of critical dependencies on non-EU technologies and a focus on dual-use technologies that can benefit both civil and defence applications. The European Commission proposes that large parts of the tenth Multiannual Framework Programme will be structured around the four policy "windows" of the European Competitiveness Fund, including one dedicated to "resilience and security, the defence industry and space".

Notes: 1. This is not a new theme for the European Commission, which considers investment in innovation and better use of civilian technology in defence as key to enhancing Europe's technological sovereignty and reducing its strategic dependencies. The European Commission published the "Action Plan on Synergies between Civil, Defence and Space Industries" in 2021, which aims to enhance complementarities between EU civil and defence programmes and instruments, promote "spin-offs" from defence and space R&D for civil applications, and facilitate "spin-ins" of civil-driven innovation into European defence co-operation projects. It followed this up in 2022 with its "Roadmap on Critical Technologies for Security and Defence". Established in 2021 with a budget of EUR 8 billion over 7 years, the European Defence Fund promotes R&D co-operation between public research (typically research and technology organisations rather than universities) and firms. It supports competitive and collaborative projects throughout the entire R&D cycle, including design, prototyping and testing. 2. This white paper also integrates a series of actions to take immediately, such as activation of the National Escape Clause by member states, adoption of the Regulation on Security and Action for Europe, launch of the Strategic Dialogue with the defence industry, and a European Armament Technological Roadmap on investment into dual-use advanced technological capabilities in 2025. 3. The European Commission also published two independent expert reports on dual-use research and innovation (R&I) in June 2025 to inform decision making for the next generation of EU funding programmes. The first is a policy brief prepared by the Expert Group on Economic and Societal Impact of Research and Innovation that highlights the strategic role of dual-use R&I funding to foster security, strategic autonomy, competitiveness and sustainability, and recommends the adoption of a dual-use-by-design approach in future EU funding programmes (European Commission, 2025[21]). The second report, prepared by a small group of experts from both the civil and defence R&I communities, offers concrete examples and case studies on how dual-use R&I can work in practice (European Commission, 2025[22]).

In another example, the promotion of specific critical technologies in Japan's Economic Security Promotion Act (2022) points in similar directions (Box 2.3).

Box 2.3. Japan's economic security policy

Japan has been a pioneer in economic security policy with a view to minimising its vulnerability to economic coercion. Its main policy is the 2022 Economic Security Promotion Act, which sets out to enhance Japan's strategic autonomy and pursue "strategic indispensability" through superior, made-in-Japan technologies on which the rest of the world depends. The act defines four pillars of action: 1) supply chain resilience; 2) securing essential infrastructure; 3) developing cutting-edge critical technologies; and 4) non-disclosure of patents. The National Security Secretariat acts as a co-ordinating body for these efforts and an Economic Security Promotion Office has been established in the Cabinet Office to help unify economic security policies and ensure coherency across all government ministries and agencies.

In addition to these government-wide initiatives, individual ministries are also undertaking their own efforts to enhance economic security. For example, in 2023, the Ministry of Economy, Trade and Industry (METI) published its Economic Security Action Plan, which is centred on the "3Ps", defined in Japan (as in the European Union) as promote, protect and partner. METI has also established a Trade and Economic Security Bureau to formulate and promote policy related to economic security within its jurisdiction. The Action Plan was updated in 2024 and again in May 2025 (METI, 2025[25]), with the most recent version highlighting the need for Japan to adapt to changing conditions in the international system since the previous edition. The 2025 edition outlines four sets of measures:

1. *Further integration and updating of the 3Ps to strengthen Japan's industrial and technological bases*. Among the announced measures are an expanded list of promoted critical technologies that cover various new materials and technologies critical for economic and national security; a new industrial value chain approach that further strengthens measures at each layer of the entire value chain, including research and development, procurement, production, and sales; and a more strategic approach to attracting and retaining highly skilled foreign talent to promote Japan's strategic autonomy and indispensability and prevent the unintended leakage of technology.
2. *Toward the reconstruction of a rules-based international economic order as a global public good*. This includes promoting the "Run Faster Partnership" scheme, which integrates industrial promotion and industrial protection measures aimed at co-creating industrial and technological bases with like-minded countries (with an initial focus on the Indo-Pacific region); and a more proactive role in international strategic rule-making and standardisation.
3. *Promotion of public-private dialogue*. This includes establishing a multi-layered public-private dialogue mechanism; developing codes of conduct and guidelines as references for firms contributing to Japan's economic security; and supporting firms in establishing information security systems.
4. *Strengthening economic intelligence*. In addition to existing scenario analysis, tabletop exercises, supply chain analysis and technology analysis, METI will recruit external experts with high expertise, e.g. in specific technology and industrial areas; establish a strategic dialogue platform between private sector think tanks and the government; and, together with the National Security Secretariat and Cabinet Office, establish an economic security centre to enhance the government's economic intelligence capabilities.

Notes: The updated 2025 Action Plan highlights four "tectonic shifts": 1) the erosion of the liberal international economic order; 2) the intensification of competition for technological hegemony (centred on artificial intelligence) between China and the United States; 3) the growing importance of energy security; and 4) intensifying competition in next-generation strategic fields (e.g. space, oceans and unmanned aerial systems) essential to national security among major but also emerging powers.
Sources: NSS (2022[23]); METI (2024[12]; 2025[25]); Suzuki (2023[24]).

Among the main elements the act identified are Japan's technological capabilities framed as economic measures related to ensuring national security. What marks a sharp departure from the past, though, is a new R&D initiative based on the act called the "K Program" (the Program for the Development of Key Technologies for Economic Security). This is a joint initiative of the Cabinet Office; the Ministry of Education, Culture, Sports, Science and Technology; and the Ministry of Economy, Trade and Industry (METI) that focuses on technologies that contribute to securing national economic security in domains such as maritime, aerospace and cyberspace. The K Program currently has a budget of up to JPY 500 billion (EUR 3 billion) over ten years (NSS, 2022[23]; Suzuki, 2023[24]).[16]

> *There is renewed interest in promoting dual-use research as economic and national security agendas become increasingly entwined*[17]

These short accounts of emerging European and Japanese economic security policies highlight governments' expectations of the far-reaching consequences of emerging technologies like artificial intelligence (AI) and quantum computing, including for national security. They also point to governments' renewed interest in promoting dual-use R&I – involving both the civil and defence sectors – to foster economic and national security. As outlined in Chapter 1, governments are looking to actively exploit synergies between policy goals, including security and economic competitiveness, to ensure maximum return on and efficiency of STI investments. With defence budgets growing considerably in many OECD countries, including in R&D (see Chapter 1), governments are keen to leverage these new expenditures for civil purposes, too. It also seems likely that some civil R&D will be partly labelled as contributing to defence and security as countries aim to meet ambitious defence spending targets over the coming decade. Both phenomena contribute to the emergence of more explicit dual-use agendas.

While dual-use ambitions can be realised through multiple channels, two points of policy focus are emerging. The first focuses on ways to better anticipate both civil and defence needs when conducting low technology-readiness level (TRL) research related to general purpose technologies, such as AI and quantum computing, even when the field of application is not yet known. Many general-purpose technologies are inherently dual-use, and an approach that embodies a "dual-use-by-design model", as discussed in the context of the European Union's next framework programme (see Box 2.2), would aim to raise the awareness and reflection of researchers, administrators and funders on the potential end uses of their research. Such increased awareness and reflection would seek to promote early detection of the dual-use potential of scientific output, with a view to enhancing understanding of both the risks and opportunities (European Commission, 2025[21]). It would also aim to promote a simultaneous alignment with civil and defence requirements, thereby minimising the modifications required to align a given technology with civil or defence standards when targeting respective markets (European Commission, 2025[22]).

The second point of policy focus concerns strengthening technology transfer between civil and defence applications at higher TRLs. While many governments have long supported two-way linkages between the civil and defence R&I systems, rapid and disruptive technological developments in the civil sector have seen governments pay growing attention to their dual-use potential in the defence sector. Accordingly, defence research funding programmes are increasingly opening and commissioning research from the civil research system.

Links between civil and defence research have been historically stronger in some countries than in others. For example, the United States has had a long-standing relationship between civil and defence research as a core feature of national security and science policy. The Department of Defense is an important funder of basic research in universities and support for doctoral programmes in a range of fields. Organisations such as the Defense Advanced Research Projects Agency have sponsored path-breaking research and facilitated new scientific networks, drawing on leading university scientists as programme managers and researchers (see Chapter 1).[18] By contrast, Germany and Japan have historically maintained strict separation between civil and defence research. For example, Germany's "civil clause" excludes most public universities from defence-related research. This is currently under review, with the Federal Ministry of Research, Technology and Space discussing with other research funders the extent to which funding incentives can be used to increase co-operation between civilian and defence research in appropriate areas.[19] In other countries, such as Australia, France and the United Kingdom, while some universities and civil public research institutes have a long history of working with the defence sector, linkages are less developed and systemic than in the United States.

Despite this history of linkages, the civil and defence research systems remain relatively distinct and somewhat independent of one another, having, for instance, their own lead ministries, funding bodies and programmes, research centres and infrastructures, and rules and regulations on what knowledge can and cannot be openly shared. Defence R&I ecosystems remain relatively closed compared to their civil counterparts and are still highly nationally organised. But as economic and national security agendas become more closely entwined, there is growing convergence in the design of funding and other public policy interventions that support civil and defence research and technology development. This could signal the emergence of a more integrated R&I system that sees civil research organisations and researchers further contribute to and exploit defence and security research.

Dual-use research raises several practical and more fundamental questions for civil research systems and policies

Dual-use R&I can be subject to extensive and complex export control compliance measures, including dual-use export control regulations, that introduce additional administrative overheads, significantly prolong development cycles and impose higher costs. Secure development environments with high-security zones and restricted access may also need to be established, implying changes in the organisation of the campus, research teams, data management and IT systems, among other things. However, academic basic research has traditionally been exempt from many of these restrictions. For example, in the United States, the Department of Defense funds considerable research at universities that is inherently dual-use but also unclassified. It tends to be at the application level that distinctions are made between civil and defence uses, and separations are put in place to protect secrecy on the defence side. This distinction could become blurred if R&D funding programmes that are notionally civil become "dual-use-by-design" and target low TRL research that must already consider a range of uses, including for defence.

Talent constraints are another important challenge due to the scarcity in many OECD countries of professionals with both technical expertise and the required security clearances. Leading universities are international in their staffing, and in many systems, foreign doctoral students and postdocs play key roles. Obtaining security clearances can be a long and cumbersome process when hiring foreign researchers and doctoral students, and certain nationalities are likely to be excluded in some contexts. The classification of knowledge as sensitive or classified will also restrict its open dissemination, which could discourage early-career researchers who depend on open publication for their career progression (see Chapter 4). Finally, ethical considerations might also limit scientists' availability and acceptance to engage in research with potential military applications (European Commission, 2025[22]).

At the same time, international competition for leading scientists has become more fierce

Despite possible future restrictions on hiring certain foreign researchers in certain fields, attracting international talent, including leading scientists, remains an important approach for countries to bolster research and technical capabilities that underpin their economic and national security. Those that do not join the global competition for highly skilled migrants risk falling behind (OECD, 2023[26]). OECD countries have for some time offered different types of incentives to attract leading scientists from abroad, including fellowships, grants, tax breaks, special visas and pension portability.[20] Among these measures are talent programmes, which target leading overseas scientists with financial incentives and entry and settlement support. These programmes have become increasingly popular in recent years and often target specific areas of science and technology where countries are seeking to deepen their capabilities. Box 2.4 provides selected examples of recent initiatives.

Box 2.4. Examples of recent talent programmes to attract overseas scientists

The European Union and its member states offer a variety of funding opportunities open to researchers outside Europe. In May 2025, the European Commission announced a EUR 500 million package for 2025-2027 to attract and retain researchers based outside the European Union (EU). It includes the "Choose Europe for Science" initiative, which was launched in 2025 to attract and retain top research talent globally. It also includes the European Research Council Advanced Grant, which provides additional support to researchers moving from non-EU countries, who can apply for an additional EUR 2 million to cover eligible start-up costs (European Commission, 2025[27]).

At the EU member state level, in 2023 the Spanish Agencia Estatal de Investigación established the ATRAE programme, which awards grants to recruit established, internationally recognised research talent (among the top 10% of global researchers in their field) who have recently spent a significant period of their professional activity abroad. The 2025 call is worth EUR 40 million, with individual grants of up to EUR 1.2 million each. Their purpose is to promote progress toward a more competitive science, technology and innovation system at both the national and international levels.[1]

Germany's Federal Ministry of Research, Technology and Space launched the "Global Minds Initiative" in 2025 directed at excellent international researchers. The initiative builds on programmes of the Alexander von Humboldt Foundation and the German Research Foundation and aims to signal a culture of welcome in Germany and to offer a safe haven for scientific freedom. Funding is based on scientific excellence and is open to all themes.[2]

France launched the "Choose France for Science" platform in 2025 as part of its commitment to welcome international researchers who wish to work in an environment conducive to academic freedom. Operated by the French National Research Agency, it enables universities, schools and research organisations to apply for up to 50% co-funding from the government to host researchers.[3]

Also in 2025, the Swedish Research Council issued a call for grants of SEK 2 million to enable Swedish higher education institutions and other research organisations to recruit prominent researchers who are active outside Europe. The grant is to cover expenses for the recruitment and salary for employment in Sweden during a limited period.[4]

"Science Hub Denmark" is a nationally co-ordinated initiative aimed at enhancing the global visibility of Danish research and career opportunities in natural sciences, engineering and life sciences. It promotes Denmark as an attractive destination for top-tier international researchers, with a strong focus on excellence, societal impact and quality of life.[5]

Beyond Europe, Korea launched its "K-Tech Pass" in 2025 to attract global talent in advanced industries, including semiconductors, secondary batteries, displays, biotechnology, robotics and the defence sector. The scheme offers both entry and settlement support to foreigners with expertise in advanced technologies who have signed an employment contract with Korean firms in high-tech industries.[6]

China has scores of talent programmes operating at the national, regional and city levels. They mostly focus on attracting students and professionals from the Chinese diaspora to return to China. Perhaps the best known and one of the largest was the "Thousand Talents Programme", which operated between 2008 and 2023 and is estimated to have attracted 7 000-8 000 participants. The part-time version of the programme attracted close scrutiny from several OECD Member countries, since programme participants moved back and forth and often set up a laboratory in China that mirrored their research lab in the OECD, thereby promoting knowledge and technology transfer on a regular basis (Barteau and Rovito, 2024[28]). The programme contributed to growing research security concerns in OECD countries,[7] particularly around conflicts of interest and conflicts of commitment among participating scientists.

Notes: 1. For further information, see: https://www.aei.gob.es/en/node/5066. 2. For further information, see: https://www.bmftr.bund.de/EN/Research/ScienceSystem/global-minds-initiative-germany/global-minds-initiative-germany.html?nn=1102680. 3. For further information, see: https://france2030.agencerecherche.fr/ChooseFranceForScience-2025/accueil.php?lang=EN. 4. For further information, see: https://www.vr.se/english/just-now/news/news-archive/2025-04-02-new-grant-for-recruiting-researchers-active-outside-europe.html. 5. For further information, see: https://research.state-of-denmark.com/about.
6. For further information, see: https://www.kotra.or.kr/gtc_eng/subList/41000060003. 7. For example, the 2022 CHIPS and Science Act prohibits US-based researchers with federal funding from participating in foreign talent recruitment programmes sponsored by China or the Russian Federation.

Protection through research security measures

There is a growing concern about hostile actors that exploit international research collaboration to acquire research and expertise to accelerate their technological capabilities in areas critical to national and economic security. Without attention and effective management, there is anxiety that such actions may have implications for national security, economic competitiveness and the integrity of research collaboration (James et al., 2025[29]). Many OECD countries now consider unauthorised information transfer and foreign interference in public research a serious national and economic security risk, and research security, including preventing undesirable foreign state or non-state interference in fundamental and applied scientific research, has become a high priority in STI policy (OECD, 2022[30]).

While countries have well-regulated export control systems for research on chemical, biological, radiological, nuclear and explosive technologies, it is less easy to control the intangible transfer of data, information and know-how from scientific research carried out without a specific practical application in mind. This is the case for basic research, which has traditionally been exempt from export controls. At the same time, it is recognised that knowledge from many areas of basic research could be considered as potentially dual-use and, as highlighted above, policymakers are now considering ways to raise awareness among researchers and funding agencies to take this perspective into account in low TRL research. This has led to closer scrutiny of international scientific collaborations and publication practices that were previously liberal, with entire scientific fields, such as AI and quantum computing, increasingly classified as “critical”, “sensitive” or “security-relevant” to provide them with protection against espionage and foreign influence and to secure competitive advantages (German National Academy of Sciences Leopoldina and German Research Foundation, 2024[31]).

Protecting data, information and know-how are not easy in the Internet era and restrictions on access may conflict with research integrity principles and open science (OECD, 2022[30]). Scientific research operates within a global research ecosystem that relies on autonomy, openness and free exchange to function effectively.[21] A blanket application of strict research security measures would pose a direct or indirect risk to the quality, productivity, integrity and, therefore, the societal and economic value of the national research system (James et al., 2025[29]). Developing the capacity to identify and manage genuine security risks while preserving the integrity of the global research ecosystem has, therefore, become a priority for many governments.

Research security threats may result from the hostile activities of threat actors or the poor risk management practices of research-performing organisations or individual researchers. In 2022, the OECD released a policy paper entitled “Integrity and security in the global research system” which made recommendations on how various actors – including national governments, research-funding agencies, research institutions, universities, academic associations and intergovernmental organisations – should approach research security and outlined efforts already under way. Recommendations included integrating research security considerations into national and institutional frameworks for research integrity; promoting a proportionate and systematic approach to risk management in research; and working across sectors and institutions to develop more integrated and effective policy (OECD, 2022[30]).

These themes are addressed below, but since the report's publication, research security measures have continued to expand globally, driven by heightened awareness and the evolving nature of security threats. There has been a sharp rise in the number of policy initiatives focused on research security and the number of countries deploying them. Only 27 national policy initiatives were reported in 2018 in the *STIP Compass database*.[22] By 2025, that number had grown almost tenfold to more than 250. The interest in research security has expanded worldwide, with the number of countries with research security policies more than trebling over the same period, from 12 in 2018 to 41 in 2025.

Coupling of research security and integrity

While governments are putting measures in place to improve research security, they are at the same time emphasising research integrity, which refers specifically to certain values, norms and principles that constitute good scientific practice (freedom of scientific research, openness, honesty, ethics, integrity, accountability, etc.) and regulate international research collaboration (reciprocity, equity, non-discrimination, etc.). Research integrity applies to the behaviour of individual scientists, but also to research ecosystems, with a particular focus on mitigating national and economic security threats and foreign interference. As international collaboration becomes more widespread and the geographic distribution of scientific production changes, mitigating unauthorised information transfer and foreign interference needs to be included in considerations of research integrity. Increasing transparency, disclosing potential conflicts of interest and conflicts of commitment, and managing risks are aimed at strengthening both research integrity and security and are considered essential for promoting trust in science (OECD, 2022[30]).

Policy support is increasingly focused on research security implementation measures

While many earlier policy initiatives focused on raising awareness of research security as an issue and developing policy intelligence, such as evaluations of country-specific risks, the more recent focus has been on developing strategies, agendas and plans and providing support for their implementation. There has also been growing use of regulation, soft law and oversight since 2020. This shift indicates that countries are tightening up their research security efforts, transitioning from simply raising awareness and gathering intelligence to more concrete planning and implementation. These efforts primarily target research-performing organisations and funding agencies. The extent of initiatives focused on implementation reflects the extent to which these actors need support operating in a changing environment as well as the extent to which this environment is disrupting established practices. The most common categories of implementation support among recent policy initiatives are the development of guidance, self-service tools and advisory services (Box 2.5). Governments, funding agencies and research-performing organisations are also establishing dedicated organisational structures to promote research security.[23]

Box 2.5. Emerging types of support for research security implementation

Guidance development

Recent guidance documents provide frameworks for implementing newly issued strategies or directives or add detail to previously issued guidance. These are designed not only to help institutions navigate the evolving landscape of research security but also to help create a culture of accountability. For instance, the Norwegian Directorate for Higher Education and Skills, in collaboration with the Research Council of Norway, has issued *Guidelines and Tools for Responsible International Knowledge Cooperation* (Norwegian Directorate for Higher Education and Skills, 2023[32]). In the United States, the White House Office of Science and Technology Policy has published *Guidelines for Research Security Programs at Covered Institutions*. These outline expectations for research security programmes in relation to cybersecurity, foreign travel security reporting, research security training and export control training (White House Office of Science and Technology Policy, 2024[33]). In Austria, the Ministry of Innovation, Mobility and Infrastructure (Bundesministerium für Innovation, Mobilität und Infrastruktur) is supporting research security in the applied research sector. Measures include guidance to help funding applicants self-assess the risks of possible joint projects and partners by asking the right questions, giving advice on how to identify red flags and general information on research security.

Self-service tools

With the increasing complexity of research security regulations and guidance, recent initiatives have included practical tools to help universities and research institutions apply this guidance in their day-to-day work. For example, the UK government's National Protective Security Authority and National Cyber Security Centre have released a research security maturity self-assessment tool, the Trusted Research Evaluation Framework. Complementing existing Trusted Research guidance, the framework is aimed at helping academic institutions in different stages of their research security journey understand what "good" looks like across seven areas of activity. It defines what constitutes foundation, intermediate and developed capacity for multiple evaluation dimensions (National Protective Service Authority, United Kingdom, 2024[34]).

Advisory services

The establishment of advisory bodies has become a cornerstone of recent research security efforts, reflecting research institutions' need for expertise navigating research security requirements, assessing risk in projects and evaluating potential collaborations. For example, Denmark established the Centre for Innovation and Knowledge Security within the Danish Security and Intelligence Service in 2023 to proactively advise its research institutions on how to handle threats from foreign states. The centre was created to address the growing risks of espionage, intellectual property theft and foreign interference in research.[1] The United Kingdom's partnership approach to research security engages universities through its Research Collaboration Advice Team and aims to support the research sector to take informed decisions on research collaborations.[2]

Notes: 1. For further information, see: https://pet.dk/en/our-tasks/security-advisory-services/the-objective. 2. For further information, see: https://www.gov.uk/government/groups/research-collaboration-advice-team-rcat.

Vetting international research collaborations through project- versus list-based approaches

Authorities are placing restrictions of varying degrees on collaboration with certain research organisations or countries. In some cases these are linked to identified fields of research that reflect geopolitical and economic security considerations. For example, the Government of Canada's Policy on Sensitive Technology Research and Affiliations of Concern entered into force in 2024 and stipulates that any research grant or funding application in listed sensitive technology research areas will not be funded if researchers involved in the application activities are in receipt of funding or in-kind support from listed research organisations connected to military, national defense or state security entities that could pose a risk to Canada's national security (Innovation, Science and Economic Development Canada, 2024[35]).[24]

Other countries are establishing project-based approaches to identify sensitive research collaborations rather than relying on defined field- or affiliation-specific restrictions. The German federal government published its Strategy on China in 2023, setting a framework for secure co-operation with China amidst systemic rivalry (Federal Foreign Office, Germany, 2023[36]). The German Research Foundation, the German Science and Humanities Council, the German Academic Exchange Service, and the Max Plank Society subsequently published recommendations to support scientists, research institutes and universities in navigating this new context. They deliberately refrain from drawing red lines around specific countries, partner institutions or research topics and instead endorse case-by-case assessments.[25]

Similarly, a 2024 JASON study *Safeguarding the Research Enterprise*, contracted by the US National Science Foundation (NSF), recommended identifying sensitive research and risks to collaboration at the project level during research proposal evaluation research. It provides an alternative to sweeping restrictions on all collaborations in listed high-risk areas. This process-based approach has been newly adopted in the NSF's Trusted Research Using Safeguards and Transparency (TRUST) framework.[26] Inspired by this example, the Japan Science and Technology Agency (JST) has recently introduced a pilot scheme, JST-TRUST, that it applies to its calls for proposals on quantum science and semiconductor research. The scheme involves screening experts' proposals, asking principal investigators how they do due diligence on their projects. Based on this, they consider risk-mitigation measures, to be set by the JST, if necessary. The JST-TRUST also assists with monitoring and guidance on research outcomes and publishing.[27]

Reframing science diplomacy to further both national and multilateral goals

The third type of STI securitisation policy intervention is rooted in the projection of national interests in international regulations, norms, standards and alliances. In this regard, science diplomacy, defined as the use of science for foreign policy purposes, has become an increasingly prominent instrument to pursue not only multilateral goals, but also national interests. While some supporters of science diplomacy still predominantly highlight its global public goods aspects,[28] today it is widely recognised that science is increasingly used as a strategic tool to secure national interests and power, and for leverage in interstate rivalry. This duality is hardly new, but as strategic competition has become more prominent in the current geopolitical environment, perceptions of science diplomacy have shifted, and it has become more institutionalised as an external foreign policy tool.

Along these lines, the 2025 revised science diplomacy framework of the American Association for the Advancement of Science and the United Kingdom's Royal Society acknowledges the new era of disruption and is "darker, more realistic, and hard-edged, than its predecessor" from 2010 (The Royal Society and AAAS, 2025[37]). The European Commission's *European Framework for Science Diplomacy*, also published in 2025, makes similar observations, acknowledging that "science and technology are pieces on the global geopolitical chessboard" (Gjedssø Bertelsen et al., 2025[38]). Box 2.6 briefly outlines both reports, which are expected to influence science diplomacy policies.

Box 2.6. New landmark frameworks for science diplomacy in 2025

Science diplomacy in an era of disruption (American Association for the Advancement of Science and The Royal Society)

This report updates the 2010 framework for science diplomacy issued by the American Association for the Advancement of Science and The Royal Society. It argues that a more fragmented and dangerous world, impacted by global challenges and technological disruption, necessitates a revised approach to how science and diplomacy interact. The document proposes a simplified two-dimensional framework: science impacting diplomacy (the different ways that science interacts with diplomatic objectives) and diplomacy impacting science (the ways that diplomacy interacts and engages with the scientific enterprise).

The consultations that informed this report highlighted several key messages. For example, while science advisory mechanisms are increasingly integrated into national and multilateral institutions – reflecting the fact science is now ever more central to foreign policy – scientific and diplomatic interests may not always coincide. Treaties governing global commons sometimes conflict with sovereign national interests, prompting a re-examination of scientific values once thought universal and their implications for international scientific collaboration. The report also noted the increasingly influential roles of non-state actors, such as major companies and philanthropic organisations in the changing landscape of science diplomacy.

A European Framework for Science Diplomacy (European Commission)

With science and technology increasingly becoming a geopolitical currency, the European Union has concluded that science diplomacy can help it to project soft power and pursue its economic interests and fundamental values more effectively. Accordingly, the European Union launched the report, a *European Framework for Science Diplomacy*, in 2025, which is expected to be followed up with a science diplomacy strategy later in the year. The report recognises paradigm shifts in science diplomacy, driven by geopolitical and technological changes. It proposes a European-wide approach to science diplomacy that preserves spaces for exchange, fosters a shared responsibility for addressing common challenges and protecting global public goods, and defends Europe's strategic interests. In particular, the framework highlights the need for a strategic use of science diplomacy in the current geopolitical context, involving enhanced strategic intelligence capacity (e.g. using foresight) and strengthened science diplomacy in delegations and embassies. The report provides concrete recommendations and actions on how European leadership in science diplomacy can be achieved through strategic, operational and enabling instruments.

Note: To elaborate: Strategic instruments for European science diplomacy focus on setting clear priorities and making science diplomacy visible, identifying the appropriate balance between openness and restrictedness in international science co-operation, and leveraging science diplomacy to address global challenges and sustainably manage global public goods and commons, including through partnerships with countries in the Global South. Operational instruments aim to establish the necessary structures for EU leadership in science diplomacy, foster science for policy and foresight ecosystems to enhance foreign and security policies, and strengthen the role of science and technology within diplomatic representations. Enabling instruments seek to create and connect science diplomacy communities, train and empower Europe's current and future science diplomacy professionals, and advance the frontiers of science diplomacy through research and innovative approaches to strengthen the overall capacity and expertise in the field.
Sources: Gjedssø Bertelsen et al. (2025[38]); The Royal Society and AAAS (2025[37]).

Scholars and practitioners have debated ways to define, categorise and frame the different shapes and forms science diplomacy can take (Turekian, 2018[39]).[29] This chapter does not seek to create an additional framework, but rather identifies three key aspects to consider:

1. The co-operative nature of science diplomacy: Science diplomacy for global public goods and development.
2. The competitive nature of science diplomacy: Science diplomacy in pursuit of national interests.
3. The hybrid nature of science diplomacy: Non-state actors and Track 2 diplomacy.

Each of these is further elaborated below.

Co-operative science diplomacy for global public goods and development

This form of science diplomacy strongly emerged in the 1990s and involves a mix of foreign policy and scientific personnel, often meeting in multilateral fora, to address global challenges like climate change, biodiversity loss, health security issues, etc. Examples include the Paris Agreement on Climate Change. In some fields, science diplomacy communities have emerged according to the nature of the scientific domain or natural resource in question, such as water diplomacy, health diplomacy, cyber diplomacy, etc. It is the sort of science diplomacy that some think is most at risk from rising geopolitical tensions and national security policies. By way of example, Box 2.7 describes ongoing ocean science diplomacy and its recent roles in the third United Nations Ocean Conference in Nice (France).

Box 2.7. From data to diplomacy: How ocean science shapes policy and trust

The ocean plays a vital role in the economies and livelihoods of hundreds of millions of people. If treated as a single country, the ocean economy would have ranked as the world's fifth-largest economy in 2019, contributing 3-4% of global gross value added between 1995 and 2020 and supporting up to 133 million full-time jobs (OECD, 2025[40]). But the ocean is under many pressures, threatening not only ocean health but the future of the ocean economy as well.

Peer-reviewed science provides objective criteria that help reconcile economic ambitions with global environmental imperatives in ocean governance and management. Grounded in data, peer engagement and shared objectives, scientists from different countries can build co-operation and trust where traditional diplomacy sometimes falters, resulting in tangible policy outcomes and informed decision making. The importance of ocean science diplomacy was clearly apparent during the recent third United Nations Ocean Conference (9-13 June 2025), where the integration of up-to-date scientific findings on the state of the ocean shaped commitments anchored in shared evidence.

For instance, responding to the need for science-based marine protected areas – with the objective of conserving 30% of the ocean by 2030 – countries committed to joint ocean exploration missions and enhanced transparency in areas beyond national jurisdiction in the high seas. Notably, over 20 countries ratified the "High Seas Treaty", a major diplomatic outcome of the conference. Once in effect, potentially as early as 2026, the agreement will establish a new legal framework for governing the high seas, contributing to the conservation and sustainable development of marine biological diversity. Science indicators and sustainable ocean data observations – spanning weather patterns, biodiversity, carbon cycles and fisheries – will provide a shared evidence base to guide policy and enable scientifically informed negotiations.

Source: OECD (2025[40]).

A related consideration is the participation of low- and middle-income countries (LMICs) in these international co-ordination efforts. For example, since LMICs are expected to account for much of the growth in global carbon emissions until 2050, it will be important for the global community to support multilateral and club-based STI collaborations that include or are driven by representatives of the Global South.[30] International STI co-operation can help strengthen the national STI capabilities of LMICs, allowing them to better engage in global STI collaboration and decision making and contributing to their overall economic development.

Competitive science diplomacy in pursuit of national interests

The view of science as a purely collaborative, objective and unifying force capable of overcoming deep political divides is challenged by the reality that science can be a geopolitical asset, blurring the lines between its perceived non-political nature and its role in power dynamics (Runguis and Flink, 2020[41]). Governments are strategically harnessing scientific expertise and international collaboration to advance their country's geopolitical influence, economic competitiveness and security objectives, often involving a deliberate balance between openness and restrictive measures to safeguard sovereign interests.

Along these lines, many countries are bolstering the science capacity of their foreign ministries and missions. For example, some countries have a large representation of science and technology diplomacy counsellors or attachés in missions abroad. The United Kingdom, for instance, has a well-established network of approximately 130 staff in over 65 locations across the world, building collaborations that aim to maintain the country's scientific base, support the competitive advantage of the United Kingdom's innovative businesses, and address shared opportunities and threats. These work with local science and innovation organisations to project UK STI excellence and leadership globally, build and facilitate STI of value to the United Kingdom, and provide insights and intelligence. While the thematic focus is different for each country, priorities include opportunities and risks from critical and emerging technologies, addressing climate change and biodiversity loss, and health security.[31] Other G7 countries and China have similar operations, but some smaller countries are also active. For example, Hungary maintains an international network of science and technology attachés stationed at 15 key locations in major STI partner countries and centres of competitiveness and innovation (Asia-Europe Foundation, 2025[42]).

Hybrid science diplomacy involving non-state actors and Track 2 diplomacy

Science diplomacy involves an increasingly hybrid approach, combining and intertwining Track 1 (formal diplomacy primarily led by diplomats and other state actors) and Track 2 diplomacy (informal diplomacy, involving non-governmental participants and informal dialogue) (Ruffini, 2020[43]; Turekian and Gluckman, 2024[44]). While Track 1 diplomacy involves the direct pursuit of state interests through official channels and supports the negotiation of international treaties and formal agreements, Track 2 diplomacy is considered a means by which non-state actors, particularly academics and scientific organisations, can contribute new ideas and relationships to the official diplomatic process by incorporating leading thinkers from outside governmental structures. Through the soft power of science, they can establish personal scientific networks to foster trust where official diplomatic links are otherwise weak or non-existent. Box 2.8 outlines some widely cited examples.

Box 2.8. Examples of Track 2 science diplomacy

While Track 2 diplomacy might be officially sanctioned by governments, it can also be driven by the professional interests of scientists. Various Cold War era links between the West and the Soviet Union are often cited as examples, such as the Pugwash conferences, which brought together scientists from both sides of the Iron Curtain and played a significant, behind-the-scenes role in informing and laying the groundwork for major arms control.[1] More recent examples of links include those between American and Cuban scientists over sharing weather data, leading to the development of a formal agreement to install shared GPS monitoring equipment in Cuba;[2] the Iranian public health experts who worked together with US counterparts to replicate the Iranian primary healthcare system in the Mississippi Delta;[3,4] and in the Middle East, collaboration between the Arava Institute for Environmental Studies and the Damour for Community Development, which have been organising since 2016 the Track II Forum for Environmental Diplomacy to enable key civil society organisations and individuals representing both state and non-state actors to discuss and develop cross-border strategies to facilitate formal and informal environmental agreements between Israel, the Palestinian Authority and Jordan.[5]

Notes: 1. For further information, see: https://www.nobelprize.org/prizes/peace/1995/pugwash/speedread. 2. For further information, see American Meteorological Society (2015[45]). 3. For further information, see: https://era.ideasoneurope.eu/2022/07/13/learning-from-rivals-the-role-of-science-diplomacy. 4. For further information, see: https://www.stimson.org/2025/health-and-science-diplomacy-could-pave-the-way-to-new-us-iran-relations. 5. For further information, see: https://arava.org/initiatives-working-groups.

Among non-state actors, the private sector plays an increasingly crucial and complex role in science diplomacy, wielding significant scientific, economic and political influence that can, in some cases, rival that of individual countries. Many large firms, especially global technology businesses, are major R&D funders, with their annual expenditures often comparable to or exceeding national public research programmes. Some engage directly in diplomatic efforts, cultivating relationships with foreign governments and international bodies like the United Nations and the European Union,[32] and engaging directly with them on topics like emerging technologies, often bypassing national diplomats from their countries of origin. They are also critical partners in public-private partnerships for developing large research infrastructures, such as SESAME and CERN Open Lab, and demonstrated their pivotal capacity during the COVID-19 pandemic in vaccine development and global distribution. Furthermore, the private sector is central to setting international technical standards for global trade and knowledge exchange.

Developments like these have led to the emergence of technology and innovation diplomacy (Leijten, 2017[46]), which involves combining expertise from the three traditionally separate fields of technology, business and foreign policy with a view to advancing national interests. Some countries have established a diplomatic presence near innovation hubs like Silicon Valley in recent years. Denmark led this trend in 2017 with its tech embassy in Palo Alto,[33] a move since emulated by the EU Office in Silicon Valley.[34] In another example, Switzerland has established its Swissnex global network to strengthen its profile as a world-leading hotspot of innovation. The network has offices in 6 regions renowned for innovation, backed by around 20 counsellors based in Swiss embassies worldwide. A notable feature is the engagement of public and private stakeholders from the Swiss and local education, R&I landscape, who cover at least two-thirds of the costs of Swissnex's activities.[35]

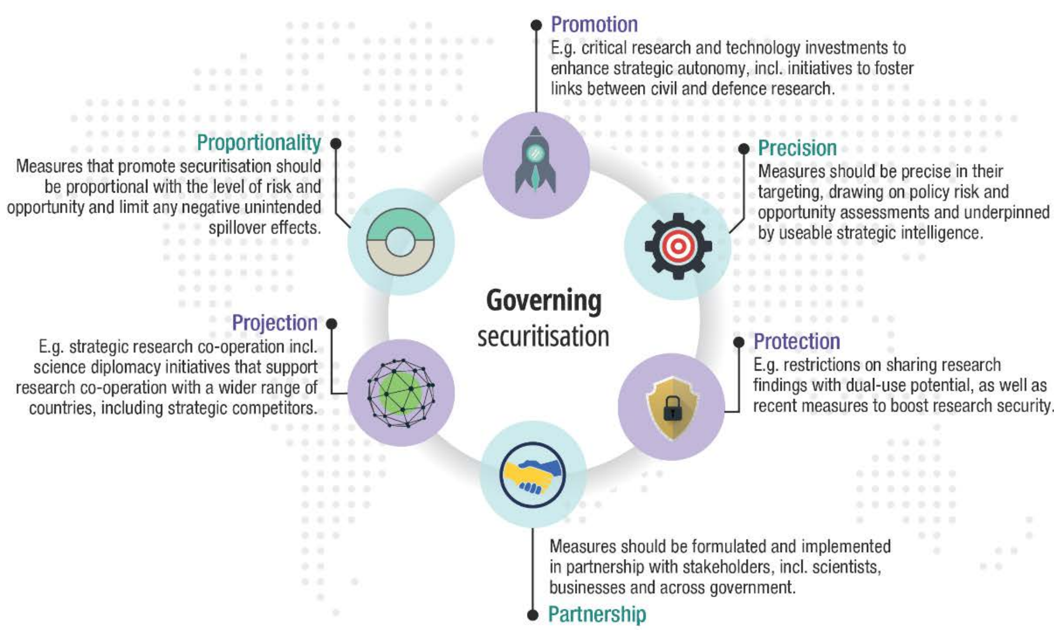
Principles for governing science, technology and innovation securitisation

These three strands of securitisation policy – critical technology promotion, research security and science diplomacy – are closely related and present policymakers with several governance challenges. Three aspects of STI policy governance particularly stand out, namely formulating the scope and focus of securitisation policies, mobilising key stakeholders to co-design and implement them, and building a knowledge and evidence base to inform policy choices and strategy:

- First are the scope and focus of STI securitisation measures. A key consideration here is their proportionality with the level of expected risk and opportunities. Governments need to strike several balances along different axes and at different levels in their policies, in particular with regards to international openness.
- Second, the R&I activities these policies seek to influence are performed by semi-autonomous researchers and private businesses. Governments must mobilise and partner with these groups for securitisation policies to succeed. They must also co-ordinate across different parts of government given the cross-cutting nature of securitisation policies.
- Finally, security-related STI policy measures should be precise and agile when targeting research, technology and industrial areas for promotion, protection and projection. This points to the need for policy risk assessment and uncertainty analysis capabilities, underpinned by useable strategic intelligence. Securitisation policies should also be monitored and evaluated to enable course corrections and promote accountability.

Proportionality, partnerships and precision are, then, a further set of "3Ps" that overlay the original security 3Ps of promotion, protection and projection (Figure 2.9).[36] They amount to principles for governing securitisation policies to mitigate risks and promote strategic co-ordination. The remainder of this section briefly discusses each in turn.

Figure 2.9. Principles for governing science, technology and innovation securitisation that promote proportionality, partnership and precision



Proportionality: Scoping STI securitisation policies that balance different values, goals and interests

STI securitisation policies are inherently concerned with balancing different values, goals and interests along different axes and at different levels. The securitisation measures outlined in this chapter all pull in the direction of enhancing national interests, primarily economic competitiveness and national security, with each challenged by the need to retain some measure of international openness and research autonomy, both of which contribute to the value of R&I activities. The success of individual measures is tied to others, and they need to work together to ensure a balanced approach to securitisation. The formulation and implementation of STI securitisation policies should, therefore, be considered together as part of a broader and balanced STI securitisation strategy (also keeping in mind that this chapter has primarily explored the public research system, and that there are several other policies relevant to STI securitisation extending across the innovation chain that should also be considered).

The focus of this section is primarily on balancing research security and international openness, but there are also other important dilemmas that policymakers need to consider. For example, technology races should incorporate safeguards to manage downside risks and bridge global technology divides. In this regard, principles and guidelines can be an attractive modality for international, transnational and/or global actors to make moral and political commitments with some flexibility and accommodation for differences and changing circumstances (OECD, 2024[47]). Relatedly, clear ethical guidelines should be established for research and technologies with dual-use potential to ensure they do not undermine human rights or societal well-being (European Commission, 2025[21]).

Balancing research security and openness and the implications for international collaboration

Research security measures raise significant questions about international research collaboration, which is an important aspect of scientific openness. Countries are striving to strike the right balance between safeguarding their national and economic security while upholding academic freedom, promoting international research co-operation, and ensuring openness and non-discrimination. Implementing overly broad or extreme security practices can stifle academic freedom, hinder innovation and disrupt valuable global partnerships. On the other hand, too little security can expose sensitive research or academic collaborations to risks, ultimately eroding safety and trust.

There is wide recognition among policymakers that research security and open science need not be cast as oppositional and can, in fact, be complementary: for instance, research security measures can enable open research practices by protecting academic freedom from abuse by malicious state actors; they also often entail greater transparency on researchers' affiliations and funding sources. In this way, they contribute to good scientific practice, but they can also be applied overzealously. The key is to find a middle ground that protects valuable work without undermining the very principles of academic freedom and the social and economic benefits of participating in open international scientific collaboration (OECD, 2022[30]; Shih, 2025[48]). The overarching principle guiding this complex equilibrium is to keep scientific engagement "as open as possible and as secure as necessary".[37] A related concept is the "small yard, high fence", where strict, robust controls are put in place to protect narrow and specific areas of science and technology considered critical to national and economic security. However, the growing emphasis on research with a dual-use character could shift countries' calculations and may introduce additional restrictions on international research collaboration (European Commission, 2025[21]).

STI securitisation measures also run the risk of creating a more fragmented global R&I landscape that is ill-equipped to tackle global challenges. Measures in one country can easily trigger unwelcome countermeasures in others and have a chilling effect on international collaboration to address shared global challenges. For instance, health-related research fields – such as pandemic preparedness and antimicrobial resistance – face an openness-versus-security dilemma. They address global challenges that depend on open scientific collaboration and data sharing to drive preparedness, recovery and resilience. At the same time, heightened openness in such sensitive health domains can increase the risk of misuse or misconduct, underscoring the need for vigilance. Acknowledging and managing this tension responsibly is essential to safeguard research integrity and ensure that international collaboration in health research can continue with confidence and maintain its positive impact.

The broader emphasis on research security has inadvertently led to a chilling effect on international research collaboration and academic mobility more broadly. Research-performing organisations are increasingly cautious about entering international research collaborations where security risks have been identified. This is in part a function of asymmetric knowledge, with research-performing organisations often complaining of being given insufficient information from security services to make informed judgements (James et al., 2025[29]). Research-performing organisations also complain of being faced with a range of ambiguities and sometimes contradictory signals. There are also risks that researchers feel pressured to self-censor or avoid high-risk but important research areas, adversely affecting R&I (Shih, 2025[48]). Furthermore, there are risks of prejudice, cultural bias and inadvertent discrimination against certain population groups in both list-based and process-based approaches to risk assessment. This is a major concern for the academic community and an area that needs to be carefully monitored as policies for restrictions on collaboration become more widespread.

While research-performing organisations have a responsibility to act responsibly in their international activities, neither individual researchers nor individual universities should be left alone in making assessments of difficult goal conflicts, and governments and funding agencies have a responsibility to provide national guidelines (Swedish Council for Higher Education, 2024[49]). It is possible to define international co-operation as fully compatible with national security rather than as something external and threatening to it.[38] To achieve this, an "intentionality" approach is crucial, requiring a deep understanding of collaborating partners' motivations, networks and their ultimate intentions for research outputs. Similarly, emphasising reciprocity in collaborations is vital to ensure mutual benefits and prevent non-reciprocal exchanges that can intensify securitisation concerns (Dawes, Salt and Smith, 2024[50]).

At the same time, research-performing organisations need to develop their own internal security capacity, which includes creating institutional policies, establishing risk management and due diligence processes, and hiring dedicated research security officers. They also need to continue raising awareness about research security among researchers and administrative staff. Building this capacity is a challenge, as institutions must do so with limited funding and in a competitive job market where these specialised skills are scarce. Similarly, governments are also struggling with these capacity constraints as the growing demands of research security put a strain on ministries and security agencies (James et al., 2025[29]).

A strategic dual-track approach is emerging, focusing on intensive collaboration with "like-minded" countries for cutting-edge technologies while maintaining broader co-operation with diverse countries for shared global challenges (Asano and Arimoto, 2024[51]; Turekian and Gluckman, 2024[44]). Policy frameworks must clearly define "red lines" for collaborations that flagrantly violate established norms, such as serious ethics dumping, direct military use by military institutions, illicit technology transfer or grave human rights violations. At the same time, they need to actively manage "grey areas" where different national and institutional contexts create challenges, to prevent inappropriate transgressions through adherence to principles of research integrity, ethics and "responsible internationalisation" (Shih, 2024[52]). To take effective decisions, a wide range of issues must be considered, such as openness, scientific advancement, global challenges, national security, economic security, ethics, human rights and democracy. Combining these diverse concerns into a single, cohesive approach is difficult but essential for achieving proportionality in STI securitisation measures (Schwaag Serger and Shih, 2024[53]).

Partnerships: Co-operating with scientists and businesses and across government

A comprehensive STI securitisation policy mix must find ways to bring a broad range of stakeholders, including governments, business and academia, into the discussion while at the same time building robust governance mechanisms essential to integrating a range of priorities and values. This is in a context where businesses and public research-performing organisations enjoy considerable autonomy, which presents co-ordination and mobilisation challenges, particularly where values and interests may be misaligned. Promotion, protection and projection policies also call for cross-government co-ordination, but this is notoriously challenging, with different ministries and agencies having their own specific operating procedures, mental models and frameworks, and community interests to serve.

Co-operation with businesses

Most R&D in technology-intensive economies is conducted in firms, where trade and investment restrictions, as well as new industrial policy measures, are felt most keenly. Involving firms in formulating and implementing STI securitisation policies is, therefore, crucial. This is perhaps most obvious in promotion policies, where, for instance, the new wave of industrial policies builds largely on public-private partnerships. Priority-setting and policy formulation in these contexts typically involve firms, which are often engaged in strategic foresight and technology assessment processes, policy formulation and design, and collaborative R&D with public sector research-performing organisations. Firms also benefit from policy incentives that seek to attract international talent and are typically engaged in their design.

This chapter has focused on research security policies affecting public research-performing organisations, but firms are also subject to restrictions, for example in the form of export controls and investment screening as part of economic and national security measures. They are also targets of cyberattacks and industrial espionage, as well as vectors. Some governments provide guidelines on countermeasures against technology leakage in the context of overseas expansion of production facilities. Both the European Economic Security Strategy (see Box 2.2) and Japan's Action Plan for Economic Security (see Box 2.3), for example, include provisions on the security risks from outbound investments.

This chapter has also highlighted the growing prominence of large leading technology firms in technology diplomacy as they seek to exert influence over international norms and political agendas. These firms wield significant control over critical technologies, raising key questions around accountability, equity and governance, particularly as development of these technologies resides largely outside the oversight of the state, and corporate interests may diverge from national interests (Geneva Science and Diplomacy Anticipator, 2025[54]). Science and technology diplomacy frameworks, involving firms and state authorities, have been updated to explicitly recognise non-state actors as integral participants, shifting from a state-only focus.

Co-operation with scientists and research-performing organisations

Directed research agendas that are oriented towards strategic goals like economic and national security must mobilise scientists and research-performing organisations if they are to succeed. Governments traditionally use managed funding programmes and other incentives for this purpose (see Chapter 1), but they must also incentivise the strengthening of linkages with other innovation system actors, notably firms, to promote innovation and national competitiveness. As already highlighted, a growing policy focus on dual-use research and technology development could have implications for civil research, in terms of its physical environment, e.g. with high-security zones and restricted access, but also in the ways research is conducted and disseminated. Targeted education and support will be needed to help researchers better understand the complexities of dual-use research, including its risks and its opportunities (European Commission, 2025[21]). But there will also be a need for scientists and universities to be routinely involved in co-designing any new arrangements.

This is already happening around research security. The primary responsibility for implementing research security belongs to research-performing organisations and especially universities, given their autonomy is secured in many countries.[39] At the time of the OECD-GSF report (OECD, 2022[30]), government research security measures were regularly criticised by the research community for being opaque or disconnected from the operational realities of research institutes. More recent initiatives show a marked improvement in how governments engage with research institutes in the development and implementation of such policies. For example, the 2024 JASON study's recommendation to adopt a process-based, rather than a list-based, approach to identifying sensitive research was developed after discussions with a range of government agencies, university administrators and experts on issues of research security (JASON, 2024[55]). Across various levels of government, universities and research institutes appear to be routinely involved as active partners in the research security policymaking process, with nearly all new policy initiatives making efforts to collect input from research stakeholders.[40]

At the same time, a range of researcher-driven initiatives has emerged to promote interactions between the scientific and diplomatic communities, many working across national borders. For example, the American Association for the Advancement of Science established in 2008 the Center for Science Diplomacy, which aims to strengthen interactions and partnerships between the two communities, as well as to develop the intellectual framework and training to support the practice of science diplomacy.[41] In Europe, the EU Science Diplomacy Alliance was launched in 2021 to facilitate interactions and dialogue, training, institutional capacity building and co-ordination of grant-seeking or use of joint funding.[42] Similarly, DiploCientífica has developed a collaborative network that brings together scientists, policymakers and the diplomatic community in Latin America and the Caribbean to build capacity and produce constructive knowledge.[43] Finally, South Africa hosts the Science Diplomacy Capital for Africa initiative that aims to facilitate cross-border collaboration between African science institutions and global partners, particularly diplomatic communities and regional bodies.[44]

Promoting cross-government policy coherence

Ministries with responsibilities for R&I, as well as funding agencies, are active in the growing securitisation of STI, although it has most often been led by ministries in other policy domains such as trade, foreign affairs, defence and industry. Existing links between STI policy and other policy domains remain weak in most countries and need strengthening to orchestrate government action on protection, promotion and projection policies (OECD, 2023[1]).

Strategically oriented research – for example, as part of new industrial policies – necessarily involves cross-government co-operation, particularly to help orchestrate supportive actions across the innovation chain, from basic research to technology commercialisation and diffusion. This is perhaps best illustrated by the recent popularity of mission-oriented innovation policy approaches, which typically bring together several ministries and agencies to co-ordinate actions to meet specified and time-limited shared goals (see Chapter 1). The promotion of dual-use research and technologies will also call for increased co-operation between STI ministries and agencies and their defence sector counterparts to accelerate innovation and support responsible and secure technology development (European Commission, 2025[21]).

An integrated approach to research security also calls for strengthening cross-government collaborations between science and security agencies. Such collaborations are necessary to build mutual understanding of the benefits and risks of international research collaborations and to help build risk-appropriate mitigation strategies. One purpose of such collaborations has been to build a shared understanding between the scientific and security agencies on the risks facing the research sector and thus increase buy-in for research security policy actions.[45] More broadly, as research security policies proliferate, measures to streamline and harmonise overlapping guidelines, standards and organisational responsibilities are likely to be required. The establishment of new structures and new requirements for research security can come with a significant overhead in terms of costs and effort. Already, national governments and funding institutions face the need to clarify organisational roles and responsibilities within their own level of governance.[46] A growing interest in information clearinghouses and learning and discussion forums may signal a demand for improved policy coherence. This would not only facilitate more consistent implementation of research security policies worldwide but also reduce burden on researchers. The Dutch National Contact Point for Knowledge Security is often held up as a good example and is a collaboration between different government ministries to support anyone connected to a knowledge institute who has questions about opportunities, risks or practical matters concerning international research co-operation.[47]

Cross-government collaborations also aim to support faster and more effective risk identification and mitigation of potential threats. For example, the Korean Ministry of Science and ICT is developing a new security classification for national research and development projects to enable better monitoring of these projects according to their level of risk. The new classification system defines a new category of "sensitive research" that lies between the traditional categories of "classified" and "unclassified" research. This initiative is part of a comprehensive national Plan for Strengthening the Research Security System for the Establishment of a Trusted Research Ecosystem, which is the collaborative work of nine ministries and agencies. The partnership is also conducting consultations on research asset leakage and developing a research security field guide to support research institutions.

Effective science diplomacy also needs enhanced cross-government co-ordination, and the interface between diplomatic services, science ministries and research communities is increasingly important. Policy concerns revolve around strengthening institutional capacities and personnel skills while fostering a more strategic outlook in pursuing a range of means and ends.

Precision: Building strategic intelligence and risk assessment capabilities

For securitisation measures to be proportionate, they should be based on sound risk and opportunity identification and assessments that draw on knowledge and evidence on current and future developments of new STI and their potential impacts on the economy and society. This strategic intelligence draws on a broad range of methods, such as statistical benchmarking, forecasting and modelling, foresight, technology assessment, systems and pathway mapping, and technology monitoring and evaluation. Chapter 7 outlines several types of strategic intelligence practices that would likely prove useful, including horizon scanning and technology monitoring; situation analysis; forward-looking technology assessment; adaptive foresight; multistakeholder participation; and formative (real-time) evaluation. Such efforts should also combine and integrate different disciplines, for example expertise on research, science and higher education systems and dynamics with expertise on relevant countries and national and economic security. Such a multi-disciplinary approach is important for avoiding over-securitisation (Schwaag Serger and Shih, 2024[53]).

Different technology supply chains have different vulnerability risks, and the same applies to international science collaboration: different critical technologies have varying dual-use potential, for example, and countries differ in their capacities to exploit them. This variation points to the need for a targeted policy approach, underpinned by risk management assessments that draw on the best available evidence, as well as forward-looking analysis where uncertainties preclude traditional risk-based analysis (OECD, 2023[1]). Several initiatives are now under way to develop this knowledge foundation, but more is needed. Earlier descriptions of EU and Japanese economic security policies highlighted these sorts of activities (see Box 2.2 and Box 2.3).[48] Box 2.9 describes how Finland is similarly building capacity in cross-government technology assessment to inform its economic and research and technology security policies.

Box 2.9. Strategic intelligence for economic and research security in Finland

As a small, technologically advanced economy, Finland has benefited from open international research and innovation co-operation, which has guided its science, technology and innovation (STI) policy thinking throughout the post-Cold War era. With growing awareness of research security, Finland needs to reconsider its technological and business strengths and purposefully develop growth opportunities and international high value-added businesses. Alongside strong EU STI collaboration, membership to the North Atlantic Treaty Organization also influences Finland's STI collaboration with partners and opens export opportunities, including for the defence industry.

High-tech industries account for an important part of Finland's exports, including products and services, and depend on significant amounts of raw materials and intermediate products sourced from abroad. In late 2024, the Ministry of Economic Affairs and Employment established a Technology Policy Unit to enhance policy co-ordination, identify growth opportunities from technologies and deepen Finland's analytical capacities in this area as a part of an overall technology roadmap activity. This includes developing capabilities to generate strategic intelligence that aims to provide a better understanding of the challenges and opportunities from research and new technologies.

To improve cross-government co-ordination, the Ministry of Economic Affairs and Employment has also convened a working group on technology policy for regular exchange of views and co-ordination with relevant ministries and agencies. Together, this group will identify and discuss policy questions that require national co-operation and co-ordination (including research and technology security issues), strengthen goal-oriented technology anticipation and analytical capacity, and produce knowledge that supports STI and industrial policy steering.

Source: Based on correspondence between the OECD Secretariat and the Finnish Ministry of Economic Affairs and Employment and the Ministry of Education, Science and Culture.

In the research security area, several countries and institutions have developed guidance for risk assessment and avoidance of risk,[49] but there is less guidance on what proportionate risk mitigation and management means in different contexts. Not all risks can be identified and there are systemic vulnerabilities that need to be considered, such as in IT systems or peer review processes. Proportionality depends on priorities, resources and context. For example, some countries have developed blacklists of areas in which all scientific collaboration with specific countries or institutions is prohibited. Others are linking risk identification and management to TRLs. The advantages and disadvantages of different approaches in different contexts is an area where different countries and institutions could learn from each other.

As the field of research security continues to develop, there is recognition of the need for continuous learning to stay ahead of emerging risks and challenges. This includes understanding the latest mechanisms of foreign interference and effective strategies for mitigating risk. To address this need, various actors across the research landscape are moving to formalise continuous learning processes, in the form of evaluating policy and practice. This evaluative process is essential for refining existing policies and ensuring they remain aligned with broader R&I objectives.[50] Furthermore, to facilitate the sharing of best practices in research security, organisations at multiple levels are increasingly focused on ways to foster peer learning, including through discussion-based forums and central clearinghouses of vetted, up-to-date information and resources on threats and mitigation strategies.[51]

Science diplomacy measures would also benefit from greater use of strategic intelligence. Along these lines, the Geneva Science and Diplomacy Anticipator has proposed a Framework on Anticipatory Science Diplomacy to proactively govern and deploy scientific advances before they cause disruption or inequality, ensuring science serves humanity while navigating geopolitical competition. It does this by providing relevant actors with early insights into frontier science – by identifying and scoping out the major scientific advances with the highest potential to reshape humanity and the planet – thereby allowing sufficient time to assess and debate their long-term global implications, and avoid missed opportunities by proactively shaping innovation trajectories before crises emerge (Geneva Science and Diplomacy Anticipator, 2025[54]). The OECD's 2024 Framework for Anticipatory Governance of Emerging Technologies also provides structured guidance on how governments can embed anticipation into policy cycles, stakeholder engagement and innovation strategies, including at the international level (OECD, 2024[47]).

Conclusions

Among a wide range of types of international STI linkages, this chapter has focused on international research linkages and, specifically, the emerging securitisation of STI policy that now shapes them. Post-Cold War international STI co-operation arrangements are being reconfigured as they transition to a new era marked by growing geopolitical rivalry and intensified inter-state competition on emerging technologies. Signals of a less open international research system are already emerging: for instance, growing international co-authorship in scientific publications has been at the core of a more interconnected global research community over the last 30 years, but is now stagnating or even in decline.

While these developments present new challenges and considerable uncertainty, STI policymakers can influence the contours of an emerging landscape of international STI linkages. Using the "3Ps" framework of promotion, protection and projection introduced in the 2023 edition of the *OECD Science, Technology and Innovation Outlook*, this chapter has reported on how governments increasingly target critical technologies to promote both economic and national security; implement research security measures to protect against unauthorised knowledge leakage and coercion; and use science diplomacy policies to further their national interests and accordingly more strategically manage the international openness of their research systems.

These policies carry various risks and opportunities, and policymakers should pursue balanced STI securitisation policies that are proportional to the risks at hand, precise in their targeting, and based on partnerships with scientists and businesses, as well as across government. For example, securitisation policies for STI should weigh any restrictions against the benefits of open science and innovation; they should be evidence-based, drawing on risk assessments, future-oriented analysis such as foresight and technology assessment (see Chapter 7), and evaluation insights; and they should mobilise a diverse set of stakeholders – including scientists and innovative firms which increasingly accept the necessity of securitisation measures – to increase their chances of success.

Many of the skills and organisational capabilities needed for governments to pursue balanced securitisation policies for STI remain underdeveloped. New institutions, policy frameworks and governance arrangements will also be required but will take time to develop, sometimes through trial and error. Policies that promote dual-use research, research security and science diplomacy are often managed by a range of ministries and agencies yet are closely entwined. Governments need to develop policy tools and assessment frameworks that offer a systemic view and understanding of their portfolio of securitisation policies in STI and beyond to appreciate their synergies and dissonance and promote joined-up interventions. Despite the sensitivities of the policy area, governments should also engage in international mutual learning and benchmarking of emerging good practices among like-minded countries to co-ordinate and accelerate their national development plans and implementation progress. There is still much to learn and continued sharing of policy and practice will be needed, as will policy refinement in a fast-moving space.

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Notes

[1] The 2023 edition of the *OECD Science, Technology and Innovation Outlook* defined "securitisation" as the reframing of regular policy issues, such as climate change, migration and emerging technologies, into matters of "security". The term has a more common but unrelated use in finance.

[2] International STI linkages are wide-ranging. For example, academic researchers routinely co-operate and exchange across borders to advance shared scientific interests. Many researchers are also internationally mobile. In the private sector, innovative firms trade and invest internationally in the production of high-technology products and services. While international STI linkages can be led by states, they are more often built from the bottom-up, via individual researchers, research organisations and firms. The focus of this chapter is chiefly on research collaboration and international researcher mobility.

[3] International collaboration intensity can be measured as the number of a reference territory's publications where the set of listed affiliations includes at least one affiliation abroad, as a percentage of the total number of publications attributed to that territory.

[4] China's growing research capabilities have transformed the geography of international scientific collaboration over the last couple of decades. China's spending on R&D was second only to the United States in 2023, it has the largest number of R&D personnel globally, and it is at the forefront in many areas of science and technology.

[5] Early-career researchers – doctoral and postdoctoral – are often internationally mobile, but tracking their career paths can be difficult, particularly if they stop publishing and are no longer visible through bibliometric data. The absence of comprehensive data on career paths is not only a challenge for policymakers but also a problem for early-career researchers who want to make informed career choices. The Research and Innovation Careers Observatory (ReICO) is a joint initiative of the OECD and the European Commission. It aims to be the premier source for reliable data and information on careers in research and innovation (R&I). The project's goal is to create a dynamic information hub that tracks and

analyses trends in R&I talent, career paths, and mobility in OECD and EU countries, as well as other economies.

One of ReICO's core pillars is talent circulation. This theme focuses on the movement of R&I talent across institutions, sectors and borders. It explores career transitions and how mobility contributes to dynamic and interconnected innovation systems. ReICO seeks to improve the international comparability of data on researcher mobility by working closely with national contact points through co-ordinated annual data collections. These draw on national administrative records and survey data, complemented by international sources such as the *OECD Database on Immigrants*. In addition, ReICO will launch the ReICO Survey of the R&I Workforce, targeting individuals, to generate new insights. It will thus shed light on the patterns and dynamics of talent circulation and provide evidence to distinguish between brain drain, brain gain and brain circulation. See https://www.oecd.org/en/networks/research-and-innovation-careers-observatory.html for more information.

[6] Across OECD countries, the proportion of international students increases with the level of higher education. On average, they account for 5% of bachelor's students, rising to 15% of master's students and 25% of those in doctoral programmes (OECD, 2025[4]).

[7] See Mérat (2022[57]).

[8] Combined, the energy and environment SDGs account for approximately 28% of scientific production. The share of scientific publications that are deemed most likely to contribute to the energy and environment remained stable in the period 2008-2018. While the total number of indexed scientific publications grew steadily throughout the observed period, the share of publications relevant to the green transition stagnated through 2018 and moderately declined thereafter (OECD, 2025[6]).

[9] This section is based largely on OECD (OECD, 2025[6]).

[10] Citing the academic literature, the 2023 edition of the *OECD Science, Technology and Innovation Outlook* (OECD, 2023[1]) provided the following definitions: "'technology sovereignty' refers to a polity's capacity to act strategically and autonomously in an era of intensifying global technology-based competition. A related concept, 'strategic autonomy', is broader and refers to a polity's capacity to act independently in strategically important policy areas. It does not imply isolation or decoupling from the rest of the world, but rather describes a polity's capacity to develop and manage international relations independently. It is tied to technology sovereignty, insofar as the latter creates opportunities to compete at technological frontiers, with positive impacts on the polity's ability to influence global affairs. Countries' capacity to successfully develop, integrate and use emerging and disruptive technologies in military applications is a traditional measure of their strategic autonomy, but this capacity also applies to many commercial technologies, particularly those with dual-use potential."

[11] This chapter draws attention to four types of security and their implications for international STI linkages. The widest is global security, which includes food security, health security and environmental security, all areas where STI plays a central role. These cover many well-known global challenges, including pandemics, growing antimicrobial resistance, biodiversity loss, soil erosion and climate change. National security is traditionally associated with the military and other security forces, though broad definitions can also refer to various types of global security issues, such as pandemic preparedness. Defence-related national security strongly depends on advanced technologies, many of which are increasingly developed in the civil sector. Economic security refers to risks related to the resilience of supply chains, physical and cyber security of critical infrastructure, and the weaponisation of economic dependencies or economic

coercion (European Commission, 2023[11]; OECD, 2025[66]). It is also concerned with technology leakage. Finally, the chapter also refers to research security, which is concerned with preventing undesirable foreign state or non-state interference with research (OECD, 2022[30]). These four types of security are often complementary, but they can also be in tension and involve trade-offs, particularly with respect to international STI linkages.

[12] This chapter's focus on the research system is in contrast to the broader perspective of the 2023 edition (OECD, 2023[1]), which also covered "downstream" policy concerns, such as industry subsidies (promotion), supply chain vulnerabilities (protection), and strategic alliances and technical standards (projection). The aim in 2023 was to provide a high-level and broad overview of the growing securitisation of STI, whereas in 2025 the aim is to more closely explore the links between different policies, primarily in one part of the innovation chain (the research system); their implications for international research linkages; and the measures governments might take to ensure policies are proportional to risks and opportunities, designed in partnership with the main stakeholders, and drawing on a mix of knowledge and evidence.

[13] The OECD gathers publicly available data and measures industrial strategies across OECD countries through harmonised data on industrial policy expenditures, their composition, their mode of delivery and the characteristics of their beneficiaries. For further information, see: https://www.oecd.org/en/topics/sub-issues/quantifying-industrial-strategies.html.

[14] Mission-oriented innovation policies incorporate a similar ecosystem perspective, but with a narrower focus on fulfilling a specific mission, including technological missions (Larrue, Tõnurist and Jonason, 2024[56]).

[15] Measures like these are not just confined to OECD countries. In China, for instance, the 14th Five-Year Plan for National and Economic Social Development (2021-2025) and its underpinning Dual Circulation Strategy aim to achieve self-sufficiency in core technologies and reduce the country's reliance on foreign technologies, such as advanced semiconductors, where it has critical dependencies (OECD, 2023[1]).

[16] Funds are dispersed through the Japan Science and Technology Agency (JST) and the New Energy and Industrial Technology Development Organization (NEDO). The act also has introduced a public-private co-operation council that actively supports R&D under the K Program by sharing valuable and sometimes sensitive information related to public and private needs and technological solutions. This includes information on security incidents involving private enterprises that are held by relevant administrative organisations, which had normally not been shared with researchers due to confidentiality obligations under the National Public Service Act.

[17] This section draws widely on a keynote presentation given by Professor Andrew James (University of Manchester) to the Committee for Scientific and Technological Policy's 125th meeting on 6 November 2024.

[18] Inspired in part by the United States' success in developing productive linkages between its civil and defence technology ecosystems, China has been pursuing a Military-Civil Fusion initiative for several years. It aims to create and exploit synergies between economic development and military modernisation, and encourages defence and commercial firms to collaborate and synchronise their efforts by sharing talent, resources and innovations (OECD, 2023[1]).

[19] While the German federal government is in favour of leveraging synergies between military and civilian research, it recognises the need for a holistic approach to security that sees both promoted in a more complementary way.

[20] The EC-OECD *STIP Compass database* has outlined information on almost 400 policy initiatives from 60 countries related to the international mobility of human resources. See: https://stip.oecd.org/stip/interactive-dashboards/themes/TH55.

[21] Furthermore, several countries have constitutional or other legal provisions regarding academic freedom and the institutional autonomy of universities.

[22] The thematic portal on research security in the EC-OECD STIP Compass provides a unique window into research security policy initiatives worldwide. The portal enables mutual learning across countries, focusing on the types of policy instruments countries are deploying and the specific policy concerns they seek to address. As of 2025, the portal contains information on 261 research security policy initiatives from 41 countries. Following the STIP Compass policy taxonomy, the top three policy instruments reportedly used are public awareness campaigns and other outreach activities; strategies, agendas and plans; and science and technology regulation and soft law.

[23] These initiatives often involve the creation of dedicated offices or units with mandates to oversee research security policy. They centralise responsibility and expertise for research security, potentially allowing more consistent policy development and enforcement. For example, the Office of the Director of the National Science Foundation (NSF) established in 2023 the new Office of the Chief of Research Security Strategy and Policy, which is responsible for co-ordinating all research security policies across the NSF. Its responsibilities include: identifying and addressing potential risks to the research enterprise; developing policy and best practices; conducting outreach and education; communicating reporting and disclosure requirements; establishing policies to ensure compliance; and, importantly, conducting due diligence on applications for NSF awards (US Senate Committee on Commerce, Science, & Transportation, 2022[58]). Organisations with similar remits are also being created at universities and research institutions, in the United States and elsewhere. For example, in a research security survey conducted in 2023 by the Korean Ministry of Science and ICT, nearly half of the more than 90 Korean research institutes that responded had a dedicated body for research security (Presidential Advisory Council on Science and Technology, Korea, 2023[62]).

[24] This list-based approach is complemented by a broader risk assessment approach requiring general due diligence on research projects (including beyond the scope of the list), as per the complementary policy entitled the National Security Guidelines for Research Partnerships. It is also notable that the Canadian policy does not identify specific countries, but rather focuses on the risk profile of individual research organisations, only prohibiting affiliations with those that are assessed to pose the highest risk to Canada's national security (Innovation, Science and Economic Development Canada, 2024[35]).

[25] The German Research Foundation underlines that individual and institutional applicants wishing to co-operate with international partners need to explain the potential risks and benefits of the collaboration, with more detailed justifications typically required for projects with greater risks or appearance of risks (German Research Foundation, 2023[59]). The German Science and Humanities Council published a position paper on “Science and security in times of global political upheaval” (German Science and Humanities Council, 2025[65]), which gives recommendations for dealing with knowledge risks in order to protect and build a resilient society. While the recommendations by the German Science and Humanities Council and the German Research Foundation are country agnostic, the Max Plank Society and the

German Academic Exchange Service have published specific papers regarding interaction with China. The Max Plank Society emphasises the need for mutual understanding and a culturally sensitive approach for sound decisions and balanced co-operation with China (Max Planck Society, 2023[60]). According to the German Academic Exchange Service's recommendations, interaction with Chinese partners should be interest-oriented, risk-aware and competence-based (German Academic Exchange Service, 2024[61]).

[26] TRUST applies a decision tree for assessing research proposals and ongoing projects regarding personnel appointments and research support, non-compliance with disclosure and other requirements, and potential risks to national security. See National Science Foundation (National Science Foundation, 2024[63]).

[27] For further details, see: https://www.jst.go.jp/osirase/research_security/index_e.html. More broadly, the policy discussion on research security in Japan surged in 2024 during economic security policy discussions (e.g. the National Security Secretariat's expert panel on countermeasures against leakage of critical technologies). Following this, the Ministry of Education, Culture, Sports, Science and Technology issued its Report on Approach for Ensuring Research Security at Universities in December 2024 https://www.mext.go.jp/content/20250423-mxt_kagkoku-000019002_2.pdf). The CSTI Secretariat Expert Panel launched discussions to develop research security guidelines in April 2025.

[28] For instance, examples featured on UNESCO's webpage on science diplomacy [https://www.unesco.org/en/scientific-research-cooperation-why-collaborate-science-benefits-and-examples] include CERN in Switzerland, the International Centre for Theoretical Physics in Italy and SESAME in Jordan. UNESCO has also published in 2025 its report, *Science diplomacy in a rapidly changing world: Building peace in the minds of men and women* (UNESCO, 2025[69]).

[29] The growing popularity of the science diplomacy concept has led to some dilution of its meaning. As noted by the Geneva Science Diplomacy Anticipator (2025[54]), its transdisciplinary nature has made science diplomacy attractive across academic, policy and diplomatic communities, but also prone to being used as a catch-all label for any initiative involving international science collaborations, even when these lack strategic intent or demonstrable impact on foreign policy or international governance. The proliferation of the concept risks obscuring this important distinction, underscoring the need for clearer frameworks to ensure science diplomacy remains purpose-driven, coherent and impactful.

[30] The uneven distribution of research infrastructure capacities at the global level prevented equitable access to resources and data in many parts of the world during the COVID-19 pandemic, contributing to a disconnect between needs and resources. OECD country research funders recognised the problem, allocating around USD 200 million globally for COVID-19 projects that aimed to strengthen research capacity in LMICs, most of which focused on reinforcing laboratory capacity. Such a strengthening of research capacity can be an important contribution to health-crisis preparedness, but needs to be extended to provide effective global action for other ongoing and future challenges (OECD, 2023[1]).

[31] For further information, see: https://www.gov.uk/world/organisations/uk-science-and-innovation-network.

[32] For example, more information on Microsoft's work with the United Nations and international organisations can be found at: https://www.microsoft.com/en-us/corporate-responsibility/united-nations.

[33] For further information, see the Office of Denmark's Tech Ambassador at: https://techamb.um.dk/the-techplomacy-approach.

[34] For further information, see: https://www.eeas.europa.eu/delegations/united-states-america/san-francisco_en?s=253.

[35] For further information, see: https://swissnex.org/about-us/mission-and-organization.

[36] The European Economic Security Strategy (see Box 2.2) also identifies proportionality and precision as fundamental principles for any measures on economic security (European Commission, 2023[11]).

[37] Open science is a policy priority for all OECD countries. The EC-OECD *STIP Compass database* provides a window into how different countries are responding at the national policy level to promote open science. Its STI policies for Open Science portal provides information on close to 700 policy initiatives from more than 60 countries and the European Union and is regularly updated. While the information is certainly not fully comprehensive for all countries, it does provide a meta-view of where countries are focusing their efforts and, at the level of individual initiatives, provides access to summary information and links that are a valuable starting point for those who want to delve further. The portal also provides ready access to published reports and articles relating to open science policy from the OECD, other international organisations and relevant public repositories.

[38] Emerging frameworks suggest potential paths forward to promote complementarities between research security and open science. For example, in its 2023 Research Security System Improvement Plan, Korea notes that it must continue to promote international co-operation to drive innovation, even while adopting research security management strategies. A 2024 JASON report formalises this intuition by suggesting that technology maturity – as measured through the TRL framework – can guide institutions' decisions on when imposing additional controls, versus maintaining openness, might best support national security (broadly defined to include economic security). The authors suggest that while potential national security issues may be apparent as early as fundamental research stages (TRLs 1 and 2), it is not until technologies reach the pilot and demonstration phase (move from TRLs 5 to 6) that their actual significance to national security can be demonstrated and warrant substantive mitigation efforts (JASON, 2024[55]).

[39] For example, Finland's Constitution secures university autonomy. When ensuring research security, a researcher's right to choose their research topic and methods cannot be restricted. This means that the applicants for Research Council of Finland funding need to take research security into account as part of the application for research funding. For this reason, the Act on Research Council of Finland was amended in May 2025 to include a paragraph on research security. The aim is to encourage research-performing organisations to identify potential risks and threats related to security in advance. The Research Council's task is to ensure that due consideration be given to research security and to the risks associated with it in research projects, research co-operation and the use of research results.

[40] For instance, at the multilateral level, the European Union's *Council Recommendation on Enhancing Research Security*, adopted in May 2024, was developed with significant input from R&I stakeholders. The result has been a strongly positive reception from key associations such as the League of European Research Universities, an association of 24 leading research-intensive universities in Europe (see: https://www.leru.org/news/leru-welcomes-proposals-for-more-secure-research-in-the-future). At the national government level, Korea's recent efforts to develop its comprehensive Plan for Strengthening the Research Security System for the Establishment of a Trusted Research Ecosystem not only engaged 14 universities with industry-academia co-operations (OECD, 2023[68]) but it also linked to the Research

Security Advisory Committee, composed of research experts and security experts (see: https://www.msit.go.kr/bbs/view.do?sCode=user&mId=113&mPid=238&bbsSeqNo=94&nttSeqNo=3183414).

[41] For further information, see: https://www.aaas.org/programs/center-science-diplomacy/about.

[42] For further information, see: https://www.science-diplomacy.eu.

[43] For further information, see: https://diplomaciacientifica.org.

[44] For further information, see: https://www.africasciencediplomacy.org.

[45] For example, Germany is currently working on developing a strategic approach that connects the constitutionally protected freedom of science with German security and economic interests while maintaining a culture of enabling reciprocal international research co-operation with reliable partners. The German Federal Ministry of Education and Research (known since May 2025 as the Federal Ministry of Research, Technology and Space) has initiated a national process bringing together stakeholders from the scientific community, the federal ministries and governments of the Länder, industry, and intelligence services. The aim of the ongoing process is to develop a common understanding on research security and essential measures to improve the status quo.

[46] For example, the Australian Research Council's Foreign Interference and Security Risk Internal Audit identified one of the highest priority gaps as being the absence of an overarching framework clarifying different actors' roles and responsibilities (https://www.arc.gov.au/funding-research/research-security).

[47] For further information, see the National Contact Point for Knowledge Security, Ministry of Education, Culture and Science, at: https://english.loketkennisveiligheid.nl.

[48] For example, in 2023 the European Commission published a recommendation on critical technology areas for the European Union's economic security (European Commission, 2023[64]). It has also set up a Critical Technologies Observatory which identifies, monitors and assesses critical technologies for the space, defence and related civil sectors and their potential application and related value and supply chains. It also monitors and analyses existing and predictable technology gaps, the root causes of strategic dependencies, and vulnerabilities. Based on these data, the European Commission prepares a classified report for member states on critical technologies and risks associated with strategic dependencies affecting security, space and defence every two years. It also prepares technology roadmaps based on these reports, which include mitigating measures to boost research and innovation and reduce strategic dependencies affecting security and defence (European Commission, 2025[67]).

[49] For example, the NSF Office of the Chief of Research Security and Policy released its *Guidelines for Research Security Analytics* in 2023 to support the implementation of its congressionally mandated role. This includes performing risk assessments of NSF proposals and awards using analytical tools to assess non-disclosures of required information. These guidelines include a breakdown of which agency personnel may conduct research security-related activities, what monitoring activities are allowed and with what resources they are conducted, how information will be validated to ensure accuracy, and how information may be shared within the NSF and externally. This level of specificity not only clarifies roles within the NSF but also sets a standard for accountability in research security.

[50] For example, in the United States, the NSF has launched the Research on Research Security Program to assess the methods for identifying research security risks and strategies for preventing and mitigating them. The programme seeks to better understand the nature, scope, challenges and potential of this field – including the critical areas of cybersecurity, foreign travel, research security training and export control training – with the aim of informing best practices and guidance for the research community. For further information, see: https://new.nsf.gov/news/nsf-announces-research-research-security-program.

[51] The NSF has also announced a 5-year USD 67 million investment to establish the Safeguarding the Entire Community of the US Research Ecosystem (SECURE) Center, an information clearinghouse. The SECURE Center will disseminate information and reports on risks of foreign interference, provide research security training to relevant communities, and serve as a bridge between the research community and government funding agencies on security concerns. For further information, see: https://new.nsf.gov/news/nsf-backed-secure-center-will-support-research.

3 Expanding the benefits of investments in science, technology and innovation

This chapter discusses the importance of broadening the benefits from and participation in innovation across different social groups, regions and industries. It discusses how the particular challenges facing science, technology and innovation (STI) policymakers in 2025 – accelerating frontier technology development, building resilience and improving sustainability – interact with the channels through which the benefits of innovation are distributed. It concludes by identifying key implications for STI policymakers.

Key messages

- **Long-standing challenges, changing contexts.** Many of the participation and inclusion challenges facing science, technology and innovation (STI) policy in 2025 – such as underrepresentation, concentration of opportunity and the importance of diffusion – echo patterns observed throughout the history of technological change. While the participation imperative is not new, the evolving context of rapid technological shifts, geopolitical competition and urgent societal challenges makes it even more vital for policymakers to address barriers that have persisted across past transformations.
- **Innovation is inherently concentrated, but broader benefits require deliberate diffusion efforts. Innovation activities naturally cluster among leading firms, sectors and regions due to economies of scale and knowledge spillovers. However, translating these concentrated innovations into economy-wide productivity gains and societal benefits requires dedicated policies and investments in diffusion mechanisms.**
- **Broadening participation is a key lever for expanding innovation benefits. Beyond the diffusion of existing technologies, widening who participates in creating and shaping innovation directions can enhance both the quality and societal relevance of technological development while ensuring benefits reach more diverse populations.**
- **Regional and industrial concentration shapes inclusion opportunities.** Innovation activities are highly concentrated among leading firms, sectors and regions, creating uneven opportunities for participation and benefit. Workers in highly innovative environments have greater access to high-value jobs and career advancement while those in lagging areas face limited prospects.
- **STI policies may face trade-offs between excellence and inclusion**. Policies directly promoting participation and those supporting centres of excellence for reasons of expediency play important roles for STI policies. What is key for the STI policy mix is supporting frontier advancement while facilitating broad-based access to benefits and participation.
- **Co-ordination across policy domains is essential.** Persistent participation gaps despite targeted STI interventions demonstrate that achieving inclusion requires co-ordinated action across education, labour market, social and regional development policies. STI policies alone cannot address deep-rooted structural barriers and need to be co-ordinated with other policy domains.

Introduction

Technological innovation and diffusion significantly improve people's lives across and beyond the OECD. Whether through improvements in labour productivity, the quality of and access to medical and educational services, or in ensuring stable and affordable access to energy, technological innovation and diffusion can be significant forces for positive economic, societal and environmental progress. As policymakers increasingly direct STI investments toward strategic objectives – competitiveness, resilience and sustainability – this chapter examines why and how ensuring their broadly distributed benefits has become essential for policy success.

Broadening the participation in and widening the benefits from innovation have been recurring themes in international STI policy discussions, including in the 2018 and 2021 editions of the *OECD Science, Technology and Innovation Outlook* (OECD, 2018[1]; 2021[2]; Paunov and Planes-Satorra, 2021[3]). These discussions underscore the point that wider participation in technological innovation and diffusion not only enhances economic outcomes but can also improve the quality and societal relevance of innovation itself. While these insights remain valid for 2025 and beyond, policymakers face new challenges arising from emerging trends in STI.

The first challenge is the post-COVID increased focus in directed STI policies addressing strategic imperatives such as technological resilience and competitiveness (OECD, 2024[4]; Paunov and McGuire, 2022[5]). While this strategic focus is essential for national competitiveness, the risk is that the urgency and scale of these investments may inadvertently reinforce existing patterns of concentration. When finite public resources are rapidly deployed to achieve technological breakthroughs, they often flow to established centres of excellence – leading research institutions, flagship companies and innovation hubs – that can deliver results quickly, potentially widening gaps with other regions and actors unless accompanied by parallel investments in diffusion and capacity building.

The second consideration is that the vast majority of employment across the OECD is in low or medium innovation-intensive sectors, including those such as healthcare and education, where technological diffusion could significantly improve productivity and social outcomes. It is therefore important to ensure that efforts to push the technological frontier do not impede efforts to accelerate the diffusion of technological innovation where uplifts from productivity could be both economically and socially significant.

The third consideration is that innovation-intensive manufacturing industries face the dual challenge of adopting digital and low-carbon technologies simultaneously, creating a temporal challenge for firms and workers in those industries to contribute to and benefit from technological innovation.

The fourth consideration is that market concentration dynamics in some innovation-intensive sectors may affect the distribution of innovation opportunities and benefits. Understanding these dynamics and their implications for STI policy design requires policy attention and potential co-ordination with other policy domains (OECD, 2024[6]; 2023[7]).

These dynamics suggest several areas where STI policymakers can take action:

- Strengthening diffusion policies to broaden participation in and benefits from technological innovation, revisiting best practices from technological, regional and sectoral diffusion initiatives for the contemporary context.
- Embedding strategic reflections in the policy design process on how the strategic agenda-setting for STI may impact participation in and benefits from publicly funded STI, and how policymakers in STI and other policy areas could address the economic and social implications of these impacts.
- Better understanding of the relationship between competition and technological innovation and diffusion, both within and across economies.

This chapter begins with a brief overview of the differentiated and at times lag effects of technological innovation and its diffusion through history. It then proceeds with a discussion of a simplified framework to clarify how participation in innovation affects the direction of technological progress and the distribution of its outcomes. The chapter then discusses how participation in technological innovation and its diffusion interact with the imperatives facing STI policymakers today, such as competitiveness and resilience. It then outlines some of the key channels through which the framework set out could inform STI policy in 2025 and the years ahead. The chapter concludes with some overarching considerations for policymakers as they consider the importance of broadening the participation in and benefits from technological innovation as they design and implement STI policies in the years ahead.

Why should policymakers care about broadening participation in science, technology and innovation?

The transformative changes currently underway, including the digital and green transitions, share critical characteristics with transformative technological changes throughout history, particularly in how they create concentrated benefits during development phases and uneven diffusion patterns that can limit the ability of all sectors of the population to benefit. Historical analysis of major technological transitions, notably the First Industrial Revolution (1760-1840), reveals persistent patterns where the benefits of breakthrough innovations initially concentrate among those with access to capital and technological infrastructure while broader societal gains emerge only through deliberate diffusion mechanisms and often significant social and political intervention (Acemoglu and Johnson, 2024[8]; 2023[9]; Hobsbawm, 1962[10]).

The mechanisation of British textile production, for instance, demonstrates how technological advancement can simultaneously drive productivity growth while displacing entire categories of skilled workers – handloom weavers saw their real wages more than halve between 1806 and 1820 as power looms replaced traditional craftsmanship, illustrating the stark short-term distributional consequences of technological change (Feinstein, 1998[11]; Voth, 2003[12]).

What distinguishes contemporary digital and green transitions from earlier technological revolutions is not just their speed and scope, but the recognition that broad-based and widely shared benefits from innovation are neither automatic nor guaranteed. Unlike previous eras where distributional consequences were often treated as inevitable byproducts of progress, today's transitions occur within policy frameworks that explicitly acknowledge the need for participatory approaches to technology development and diffusion.

The evidence from historical transitions suggests that without deliberate intervention, technological progress can create persistent inequalities, even after decades of economic growth. Improvements in living standards for displaced workers during the Industrial Revolution were minimal and required sustained social and political action to materialise (see Feinstein (1998[11]); Allen (2007[13]); or Acemoglu and Johnson (2024[8])). This historical perspective underscores why current policy debates around frontier technologies like artificial intelligence (AI), quantum computing and clean energy systems must simultaneously address the concentration of development capabilities and the mechanisms for ensuring broad-based access to the benefits of technological progress.

The framework that follows in this chapter builds on these historical insights to distinguish between development dynamics, which determine who participates in innovation processes and where innovation capabilities concentrate, and diffusion dynamics, which shape how innovations spread across different populations, regions and economic sectors over time. Understanding this distinction is crucial for contemporary STI policy, as the evidence suggests that addressing inclusion challenges requires different approaches at the development stage (where the focus is on broadening participation in frontier research and innovation) versus the diffusion stage (where the emphasis shifts to ensuring widespread adoption and benefit-sharing across diverse communities and regions).

How does technological innovation impact society, and how does broader participation in innovation affect the direction of technological innovation?

There are two key dimensions for understanding how technological innovation interacts with socio-economic outcomes. The first is to consider how the development and diffusion of new technologies affects the outcomes of different groups, and the skills and capacities they may require to benefit from these technologies. The second is to consider how participation in the development of technological innovation affects the direction and quality of that innovation. These two dimensions interact in ways that affect the inclusiveness of the gains from innovation (e.g. better health outcomes, better education access, higher productivity) and the alignment of innovation with social needs.

These outcomes are how different groups in society benefit from new technologies and innovations in the following ways (Figure 3.1):

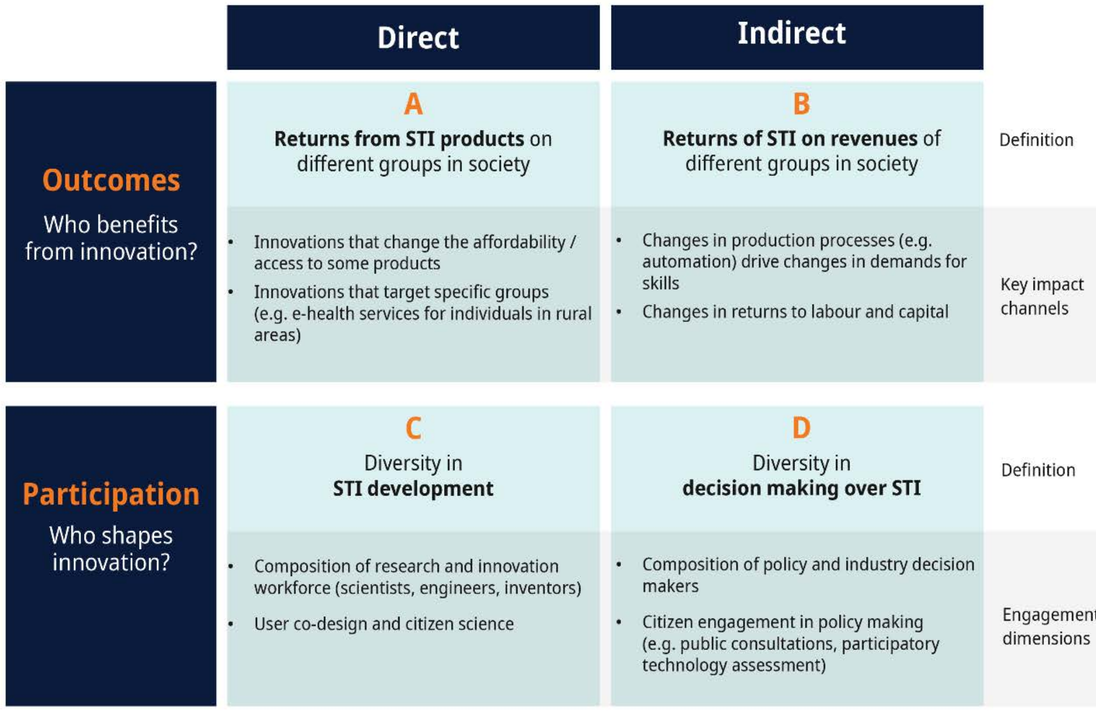
- *Direct impacts* [quadrant A]: Different socio-economic groups may benefit differently from new technologies and innovations. Several conditions determine access to the benefits of innovation, including price, geographic availability, required infrastructure, user capabilities (such as digital or technical skills) as well as the very purpose of the innovation, which may cater to the needs of specific groups of the population. Social innovations are a specific sub-set of innovations aimed at addressing unmet social needs – particularly those affecting marginalised or underserved groups.
- *Indirect impacts* [quadrant B]: Wider economic and social impacts accrue indirectly by affecting returns to labour and capital impacted by innovation and technology. Changes in production processes driven by innovation, such as automation and the wider application of AI in production, can alter demands for skills or capacities and affect demands for different types of assets (capital, land, etc.). Moreover, technological progress can change the relative returns to labour and capital (see Autor et al. (2017[14]) and Guellec and Paunov (2017[15]) for a discussion).

Participation refers to the opportunities that different groups in society have to shape technological progress in the following ways (Figure 3.1):

- *Direct participation* [quadrant C]: Individuals can engage directly in the design and development of technology and innovation by being part of the research and innovation workforce. Such engagement requires having specialised skills and capacities, which vary depending on the types of activities undertaken. Beyond professional research and innovation roles, citizens more generally can engage in a myriad of other ways, ranging from weak engagements, such as providing user feedback that influences product development, to more substantial involvement, like contributing to open-source and citizen science projects (OECD, 2025[16]).
- *Indirect participation* [quadrant D]: Individuals may also engage indirectly in shaping innovation and technology development by participating in industry or policy decision-making processes (e.g. taking key investment decisions, shaping institutional choices over adoption); engaging in public consultations, participatory technology assessment or participatory research agenda-setting exercises influencing the directions of public or private choices on innovation and technology; and, more passively, shaping demand.

The relationship between innovation and inclusion can, therefore, be explored through four dimensions, as illustrated in Figure 3.1.

Figure 3.1. Four key dimensions of participation in innovation and its outcomes



What are the implications for science, technology and innovation policy today?

Building on the historical context and framework from the previous section, this section examines how participation dynamics interact with today's STI policy imperatives. Key priorities policymakers face in 2025 include accelerating the development of strategic technologies, navigating green and digital transitions while ensuring competitiveness, enabling broad-based diffusion to meet productivity needs, building consensus around STI directions, and operating with agility amid fiscal constraints. Where possible, evidence from gender, regional and industrial participation is provided to illustrate these dynamics.

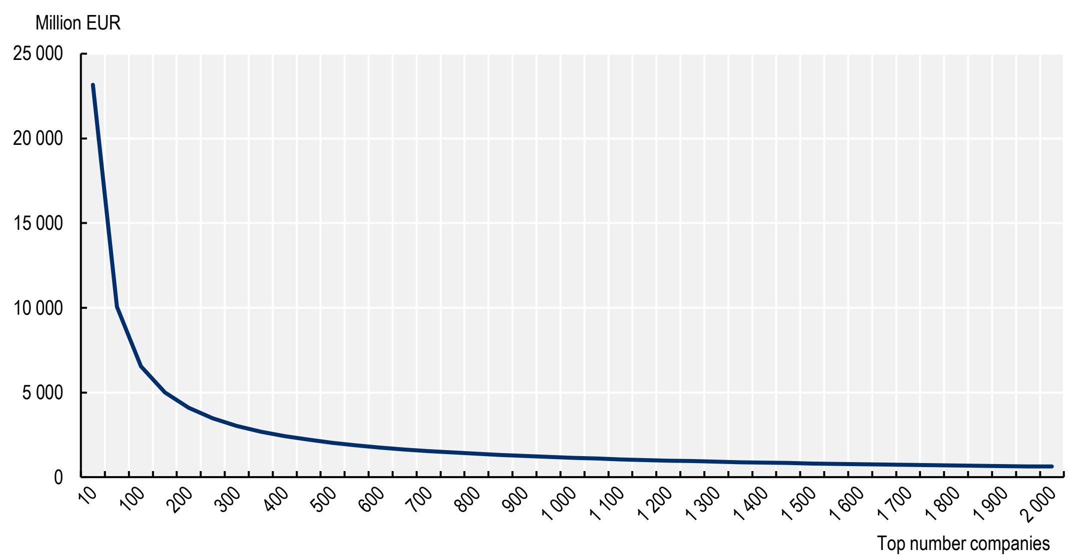
Navigating excellence and inclusion in an era of strategic competition

This subsection addresses how the framework's distinction between outcomes and participation – across both direct and indirect channels – plays out at the frontier of STI policy. Frontier-oriented investments and "directional" STI policies are intended to deliver significant economic and technological gains, but they risk concentrating both the direct benefits (A: who reaps the returns from new STI products) and the indirect structural effects (B: who benefits from changing skill and capital demands) among established actors. Frontier-oriented STI investments thus face a resource allocation challenge: directing finite budgets toward established centres of excellence – which may be entirely rational for achieving rapid breakthroughs – can inadvertently concentrate both innovation returns and structural benefits among already capable actors. This creates tension between the immediate imperative to develop strategic technologies and the broader goal of ensuring widespread access to innovation benefits, particularly when existing diffusion mechanisms are already strained.

The rapid pace of digital and green transitions, combined with intensifying geopolitical competition around frontier technologies, has fundamentally altered the policy landscape for STI systems. Major economies have launched significant directed investments – such as the European Union's European Chips Act – that aim to build capabilities in AI, quantum computing, semiconductors and clean energy technologies. These policies reflect a new era where STI policy is increasingly "directional", pursuing specific mission-oriented objectives while navigating complex trade-offs between technological leadership and inclusive participation (Arnold et al., 2023[17]; Larrue, 2021[18]; Mazzucato, 2018[19]; OECD, 2024[4]).

A variety of metrics show that technological innovation is already highly concentrated at the firm, sectoral and regional levels. For evidence at the firm level, data on top research and development (R&D) investors show that the top 100 companies (in terms of R&D investments) account for around a striking 50% of global R&D in 2023 (Figure 3.2) There is also significant concentration within that group of top R&D investors: on average, the top 10 companies invested more than double the amount than the top 50 (including the top 10), and the top 50 invested on average over 50% more than the top 100. Top R&D investors also account for an important part of national R&D.

Figure 3.2. Average R&D investments of the top global 2 000 companies, 2023



Source: European Commission: Joint Research Centre, NINDL, E., NAPOLITANO, L., CONFRARIA, H., RENTOCCHINI, F., FAKO, P., GAVIGAN, J. and TUEBKE, A., The 2024 EU Industrial R-D Investment Scoreboard, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/9892018, JRC140129.

StatLink https://stat.link/rm5gnt

Innovation is also geographically concentrated in a limited set of "innovation leader" regions across OECD countries, which collectively generate the bulk of national R&D and scientific output. While such a concentration can encourage economies of scale and knowledge spillovers, persistent innovation leadership and a decline in entry and job reallocation rates signal rising barriers to new entrants. However, this concentration pattern may be evolving in frontier technology areas: in fields like AI and quantum computing, smaller firms such as OpenAI, Anthropic and specialised quantum start-ups are driving significant breakthroughs alongside established tech giants, suggesting that technological disruption can still create opportunities for new entrants to challenge incumbent advantages.

In the context of public support for frontier technology development, the question for policymakers is to what extent the pursuit of research excellence and support for pre-existing clusters with strong capacities reinforces these concentration dynamics, and what are the implications of that concentration? When governments allocate finite resources to leading firms, research institutions and regions that already possess established capabilities, they may achieve technological breakthroughs more efficiently but risk widening gaps with lagging actors (quadrants B and C in Figure 3.1). For instance, while progress in AI and automation may benefit those with complementary skills and capital assets, it can simultaneously reduce returns to routine labour and concentrate benefits in technologically advanced regions. The challenge for policymakers is determining when such concentration is a necessary short-term cost for long-term competitiveness and when it creates structural barriers that ultimately undermine innovation system resilience.

Concentrating resources in frontier technology development can be a highly effective strategy, especially when leading firms, industries and research institutions – often clustered in specific regions – already possess strengths that policies can leverage. In a globally competitive environment, building on these existing capabilities may offer the best chance for success. Spreading resources too broadly can dilute their impact, resulting in well-intentioned but ultimately ineffective outcomes. Furthermore, technological diffusion may occur over time through market forces, collaboration and talent mobility. They also depend on whether the effects of concentration are temporary or long-lasting, i.e. whether frontier developments will eventually lead to improved outcomes that spread more broadly across society over time.

The downside, however, may be a widening gap with those already lagging behind, challenging also the wider diffusion of frontier technologies, which in turn can reduce possibilities for their further development as demand and user experiences play important roles in shaping innovation pathways. The allocation of limited public resources to firms and institutions that already have well-established capabilities may further reduce possibilities for others to participate in frontier technology development and benefit from its diffusion.

Recent OECD work has widely discussed tension between concentration (which may promote excellence and rapid technological development) and inclusion. The OECD's Industrial Policy Framework demonstrated that effective industrial strategies must balance productivity growth with addressing societal challenges, including inclusion, through co-ordinated approaches that address complementarities between different policy instruments (Criscuolo, Gonne and Lalanne, 2022[20]). Recent OECD analysis shows that industrial policies increasingly target societal goals, with green transition objectives comprising 18.6% of national STI strategies, followed by social and regional inclusion at 9.9% (Paunov and Einhoff, 2025[21]).

The potential unintended negative impact of these STI policies (as well as the above-mentioned frontier technology policies) on broader participation does not imply that they should not be pursued, as they address other important policy priorities – such as economic competitiveness, resilience and national security. Strategies that support frontier technology development are an example of the many rationales justifying STI policy. From a Schumpeterian perspective, technological change inherently involves disruption and renewal, and OECD countries have well-established social policy frameworks that can help mitigate the social and regional impacts of such transitions. The key point is to recognise that technology policy choices are not neutral, and that they have an impact on the distribution of wealth, income and opportunities across firms, industries and places (and ultimately individuals) well into the future. The other key insight is that there is a role for STI policy to complement other efforts in shaping the nature of transitions.

From development to diffusion and adoption: The need for policy differentiation

The relationship between knowledge creation (quadrants C and D in Figure 3.1, who participates in and shapes STI development and governance) to widespread technology adoption and benefit-sharing (quadrants A and B in Figure 3.1, who directly and indirectly gains from STI products and changing economic returns) reveals distinct yet interdependent policy challenges. Effective STI systems require not only excellence at the frontier, but also robust, inclusive mechanisms for diffusion, ensuring diverse actors have the capacity and opportunity to participate in innovation and be able to enjoy its benefits.

Frontier-oriented STI policies now face a double mandate: continue pushing the technological boundary and consider how diffusion and adoption policies can be integrated into these policies. Recent OECD evidence on AI adoption shows why this matters: uptake is still twice as high in large firms and advanced regions as in smaller firms and peripheral areas, owing to scale-dependent fixed costs, data requirements and superior absorptive capacity (OECD, 2024[22]).

Effective adoption of innovation is essential for ensuring that the benefits of new technologies reach a broad swathe of society and the economy but is hindered by highly uneven spatial and sectoral innovation activity. Workers in “leader” firms, sectors and regions consistently achieve higher wages and revenues, while those in “laggard” environments capture fewer gains. For example, patenting is overwhelmingly concentrated in large urban areas, with 90% of patent applications coming from urban inventors and large urban regions having significantly higher patenting rates than medium-sized or smaller areas (OECD, 2024[23]).

This reflects both the structural advantages of co-location and the cascading disadvantages faced by less connected or less innovative regions. Moreover, increasing entrenchment among market leaders, as seen in the declining rates of firm entry and job mobility, limits the spread of new technologies to lagging places and firms. Addressing these challenges requires targeted policy interventions – such as improving infrastructure and connectivity, advancing skills development in underperforming areas, and supporting technology adoption in small and medium-sized enterprises (SMEs) – to facilitate broader and more equitable diffusion and participation throughout the innovation system.

The push to align economic competitiveness with sustainability presents its own particular diffusion challenges. The evolution of labour and skill demands in emerging sectors, such as the move to electric vehicle production, requires new competencies not always possessed by workers in sunset industries (Curtis, O’Kane and Park, 2023[24]). If skills development and retraining lag behind technological change, this transition may end up benefiting only a narrow pool of workers in specific regions or firms. STI policy must, therefore, link innovation support to strategic workforce development and ensure that knowledge, infrastructure and market opportunities reach participants beyond traditional innovation leaders, including those in less advantaged sectors and places.

Policy design has to distinguish between two separate bottlenecks. Knowledge diffusion determines who can join the inventive process while technology adoption decides who can turn new ideas into social and economic value. Because the obstacles differ, skills and research networks on the one hand, data readiness, finance and managerial know-how on the other, each stage needs its own toolkit. Capacity building must simultaneously broaden participation in technology creation and equip diverse regions, sectors and communities to adopt innovations at scale.

Diffusion policies, whether embedded in technology frontier programmes or deployed in parallel, are the main lever for widening the benefits of and participation in STI; Table 3.1 shows examples of relevant diffusion policies. They only work when actors possess sufficient absorptive capacity, i.e. the ability to spot, absorb and apply external knowledge. Investing in those capacities is thus essential to share the gains from innovation more equitably, including across borders. For developing economies, building such capabilities is a prerequisite for meaningful engagement in global STI systems.

Translating this into practice poses a governance challenge: responsibilities for funding and decision making must be split judiciously between national and subnational authorities so that national strategic aims align with regional strengths and opportunities. Regional policymakers, in particular, need diagnostic tools to see where their ecosystems can credibly participate in strategic, frontier-technology domains.

Survey data from the G7 and Brazil (OECD, 2025[25]) reveal that diffusion frictions – acute skill shortages, low data maturity and uncertainty over returns – now trump simple awareness gaps. Firms rate three policy responses the highest:

1. modernised qualification frameworks plus hands-on, sector-specific training
2. higher quality, easily accessible public data

3. streamlined collaboration with universities and dedicated diffusion agencies.

Although dedicated technology diffusion agencies are well regarded, they currently serve only a minority of firms, underscoring the need for scalable sign-posting services, SME-oriented vendor-selection guidelines and clear accountability frameworks for safe AI use. Comparable international surveys and rigorous evaluation of these agencies are critical to identify and share what works.

Table 3.1. Examples of science, technology and innovation diffusion policies

Regional STI and development policies for lagging regions
Definition: Targeted programmes that aim at strengthening the innovation capacities of regions, especially those with lower economic or technical performance.
Examples: In European Union countries, Smart Specialisation Strategies aim at boosting regional economic transformation by supporting the unique strengths and competitive advantages of each region. In Germany, the Structural Development Act supports coal-mining regions' transition towards more sustainable economic activities and high-quality jobs.
Technology diffusion and adoption policies
Definition: Policy measures that aim to foster widespread adoption of technologies in firms, often focused on small and medium-sized enterprises (SMEs) and less competitive industries and regions.
Examples: Grants or subsidies for the adoption of digital technologies in firms, specially SMEs (e.g. Support Programme for Digital Innovation Hubs in Spain); demand-side policies that encourage and/or create incentives for the adoption of low-carbon technologies (e.g. the proposed use of contracts for difference in the EU Hydrogen Strategy, which can facilitate the adoption of low-carbon technologies and fuels in hard-to-abate industries and support their future competitiveness).
Policies supporting collaboration and co-creation among diverse actors
Definition: Initiatives that encourage and derisk joint research and innovation among diverse actors – including SMEs, large firms, research institutions and sometimes government – with a view to co-developing and commercialising new technologies.
Examples: The United Kingdom's Advanced Propulsion Centre, supporting collaborative research and development (R&D) for low-carbon vehicle technologies; Canada's Next Generation Manufacturing Cluster, promoting joint innovation in advanced manufacturing; and Germany's Clusters4Future initiative, bringing together all stakeholders in the development of new value chains.
Policies supporting international diffusion
Definition: Policy measures that aim to support the international diffusion of knowledge and technology to developing countries. These often include support for participation in international scientific networks; science, technology and innovation (STI)-focused official development assistance; and voluntary technology transfer on mutually agreed-upon terms.
Examples: Korea's Science and Technology ODA Programme, supporting developing and less developed countries in strengthening their STI capacities and social well-being, and its International Cooperation Programme in S&T, a broader initiative managed by the National Research Foundation of Korea to promote international STI collaboration and mutual capacity building; and Japan's Science and Technology Research Partnership for Sustainable Development promoting international joint research with developing countries by combining official development assistance and science and technology to tackle global challenges, and enhancing international STI co-operation by boosting self-reliant R&D capacity, strengthening research networks, and training future talent in both Japan and partner countries.

Sources: European Commission (2025[26]), APC (2025[27]), NGen (2025[28]), Federal Ministry for Economic Affairs and Energy (2025[29]), Japan Science and Technology Agency (2025[30]) , EC-OECD (2025[31]).

Broadening participation in and the benefits from research and innovation

If policymakers want the benefits of the development and diffusion of technologies to be truly broad-based and shared, STI policies need to dramatically accelerate efforts to address participation imbalances. While this subsection focuses on gender as a salient lens, the structural and systemic challenges described here apply – often with added complexity – to other groups that face barriers, such as people from lower income backgrounds, minority groups and regions that have undergone significant deindustrialisation.

Over the past decade, women's participation in STI has notably increased, although gaps persist. Globally, the share of 25-34-year-olds with tertiary education rose from 23% to 27.5% between 2013 and 2021, and in OECD countries from 45.6% to 53.7% (OECD, 2024[32]), outpacing men in both cases. Yet this progress masks persistent disparities in key fields. In 2021, just one-third (32.5%) of graduates in science, technology, engineering and mathematics (STEM) were women, up only marginally from 31% in 2013. Representation varies sharply by discipline: women make up a slight majority in natural sciences, mathematics and statistics (53.6% of graduates), but only 27.8% in engineering and 22.7% in information technology.

These educational gaps carry through into research and innovation careers. Despite a modest increase – from 34.7% to 35.6% between 2013 and 2021 – on average women still account for just over a third of R&D personnel in OECD countries. National shares vary considerably, with some countries approaching gender parity (Iceland, Latvia and Lithuania) while others continue to record comparatively low shares despite progress in recent years (Czechia, Korea and Japan at ~22%). In patenting, the share of women inventors fell from 13.4% in 2013 to 11.3% in 2019 and remains below 7% in some innovation-intensive economies such as Austria, Germany and New Zealand.

Improving women's participation in STI has been a policy focus for a long time, with policymakers implementing targeted financing schemes, such as scholarships and research grants, for women to engage in STI training and activities. Table 3.2 provides examples of policy initiatives in this area.

Table 3.2. Examples of policy initiatives for women's participation in science, technology and innovation

Initiative	Details
Alliance for Women in STEM Careers, Germany	• Established in 2008, the Alliance is today co-ordinated by MINTvernetzt – a federally funded initiative under Germany's Federal Ministry of Education and Research (since May 2025 renamed the Federal Ministry of Research, Technology and Space) – and unites over 370 organisations from academia, industry, civil society and government to promote girls' and women's entry, retention and advancement in science, technology, engineering and mathematics (STEM) fields. • Between 2016 and 2021, the Federal Ministry of Education and Research provided USD 22.2 million (EUR 20.5 million) to support 55 gender-focused STEM projects within the funding guideline "Success with STEM – New opportunities for women". • The #empowerGirl internship platform, launched in 2023, features around 800 internship options across around 300 companies. • The STEM Sentiment Barometer, a data-driven monitoring tool that tracks gender trends and helps assess the impact of policies. • The MINT-DataLab, which supports evidence-based policymaking and peer learning by enabling members to access, analyse and share gender-focused STEM data via structured formats, toolkits and workshops.
Women in Science, Engineering and Technology, Korea	• Launched in 2011 and funded by the Ministry of Science and ICT, the initiative supports women's participation and advancement in STEM across education, research and industry. ○ Key programmes include the R&D Career Re-Entry Programme, which provides up to approximately USD 15 000 (KRW 20 million) per researcher to facilitate return to R&D careers after career breaks, and leadership training schemes aimed at strengthening the pipeline of women in decision-making roles.
Women in tech, Luxembourg	• Launched in 2016 as part of Luxembourg's national digital strategy, the Women in Tech initiative aims to reduce gender gaps in the digital economy by promoting women's participation, skill development and leadership in technology-related fields. Funded by the Ministry of the Economy and co-ordinated through Innovative Initiatives (previously Digital Luxembourg, a government-driven platform that fosters digital transformation and innovation across the country. • The programme is structured as an open-ended national effort, with annual programming supported by a public investment of approximately USD 290 000-350 000 (EUR 250 000-300 000) per year. Key activities include hands-on coding workshops (e.g. Rails Girls); awareness campaigns; and

	partnerships with schools, companies and international platforms such as the WomenTech Network (a privately funded global community promoting gender diversity and career growth for women in tech). The initiative also works to institutionalise inclusive recruitment and retention practices across the digital sector.
Policy for gender balance and gender perspectives in research and innovation, Norway	• In 2019, The Research Council of Norway adopted a policy to promote gender balance and integrate gender perspectives into research and innovation. The policy sets out how The Research Council of Norway will act as a national and international driver by considering gender dimensions in funding decisions and strengthening the knowledge base for inclusive and high-quality research. • The policy defines five areas of action: 1) structures for excellence, including gender equality plans and improved representation of women in international consortia and leadership roles; 2) business sector, focusing on increasing women's participation in innovation projects and private sector research; 3) career policy adapted to life phases, including additional funding for parental leave, reducing temporary contracts and promoting inclusive work cultures; 4) gender perspectives in research, through international collaboration and enhancing gender dimensions in research content; and 5) learning and interaction at The Research Council of Norway, including improved communication, awareness-raising and training on unconscious bias in grant processes.
STEM Ambassador Programme, United Kingdom	• Launched in 2002, funded by UK Research and Innovation and co-ordinated by STEM Learning (a UK-based non-profit organisation that supports STEM education and outreach), the STEM Ambassador Programme promotes gender-balanced participation and leadership in STEM by mobilising volunteers (more than 30 000 since 2002) from across STEM careers. • Ambassadors engage directly with schools, colleges and community groups through hands-on activities, career talks and real-world STEM projects, helping to challenge stereotypes and expand access to role models. • Operating through 17 regional hubs, the programme includes structured recognition through STEM Inspiration Awards, which highlight the contributions of female ambassadors and inclusive employers.

Sources: STEM Learning (2025[33]); Korea Foundation for Women in Science, Engineering and Technology (2025[34]); MINTvernetzt (2025[35]); Innovative Initiatives Digital Luxembourg (2025[36]); The Research Council of Norway (2019[37]).

Broadening participation in the governance and steering of science, technology and innovation

This subsection foregrounds quadrant D of the framework illustrated in Figure 3.1 – diversity in decision making and leadership in STI – by highlighting that participatory governance is increasingly critical as technological transformations accelerate. As technological change profoundly reshapes society, the capacity for a range of groups – not just technical experts – to influence the direction, priorities and norms of innovation becomes central to the legitimacy, equity and societal alignment of STI policy. Ensuring effective and democratic participation in STI governance elevates indirect forms of participation to a policy priority and brings the interplay between who shapes innovation and who ultimately benefits from it into sharper focus across all four quadrants.

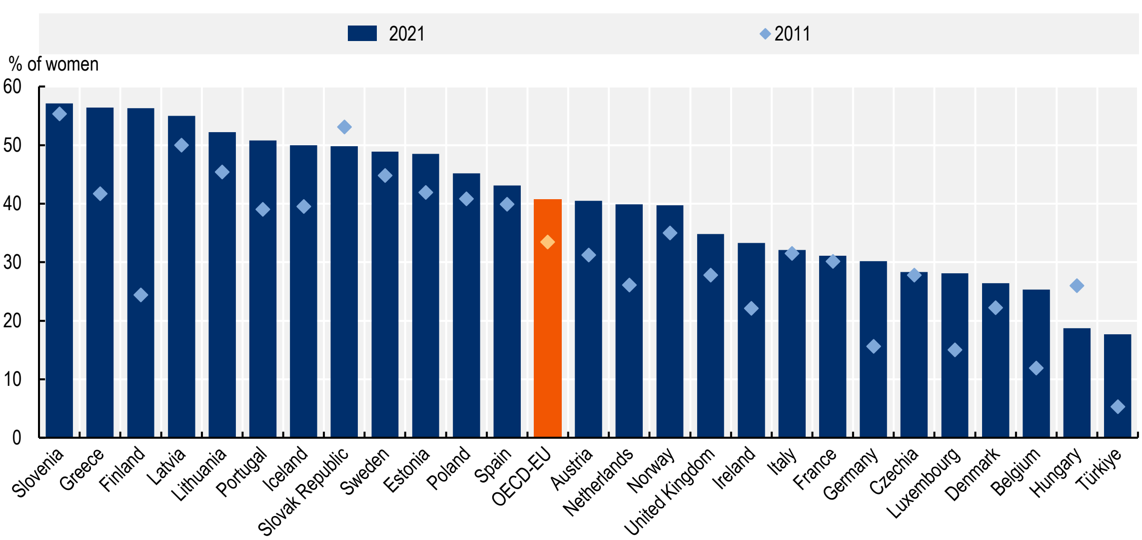
The scale and societal implications of transformative technological developments require participatory approaches to STI policy design (quadrant D of Figure 3.1). As in previous technological revolutions, today's frontier technologies will fundamentally reshape work, governance and social relations in ways that technical experts alone cannot fully anticipate or evaluate; the direction of technology development and diffusion is also much more actively shaped by policy than in the past.

The 2024 OECD Framework for Anticipatory Governance of Emerging Technologies emphasises early societal engagement to surface concerns, inform design choices and guide innovation toward more equitable outcomes (OECD, 2024[38]). This requires investing in the capacity building, consultation processes and institutional arrangements that enable diverse groups to contribute meaningfully to shaping technological directions.

When thinking about participation in the governance and agenda-setting of STI going forward, it is important to note that policymakers do so in a context where historical participation gaps remain unresolved. Women, for example, remain under-represented across entrepreneurial and leadership roles in STI. An analysis of a dataset of start-ups listed on Crunchbase covering firms founded between 2000 and 2017 in OECD and BRICS countries found that women-only founding teams accounted for less than 6% of all start-ups, while those with at least one female co-founder made up approximately 15% (Lassébie et al., 2019[39]). Evidence on European venture capital (VC)-funded start-ups based on data from private sources (Pitchbook and the European Data Cooperative) covering 39 000 investors and 85 000 entrepreneurs that were active in Europe between 2011 and 2021 (accounting for 80% of total VC firms and 52% of start-ups) indicates that, between 2011 and 2021, women comprised only 10% of founders and chief executive officers (CEOs) in those start-ups, while start-ups led solely by women captured a mere 2% of total VC funding. Among investors, only about one in seven senior-level VC investors was female, 90% of whom worked in predominantly male teams (European Investment Fund, 2023[40]).

These participation imbalances extend into senior roles across sectors shaping the future of STI. In 2020, fewer than 5% of Silicon Valley 150 companies had female CEOs, and women held only 26-34% of senior posts at Google, Apple, Facebook, Amazon and Microsoft (European Centre for Women and Technology, 2024[41]). In pharmaceuticals, just 17% of board seats are held by women (ISPE, 2021[42]), and in deep-tech start-ups under one-quarter of founding teams include a woman, with overall female founder share at 14% (Davila et al., 2024[43]). Academia and public administration show similar patterns – women lead 23.6% of higher education institutions and occupy 31.1% of board roles in the European Union (European Commission, 2021[44]).

Figure 3.3. Gender equality in senior management positions in national administrations, 2011 and 2021



Note: Organisations covered are central administrations, also referred to as ministries and/or departments of a national government led by a minister. Senior administrators are the sum of level 1 and level 2 administrators. Level 1 administrators include all administrative (non-political) positions from the head of the ministry down to the level of head of directorate or similar, where a directorate is a major section within the ministry. Level 2 administrators include all positions below the head of directorate down to the level of head of division/department, where a division/department is the first level of organisation below the directorate (i.e. the second level of functional organisation). Data refer to the OECD-EU countries plus Iceland, Norway the United Kingdom and Türkiye.
Source: OECD (2023[45]) based on European Institute for Gender Equality (EIGE) Gender Statistics (database); women and men in decision-making (WMID) authorities.

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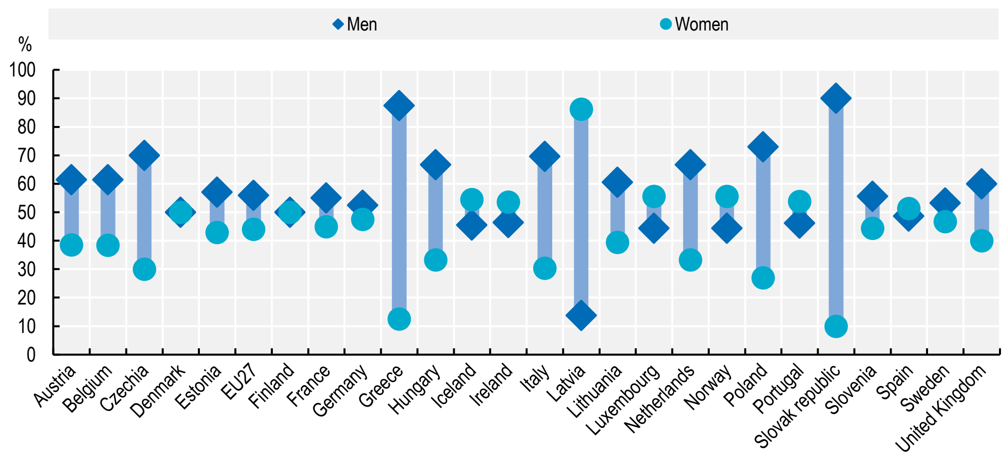
Similarly, women are also under-represented in public decision-making bodies. In August 2023, they accounted for 33% of members of parliament in national parliaments across the European Union. Only six national parliaments had more than 40% women members, while seven had less than 25%. In the case of senior management positions in national administrations, gender disparities tend to be lower and decreasing over time, although significant differences remain across countries (Figure 3.3) (EIGE, 2024[46]). When looking at research-funding organisations in the European Union, the gender composition of presidents and members of the highest decision-making body tends to be predominantly male, with some notable exceptions (Figure 3.4).

Figure 3.4. Gender composition of research-funding organisations: Members of the highest decision-making body

Percentage of total



Source: EIGE, https://eige.europa.eu/gender-statistics/dgs/indicator/wmidm_educ__wmid_resfund, accessed on 18 August 2025.

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Industrial and regional innovation concentration: The competition policy dimension

This subsection discusses how the concentration of innovation activities – across firms, sectors and regions – shapes both the distribution of outcomes (quadrants A and B) and the opportunities for participation (quadrants C and D) within STI systems. A high and rising concentration in R&D investment and innovation capacity can lead to substantial gains in technological progress but also risks reinforcing disparities in who benefits (quadrants A and B) and who is able to participate meaningfully in the innovation process and decision making (quadrants C and D). The framework clarifies that such market dynamics are not neutral: they can reinforce exclusionary patterns unless actively addressed. Recognising these risks, recent OECD work highlights the critical, complementary role of competition policy in maintaining contestable markets, safeguarding access for new entrants, and ensuring that both the outcomes and opportunities created by innovation are widely shared, not just captured by a handful of leading actors or regions.

While concentration can drive technological advancement through economies of scale and scope in R&D – particularly critical for frontier technologies like AI, quantum computing and advanced semiconductors that require massive capital investments – it also creates significant barriers to participation for smaller firms, emerging regions and new entrants.

The OECD's extensive work on competition policy in digital markets demonstrates that these concentration effects are not merely incidental but reflect underlying market power dynamics that can become self-reinforcing, as leading platforms leverage their positions to acquire talent, emerging competitors and complementary technologies (OECD, 2025[47]; 2024[6]). Addressing these inclusion challenges effectively requires co-ordinated intervention from competition policymakers, who possess the analytical tools and enforcement mechanisms to assess market contestability, prevent anti-competitive consolidation and ensure that innovation ecosystems remain accessible to diverse participants. The OECD's Competition and Innovation Framework emphasises that competition policy has a key role in facilitating innovation diffusion and allowing innovations to spread across markets, complementing STI policies' efforts to broaden participation while maintaining the competitive dynamics essential for continued technological progress (OECD, 2023[7]).

International competition also plays a decisive role in shaping the opportunities – and limitations – in low-carbon and green technologies. For example, while the People's Republic of China's strategic dominance in green technology manufacturing has profoundly altered the global competitive landscape, it has also led to a rapid deployment of what are critical technologies for economic decarbonisation (ITIF, 2020[48]). The consolidation of production in China degraded European manufacturing capacity but may also have curtailed potential technological pathways where European firms might have excelled, such as advanced thin-film technologies, perovskite-silicon tandems and other alternative photovoltaic approaches. The implication is, therefore, that the international dimension of technological competition can have a profound impact on the ability of local innovation and industrial ecosystems to participate in the opportunities that can emerge in transitions.

Co-ordinated policy action

This subsection draws together the full four-quadrant framework by emphasising that realising both broad participation in, and broad benefits from, innovation requires policy coherence beyond the STI domain itself. While STI policy can directly influence who participates in developing and using new technologies (quadrants C and D in Figure 3.1) as well as who reaps their benefits (quadrants A and B in Figure 3.1), persistent barriers to inclusion are often rooted outside STI's traditional mandate.

The evidence demonstrates that STI policies alone cannot, therefore, address all dimensions relating to the participation in STI and the benefits from its outcomes. STI governance must, therefore, co-ordinate with social, education and economic policies to tackle structural barriers that limit participation and benefit; this, of course, is not new, but the speed and implications of frontier technological innovation raises the importance of action.

Conclusions

While technological innovation can bring substantial benefits for OECD Member countries and their citizens, the pursuit of technological leadership and the uneven diffusion of technological innovation can reinforce or deepen existing divides in who participates in and benefits from the STI system. The three -quadrant framework that was introduced – linking direct and indirect participation with direct and indirect outcomes – provides one approach for policymakers to assess and address the multifaceted impacts of technological progress. Four key takeaways emerge for STI policymakers in 2025.

First, STI policies operate across multiple dimensions of participation and inclusion simultaneously. The illustrative framework shows that policies designed to advance one quadrant – such as excellence-based initiatives targeting frontier development – can have unintended consequences across the others. For instance, while such policies may accelerate innovation, they can also concentrate benefits in already-advantaged regions and actors. Effective STI policy requires explicit consideration of cross-quadrant effects and complementary measures to address potential exclusionary impacts.

Second, addressing global challenges demands both excellence and inclusion. The scale and speed required for digital and green transitions cannot be achieved through concentration in innovation alone.

Evidence from the gender participation case study illustrates that under-representation across the innovation pipeline – from education through leadership – represents a fundamental constraint on innovation capacity. Broader participation unlocks diverse perspectives, accelerates diffusion and generates the societal legitimacy essential for successful transitions.

Third, successful inclusion policies require co-ordination beyond STI. The persistent nature of participation gaps – despite decades of targeted interventions – underscores that STI policies alone are insufficient. Structural barriers require co-ordinated action across education, labour market, social and regional development policies. The framework's emphasis on both direct and indirect pathways highlights the need for this multi-policy approach.

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4 How science systems need to adapt to support transformative change

Science has a critical role to play in supporting socio-economic transformation and sustainable prosperity. Achieving this at the necessary scale and speed will require changes to key aspects of the way that science systems and academic research currently operate. This chapter explores how policies relating to research careers, research infrastructures and science's engagement with society can act as important levers to promote research that addresses the big questions around socio-economic transformation. Structural changes are required in each of these areas and the chapter discusses the critical role of research performance assessment in incentivising the necessary changes.

Key messages

- **Research careers** in academia should be attractive and accessible to the best and brightest young scientists from all walks of life, who can bring a variety of different perspectives into research. Academia needs to embrace and value research on solutions to complex socio-economic challenges that cut across disciplines and sectors. A variety of transparent career paths should be developed that recognise and enable inter-sectoral mobility and value the essential contribution of professional research support staff.
- **Research infrastructures** (RIs) play an important role as catalysts that bring together key resources – hardware, software, data, methods and expertise – across different fields and countries to promote transformative change. This catalytic role can be amplified further when RIs operate together in ecosystems to address shared goals. Flexible support and governance mechanisms for such RI ecosystems need to be developed further, particularly at the international level.
- **Engagement with society**, including responsible science communication and co-production of scientific knowledge are essential for delivering transformative change. Science communication, including its translation into policy, is not always valued within science systems. While there is an increasing number of funding initiatives to support transdisciplinary research and citizen science that underpin practical solutions, academia as a whole has yet to fully embrace these approaches.
- **Performance assessment and incentive structures** do not fully recognise or value the variety of contributions to, and outputs from, science that are necessary to support socio-economic transformations. The concept of research excellence needs to be broadened and a range of (quantitative and qualitative) measures and indicators deployed to assess different aspects of scientific performance at the individual, institutional and national levels. This needs to be accompanied by adjustments to research funding review and award mechanisms.
- **Maintaining the integrity and credibility of science** is a must. There is a danger in implementing the necessary changes that academic science becomes, or is perceived as being, overly controlled by governments. This could rapidly undermine both science and public trust in science. In an increasingly polarised geopolitical environment, it is critically important to protect the freedom and autonomy of research and promote open science while ensuring the integrity and security of the global science ecosystem.
- **International scientific co-operation is essential** to achieve the urgent socio-economic transformations necessary to ensure a healthy and prosperous future for all. Countries share common challenges in transforming their production and consumption systems and the open exchange of scientific expertise, information and data is necessary to address sustainability challenges and crises that do not recognise national borders. The integrity and security of the global research ecosystem must be strengthened, with scientific knowledge for transformations being recognised as a global public good.

Recalibrating science systems to address critical and urgent challenges

There is wide recognition of the need for transformative change in economies and societies to meet a range of challenges, including competitiveness, security and sustainability. As discussed in Chapter 1, science, technology and innovation (STI) systems are expected to contribute to transformative change but need to reform to generate and deploy relevant knowledge, technologies and innovation at an unprecedented pace and scale. This was clearly acknowledged in the Declaration endorsed by OECD Science, Technology and Innovation Ministers in April 2024 (OECD, 2024[1]), when the Agenda for Transformative Science, Technology and Innovation Policies was welcomed (OECD, 2024[2]). The Agenda provides a high-level framework that can be applied to any transformative goals, though three have been highlighted that capture many contemporary STI policy concerns: 1) promoting economic competitiveness that is fair and inclusive; 2) fostering resilience and security against risks and uncertainties posed by the growing emergence of systemic threats; and 3) advancing sustainability transitions that mitigate and adapt to a legacy of unsustainable development from climate change, pollution and biodiversity loss.

While much of the emphasis – and hope – for achieving these goals is on the future roles of technology and innovation, all three have deep implications for science and for science policy. In short, they cannot be achieved without the new knowledge that science must generate. Calls for transformative change provide an urgent stimulus for systemic and structural reforms to make science systems better fit-for-purpose to support societies in addressing ongoing and future challenges and crises. This can also be seen as an opportunity to address some of the persistent problems that have accumulated in science systems as they have tried to adapt to different socio-economic, technological and policy demands over recent years.

New scientific knowledge is essential for understanding and responding to “wicked” global challenges for informing policies and decision making at multiple scales (local to global) and for developing the new technologies that are essential for effective transformations. At the same time, science systems are themselves directly affected by the transformations they help to drive. This is perhaps most evident in the technological realm; for example, the fundamental building blocks of the digital revolution emerged from public investment in research and have transformed scientific practice. The broader social transformations that digital technologies have enabled also directly impact science: witness, for example, the targeting of scientists via social media. Science is not just a passive contributor but is a major driver of transformation and highly susceptible to the impacts of transformation. As such, it needs to play an active role in shaping transformations, optimising the benefits and limiting the potential negative consequences of its outputs.

Science systems[1] have been designed and have evolved with a dual focus on scientific excellence and promoting economic growth with societal benefit being implicit in both. The academic community is the main guarantor of excellence, while economic benefit provides the principal rationale for public investment in research. Innovation policy has a strong focus on translating scientific outputs into commercially viable products, while science policy has mainly focused on supporting the academic community and promoting research excellence, with more or less attention to societal and policy demand depending on the research domain. In this overall context, the academic research community has tended to resist the strong top-down direction of research and research portfolios have been largely shaped by the choices of individual researchers and review by scientific peers. In some fields, such as medical research, these portfolios are well-aligned with social, political and economic priorities. Science systems, as a whole, are certainly responsive to the socio-economic environment in which they operate. Collective priorities emerge bottom-up and often merge into or converge with top-down policy priorities, but this is usually a slow process and major shifts in the overall direction of collective research efforts are rare (aside from during acute crises). There is an embedded inertia in science systems which strengthens their resilience but limits the conditions under which they can be widely mobilised around shared priorities.

Over time, the archetypal science system has proven its capacity to generate new knowledge and the spillovers to society in terms of technologies and innovations have been enormous. Effective STI systems that are able to generate and exploit new scientific knowledge are a key feature of all leading economies. Scientific research has also shed light on the negative effects of some aspects of technological development and human behaviours, including the environmental impacts, and how these can be avoided or mitigated. Nevertheless, in recent years, there has been increasing debate over the scale of public investment and whether the productivity of science (i.e. costs vs. economic returns) is declining (OECD, 2023[3]). Driven by a combination of precarious working conditions for many and short-term incentives for all, science appears to have become risk-averse. The main focus of research efforts is on incremental research in established fields rather than exploring new ideas in new fields or addressing “big questions” for science and societies. In response, many countries have been introducing dedicated initiatives to support high-risk/high-return research with the explicit aim of promoting technological breakthroughs and/or addressing complex inter/trans-disciplinary challenges (OECD, 2021[4]). However, these initiatives are limited in scope and hindered by structural barriers, including dominant incentive and reward systems, in academia (OECD, 2020[5]).

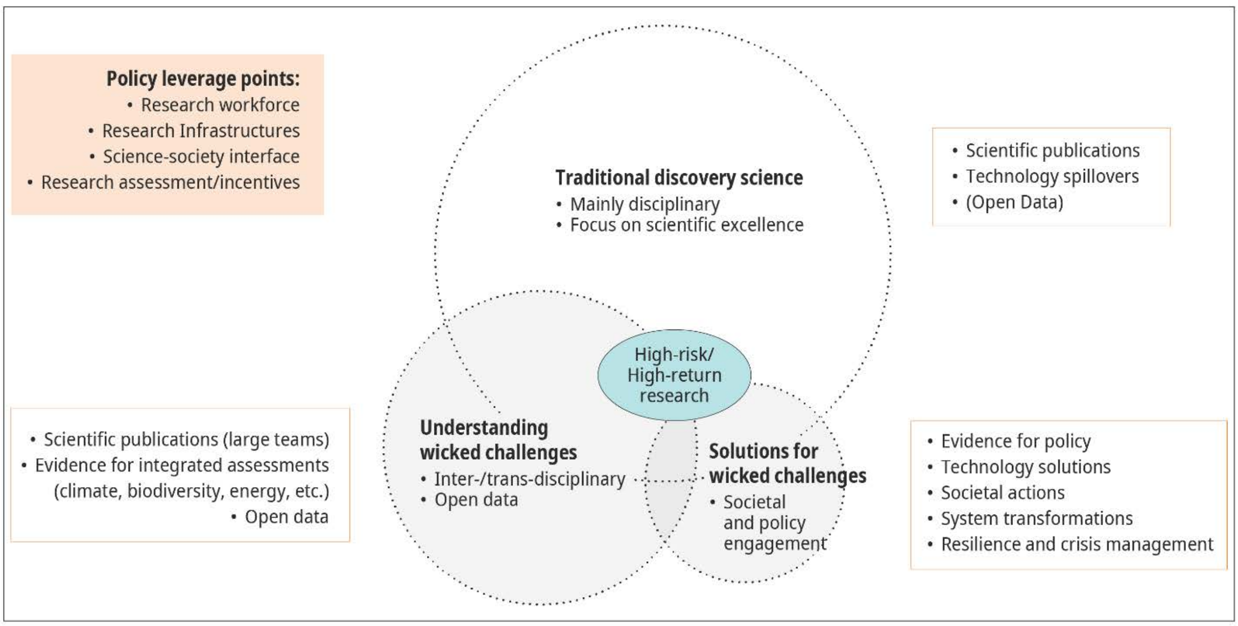
In addition to supporting economic growth and competitiveness, publicly funded academic research has a broader public good motivation that distinguishes it from most research that is conducted in the private sector. This can be illustrated, for example, by the essential role that academic research played in responding to the COVID-19 pandemic – from understanding the biology of the virus to vaccine development or detecting and monitoring infection to the application of public health and social measures. The pandemic was one of the rare instances when science systems mobilised rapidly across a wide range of disciplines and at high scale to respond to urgent societal needs (OECD, 2023[6]). The public good function of academic research is critically important with regards to societal transformations, which cannot be driven solely by economic competitiveness considerations, albeit these are the top policy priority in many countries. Nor can they be realised at the time and scale necessary by simply focusing on scientific excellence, incremental advances and knowledge diffusion. The need for new scientific knowledge to support transformative change is urgent and research systems as they currently operate are unlikely to provide this, or to ensure its effective transfer to society, at the scale and speed needed.

Openness, academic freedom and international collaboration have long been recognised as critical foundations for scientific progress for the benefit of society, i.e. for science to serve its public good function. In an increasingly fractured geopolitical world, the freedom and autonomy of academic research need to be protected and emphasised. Science can either be instrumentalised/weaponised as a tool to support authoritarian rule and accentuate inequalities between countries and populations or it can be a driving force for inclusive socio-economic transformation. The legitimate appropriation of scientific knowledge to promote national interests, including economic growth and security, needs to be aligned with the new imperative to address shared global challenges and support all countries in making the necessary transformations. There is a need for collective mobilisation based around shared values. Openness, international co-operation and benefit-sharing are essential for maintaining the trusted global research ecosystem that is necessary to address global challenges (see Chapters 1 and 2). Ensuring the integrity and security of this global ecosystem in a geopolitically divided world and protecting research from interference, coercion and misuse by malevolent state and non-state actors is a critical challenge for science policymakers (see Chapter 2).

There are three key interrelated areas that science policymakers need to pay attention to if science is to play its part in socio-economic transformations: 1) the scientific workforce; 2) research infrastructures; and 3) the interface between science and society. There is a fourth area or meta-leverage point that impacts on all of these: research assessment and incentives, including funding. A skilled research workforce and the tools and equipment that it uses, i.e. RIs, are the bedrock of any science system. A close and trusted relationship between science and society is critical for the new scientific knowledge and technologies that are necessary to achieve socio-economic transformation are to be taken up while activities that are proven to be damaging are phased out. Research assessment and incentives, including funding, are the most effective mechanisms for shaping scientific research and promoting change in scientific institutions' practices.

Figure 4.1 illustrates the current status quo with regard to different categories of research and research outputs. The policy leverage points can be used to shift this status quo and grow the smaller circles. It is important to note that this is not a "zero-sum" scenario – all research types and the intersections between them are important for achieving the transformation goals. Rebalancing cannot be achieved in a top-down control manner and, in this regard, the role of science policymakers is to catalyse and enable rather than closely direct and control. Policy actions in all four areas need to be carefully designed and implemented, respecting the established values of science and the autonomy of scientific institutions.

Figure 4.1. Scientific knowledge for transformative change



Notes: The majority of publicly funded research is traditional discovery research, with a smaller fraction focused on understanding complex socio-economic and environmental challenges and a very small proportion focused on developing and implementing solutions for these "wicked" challenges (i.e. directly supporting transformations). The boxes indicate the main expected outputs that can be assessed for each of these three areas. In each area, the amount of really new, innovative high-risk/high-return research is limited.
To more effectively support socio-economic transformation, the system needs to be rebalanced so that all four types of research are more equally supported and incentivised and, most importantly, that the intersections between the different research types are expanded. Four key leverage points on which policy can act to help achieve this rebalancing are indicated in red.
N.B. The graphic is illustrative and the relative size of the bubbles is more meaningful than their absolute size.

The rest of this chapter focuses on the four key policy leverage points – the challenges and potential policy solutions. The main sections finish with overall policy recommendations, with illustrative examples of policy actions from different countries provided as endnotes. Many more examples can be found on the EC-OECD *STIP Compass database* (https://stip.oecd.org/stip).

Building a productive scientific workforce with a diversity of talents

Ultimately, science's contribution to transformative change depends on the scientific workforce. It depends on the capacity of the research system to attract and maintain a diversity of talents – the brightest and the best from all walks of life – and provide these scientists and professional research support personnel with the necessary conditions to be creative and productive in addressing the “big questions” for science and society. This includes ensuring they have access to the necessary data and (digital) tools. Building and maintaining this capacity is essential for science to be able address many of the questions that need to be answered if inclusive and just transformations are to be effected. This means confronting a number of persistent human resource challenges, which have accumulated in research systems over several decades to the point that academic research is no longer considered an attractive or realistic career option for many aspiring young scientists who wish to contribute to science for society (OECD, 2023[7]).

Academic research and precarity

Academia fulfils an essential role not only in conducting a significant proportion of publicly funded research in most countries but also in training scientists and engineers that can work in the public and private sector, either within their country of training or abroad. While the majority of PhD trainees in science start out wanting to pursue an academic career, only a small minority will succeed. Some will leave research immediately after their PhD or move to research careers in the private sector. Many others continue to pursue their ambitions in academia until they either drop out frustrated after a succession of short-term positions or burn-out due to the hyper-competitive publish-or-perish culture that is prevalent in academia (OECD, 2021[8]). This is not good for them, for academic research or for science in society more broadly.

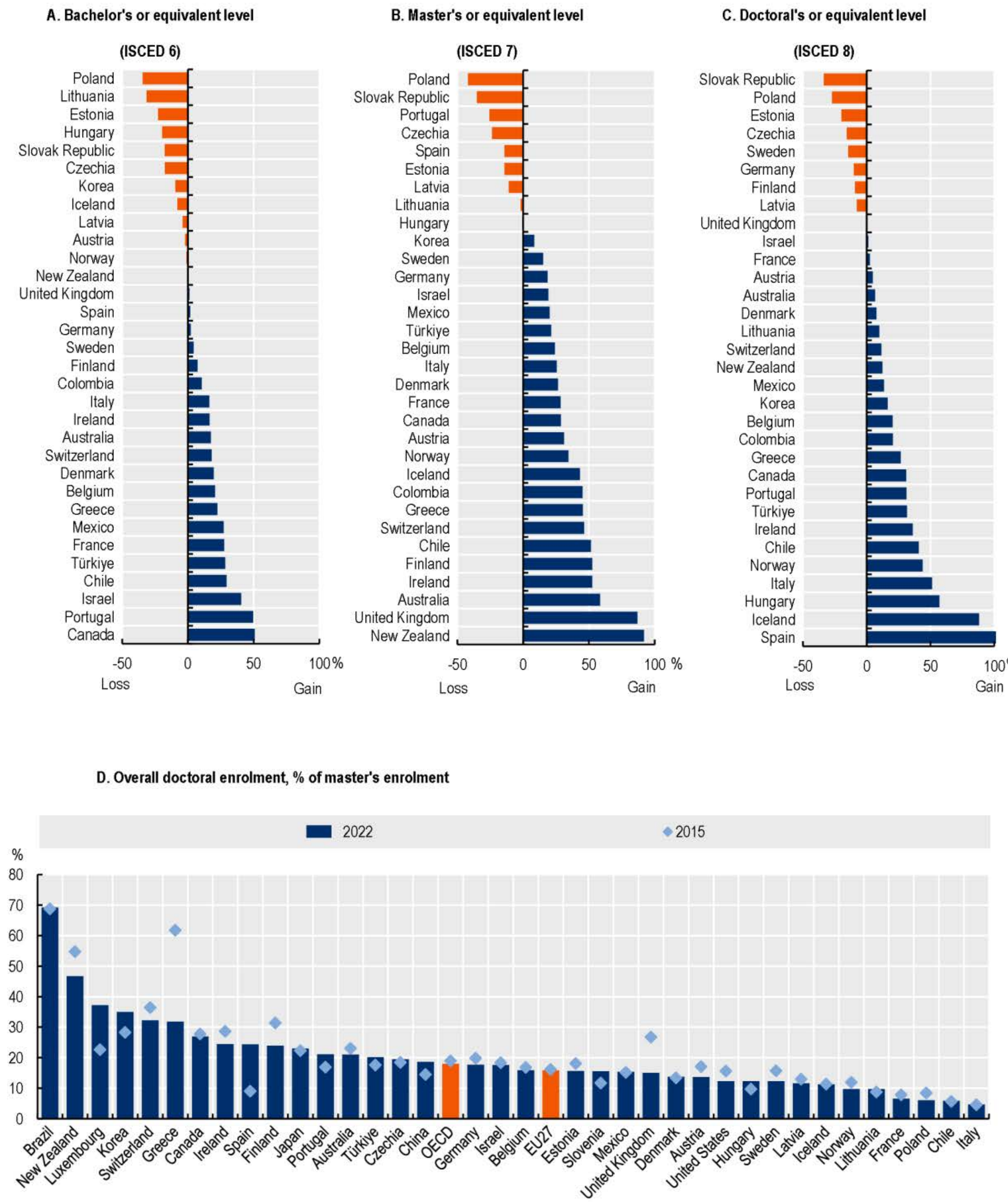
Academic research systems operate largely on the basis of multiple short-term (two to three years) research projects that are led by tenured scientists, with the hands-on research being conducted by PhD and postdoctoral researchers. Across OECD countries, most researchers under the age of 44 in academia are employed on short-term fixed-term employment contracts (Bello and Galindo-Rueda, 2020[9]). In many countries, a significant proportion of these researchers, including the majority of PhD researchers, are supported on stipends. Fixed-term employment is used as a flexible mechanism to meet short-term workforce demands but it also leads to precarity and diminishes the attractiveness of academic careers. Precarity, in turn, limits diversity both in terms of individuals and in research choices – when there is pressure to publish it is better to avoid high-risk research topics with uncertain outcomes (OECD, 2021[8]). Precarity is not simply about how funding and resources are used, although these are clearly important, it is also very much about academic career structures, workforce planning, personal and professional development processes, incentives, and rewards. Effectively addressing these issues requires a systemic approach that engages multiple actors – science policymakers, research funders, research providers/employers and early career researchers (OECD, 2021[8]; 2021[10]).

Precarity is context-specific but is an important feature of all national research systems. Precarity has increased as the emphasis on competition and (narrowly defined) scientific excellence has grown. While competition – between scientists, institutions and countries – is an important driving force for science, hyper-competition for talent and (limited) resources has serious negative effects. Shared global challenges call for collective mobilisation of the global research community and countries and research institutions should be sharing and adopting best practices to reduce academic precarity and retain diverse scientific talent, ensuring research careers remain attractive pathways for top young researchers.

Career options and competition for talent

Doctorate-level attainment in the population has grown rapidly across the OECD in the past decade, but entry rates in science, technology, engineering and mathematics (STEM) doctoral education in some countries have recently started to decline (Figure 4.2). In some countries, and in some fields, there is the perception that doctoral training is no longer attracting the best talent. In some strategically important fields such as informatics, artificial intelligence (AI) and quantum science, the decision not to pursue a PhD is simplified by attractive recruitment offers from the private sector for which a master’s degree or equivalent may suffice, at least for early career stages.

Figure 4.2. Change in STEM enrolment in higher education (2015 vs. 2022) in selected economies



Note: Panels A-C focus on STEM disciplines (science, technology, engineering and mathematics). Panel D includes all research domains, including social sciences and humanities.

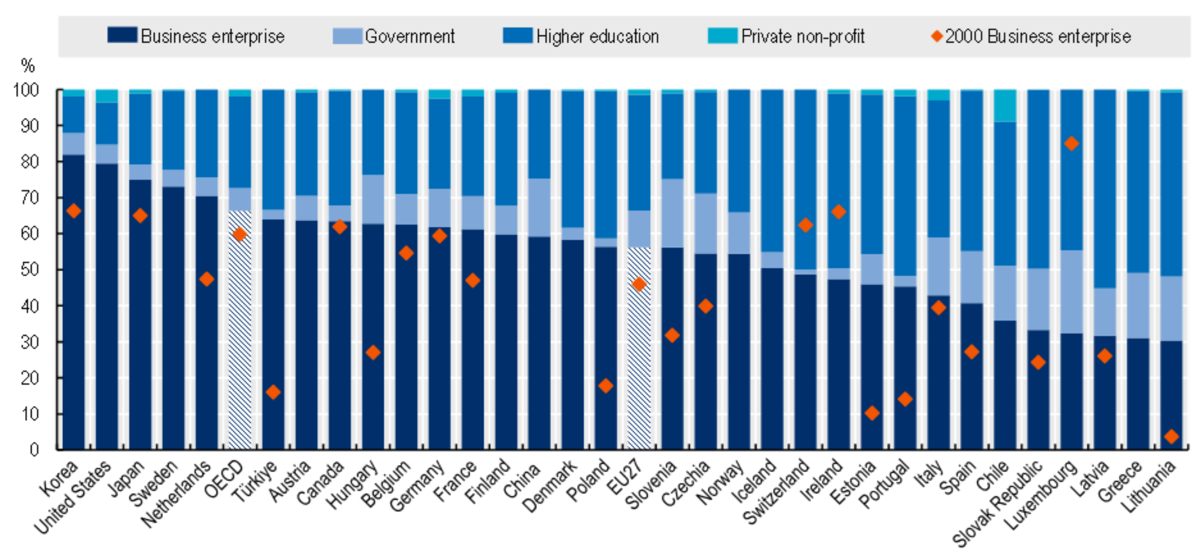
Source: Panels A-C: OECD (2025), *Education Statistics database* https://www.oecd.org/en/topics/education-access-participation-and-progression.html (accessed on 23 September 2025), Panel D: OECD (2025), *REICO database* https://www.oecd.org/en/networks/research-and-innovation-careers-observatory.html (accessed on 23 September 2025).

StatLink https://stat.link/jw9hqx

Despite indications of a recent slowdown in some countries, the number of doctorate holders worldwide has grown and there is intensified competition for limited tenured positions in academia and public research organisations (OECD, 2021[8]). According to recent global estimates, around 40% of postdocs leave academia (Duan et al., 2025[11]). While many highly skilled young scientists leave research altogether, others apply their research skills and expertise elsewhere, particularly in the business sector (Figure 4.3). From a societal perspective academic science and industrial science are complementary activities but, in practice, are distinct professions with very different career structures (Dasgupta and David, 1994[12]). Leaving academia to conduct research in the private sector is common, whereas movement in the opposite direction is relatively rare in most scientific domains (computer sciences being a notable exception in some countries). There is no revolving door – once one leaves academia it is highly unlikely they will be able to return, as their publication record and academic CV will inevitably depreciate over time. Lowering the structural barriers to entry into academia for highly skilled "outsiders" is a potentially important mechanism for expanding the diversity of perspectives and filling gaps in the public research workforce in rapidly expanding areas, such as AI and quantum science that are critical for socio-economic transformations.

Figure 4.3. Researchers per sector of employment

As a percentage of national total researchers, based on full-time equivalents, 2023 or latest year available



Notes: Provisional values for Austria, Belgium, Czechia, Denmark, France, Greece, Iceland, Ireland, Italy, Lithuania, Luxembourg, the Netherlands, Norway, Portugal, Slovenia and Spain. 2023 corresponds to 2022 for Canada, Chile and Switzerland.
Source: OECD (2025), *OECD Main Science and Technology Indicators Database*, www.oecd.org/sti/msti.htm (accessed in March 2025).

StatLink https://stat.link/nsda4r

Although the majority of PhDs and early-career researchers end up in careers outside of academia, very little attention is paid to preparing them for this or assisting them to make informed career choices. Scientific research develops individual expertise and transferable skills that can be applied in many socio-economic sectors, but these are often not appreciated at their full value. People and their qualifications are the most important tool for transferring research results and scientific thinking into the business and government sector and society more widely. For science to fully contribute to a country's socio-economic development, it is essential to institutionalise career guidance for doctoral candidates and postdoc researchers (OECD, 2023[7]; Schillebeeckx, Maricque and Lewis, 2013[13]). In an ideal world, these young researchers will be highly motivated and productive throughout their time in academia and be able to apply the precious experience and skills they have acquired in other sectors, should they choose to do so at some stage in their careers.

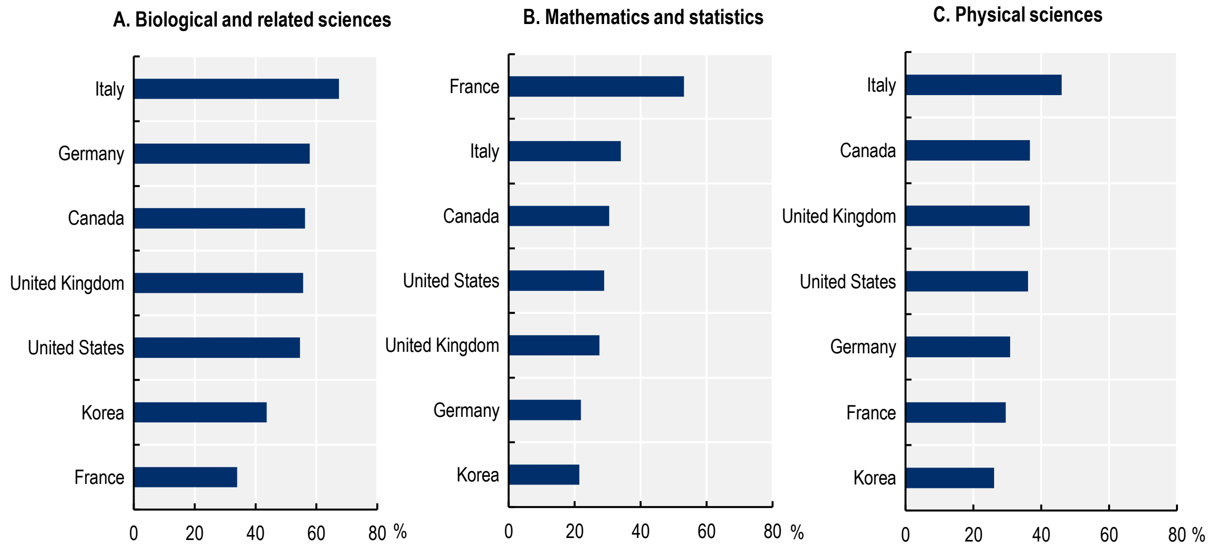
The intense competition for scientific talent is not only between the public and private sector, it is also global (see Chapter 2). Many countries and institutions are struggling to attract and maintain the highly skilled personnel they require to conduct high-quality research and support transformative change. The share of international students in doctoral degree programmes has increased in most OECD countries. However, geopolitical tensions and concerns about research security and strategic autonomy are making some previously attractive research destinations less attractive and strengthened visa regulations are impairing international mobility (see Chapter 2). At a time when science is increasingly being called upon to address global challenges, policy measures to promote the free flow of scientists need to be maintained and strengthened.

Inclusive excellence

Scientific progress and support for transformative change requires the integration of diverse ideas, perspectives and skills within the research workforce. Diverse talents and perspectives can influence the choice of research topics and methods, opening up new research avenues and spurring discovery (Kozlowski et al., 2022[14]). Empirical work on team science has shown that diversity in perspectives leads to greater productivity when effective team management practices are in place (Apfelbaum, Phillips and Richeson, 2014[15]). However, science and academia are, to a considerable extent, self-replicating. First-generation scientists who succeed in academia are rare and the rate of adoption of an academic career is low for scientists from historically under-represented groups (Hofstra et al., 2020[16]). Limited diversity in perspectives and a narrower range of research topics are not only distancing science from addressing the real needs of many sectors of society but also potentially slowing overall scientific productivity.

Studies of national research systems have provided broadly applicable evidence of disparities in opportunities across various stages of research careers, highlighting gaps in career advancement, pay, support and funding. These studies have largely focused on sex (Larivière et al., 2013[17]), race/ethnicity (Ginther et al., 2011[18]), and more recently also on the intersection of sex and race (Kozlowski et al., 2022[14]). They indicate that disparity and gaps, which vary by country and scientific field (Figure 4.4), are not due to differences in the quality of candidate individuals. Neither is quantity a strong factor, even though under-representation matters; in most countries, academia is poorly representative of the population at large. These discrepancies can be explained by a set of interconnected barriers for talented individuals from under-represented groups: relational barriers between individuals; structural barriers within research organisations; and systemic barriers rooted in cultural norms, regulations and legal frameworks (OECD, 2018[19]).

Figure 4.4. Share of female PhD graduates in different science fields in selected countries, 2022



Source: OECD (2025), *Education statistics database* https://www.oecd.org/en/topics/education-access-participation-and-progression.html (accessed on 7 March 2025).

StatLink https://stat.link/6z28jc

Promoting diverse perspectives and talents for "excellence in research" (Box 4.1) will require a concerted effort by policymakers, research organisations and funding agencies. In this, public policy has a dual role which combines steering, through the setting of standards and the provision of data and funding, with capacity building to ensure that talent is nurtured, retained and empowered across all career stages. Better data are needed to identify barriers to inclusion in research, taking into account that variables reflecting differences in background and perspectives (e.g. sex and race/ethnicity) are interconnected and mutually reinforcing, and to design and monitor policy interventions that recognise and exploit the synergy between inclusion and excellence in science.

Box 4.1. Inclusive excellence in research

Excellence in research refers to achieving the highest standards of science – rigour, ethics, significance and originality – with the aim of making an impactful contribution to knowledge and practice. Inclusive excellence in research is a concept that affirms the necessity of public policy intervention to actively promote a diversity of perspectives and the participation of individuals from different backgrounds to accelerate the advancement of science. It recognises that the notion of "excellence" is socially constructed, and its meaning is neither fixed nor universal. What counts as "significant", "original" or "impactful" can diverge considerably across different contexts, communities and disciplines, reflecting the priorities of those in positions of authority who define and evaluate these standards. A narrow focus on excellence in isolation can privilege dominant perspectives while devaluing diverse ways of knowing and practicing science (Kraemer-Mbula et al., 2020[20]; López Piñeiro and Hicks, 2015[21]).

Inclusive excellence builds on the highest standards of science, and embeds equity – that is, acknowledging that researchers have different starting points and circumstances, and creating working conditions that make the probability of success independent of these (i.e. ensuring equal opportunities) – into the core practices of scientific research, education and training, as well as promotion and resource allocation. This has implications for academic career paths, evaluation and assessment, and the leadership of teams and research organisations. It provides a strong rationale for policies and measures that address regional and institutional imbalances in the allocation of research resources within a research system.

The concept of inclusive excellence can be applied across the research system in different ways. For example, in research-performing organisations, it can offer a framework to incentivise and sustain a shift in research culture. In funding organisations, it can help to ensure equitable access to funding opportunities, for example by introducing “junior” and “senior grants” to provide a level playing field when applying for research funding.

Artificial intelligence, open data and digital skills

AI, large language models (LLMs) and robotics are changing the way science is conducted and the roles researchers play (OECD, 2023[3]). These technologies are becoming ubiquitous across research, increasing the speed and efficiency of data and information processing (Box 4.2). They are even impacting on hypothesis generation, which was until recently considered to be the prerogative of the human scientist and there is increasing discussion of (semi-) autonomous “AI scientists” (Castelvecchi, 2024[22]). However, at least for the foreseeable future, these analytical tools cannot replace the human brain and the technical skills on which science depends. Scientists remain essential for driving discovery and progress through creativity, intuition and collaboration (Popper, 1961[23]). In the new world of AI and LLMs, a diversity of perspectives is likely to be an even more important determinant of scientific progress for the benefit of society (OECD, 2023[3]).

Box 4.2. The use of artificial intelligence in science

Artificial intelligence (AI) tools in science increase the capabilities of researchers in data analysis, simulation and hypothesis generation. For example, in genomics, the use of AI has helped to identify genetic variants associated with diseases, predict gene functions and understand complex genomic interactions (Zou et al., 2018[24]). In climate modelling it has increased the accuracy in forecasting short-term weather patterns and long-term climate trends (Reichstein et al., 2019[25]), and it can speed up the development of new materials and products in a wide range of fields, including medicine (Max Planck Institute, 2025[26]).

AI has the potential to amplify scientific productivity by lowering costs and increasing research efficiency. For example, AI-powered robots can increase speed, precision and consistency in conducting experiments in laboratory environments. AI models that are trained on published scientific findings are able to anticipate human scientists in discovery. By avoiding the typical approach of local exploitation of the familiar instead of exploration of the unknown, these models can lead to insights and hypotheses unlikely to be proposed by human scientists (Sourati and Evans, 2023[27]).

In 2024, research on AI was awarded two Nobel prizes for innovations that will shape the future of medicine. The prize in physics was awarded to John J. Hopfield and Geoffrey E. Hinton (formerly of Google) for “foundational discoveries and inventions that enable machine learning with artificial neural networks.” The prize in chemistry was awarded to David Baker for “computational protein design” and to Demis Hassabis and John M. Jumper (of DeepMind) for “protein structure prediction”. It is notable that all these prize winners worked in academia and industry at different stages of their careers.

AI and large language models also raise a number of challenges for established scientific practices, particularly with regards to publications and the integrity of the scientific record (Kwon, 2025[28]; The

Royal Society, 2024[29]). This is particularly relevant when one considers the policy emphasis on open access and the dominant role that publications play in research assessment and evaluation processes.

Source: Zou et al. (2018[24]); Reichstein et al. (2019[25]); Max Planck Institute (2025[26]); Sourati and Evans (2023[27]); Kwon (2025[28]); The Royal Society (2024[29]).

AI is an area of intense competition as well as productive collaboration between academia and industry and an area where the public good ethos of academia is sometimes pitched against the commercial motivation of industry. There are signs that the predominant role of industry in AI research could lead to a narrowing in the focus of research. Recent empirical work finds that “private sector AI researchers tend to specialise in data-hungry and computationally intensive deep learning methods” and that this is at the expense of “research involving other AI methods, research that considers the societal and ethical implications of AI, and applications in sectors like health” (Ahmed, Wahed and Thompson, 2023[30]; OECD, 2023[31]). Achieving a balance between the distribution of research and expertise across the public and private research sectors is important to ensure that AI is optimally developed and deployed to achieve transformative change.

Great hopes are being placed in open science, including FAIR (Findable, Accessible, Interoperable and Reusable) data and digital tools, as a catalyst for accelerated scientific progress and innovation. Access to data from different research fields, combined with administrative and other sources, is essential for understanding and managing complex crises and socio-economic transformations. AI and other software tools and computing resources are essential for analysing these data and translating them into relevant knowledge. However, the primary requirement for trustworthy data-intensive science is digitally skilled scientific personnel – data scientists, data stewards and software engineers (OECD, 2020[32]). Making research data FAIR and maintaining it over time is not a trivial task and is largely an unsupported mandate for the scientific community. If open science and data are to inform societal transformations, then the professional digital research support staff who can make this happen need to be properly valued and supported and making data FAIR needs to be incentivised.

Team science, risk taking (and incentives)

Science is increasingly conducted in teams that are often interdisciplinary and international. Interdisciplinary and transdisciplinary research, of the kind that is needed to support socio-economic transformations, is often high-risk – it can take longer to produce publishable results than conventional research and the outcomes are less predictable at the outset. While funding for interdisciplinary and multidisciplinary projects is increasingly available, reward systems, including recruitment and promotion, continue to primarily focus on individual performance (see below). For a young researcher with career ambitions in academia, incremental research in a well-recognised research area is a much safer choice than launching into a complex new interdisciplinary area.

Recognition for contributions to team science, from both researchers and professional support staff, is an important area for improvement. There is a need to establish clear guidelines to ensure fair acknowledgment of team members’ contributions. Initiatives such as the Contributor Roles Taxonomy (CRediT) offer a structured framework for documenting individual contributions to research projects, ensuring both transparency and fairness in recognition and enabling more nuanced acknowledgment in publications (Lin, 2024[33]). However, while scientific publication outputs are important, their uptake and short-term impact, as measured by citations, is often limited in new areas that do not already have well-established communities of interest. Other more valuable outcomes for team science and interdisciplinary or transdisciplinary research, such as inputs to policy or societal decision making, are difficult to quantify and are rarely given their due credit in academic evaluations (see below).

There is a lack of attractive career paths, and appropriate evaluation frameworks, for researchers who want to work across disciplines and engage with citizens and policymakers (see above) to address complex societal challenges. Addressing this and incentivising and supporting researchers to take risks and work together to address big and complex challenges will be critical if science is to fully support socio-economic transformation.

Policy actions

1. Address the underlying structural issues that underpin research precarity and limit research choices and risk-taking for early career scientists.[2]
2. Promote "inclusive excellence" across science systems.[3]
3. Promote a variety of alternative career pathways within and beyond academia that can enable the generation and use of scientific knowledge to support transformations. Stimulate two-way mobility between academic science and other sectors, including industry.[4]
4. Continue to support and facilitate international mobility and the exchange of researchers and professional research support staff.[5]

Enabling the catalytic role of research infrastructures

In addition to talent, progress in science depends on access to state-of-the-art technologies and data (see the previous section). These are often provided as shared services, via RIs, which exist in all scientific domains and, in many cases, operate internationally (i.e. they provide access to both national and international research communities). RIs vary in nature, scale and structure and include large single-site experimental facilities, such as synchrotrons and telescopes (OECD, 2023[34]), and distributed smaller scale facilities, such as data networks or biobanks (OECD, 2017[35]). They are the backbone of national and international research systems and, as such, play a critical role in structuring these systems. They are also meeting places where different actors from different countries and sectors come together. RIs can play a leading role in promoting transformative change but this will require reforms in the way they are currently supported and operated.

Research infrastructure ecosystems

As demonstrated in the response to COVID-19, research infrastructures can play an important catalytic role in mobilising research to respond to crises (OECD, 2023[36]). They are uniquely positioned to bring together different actors, disciplines and countries to address complex scientific and societal challenges. Depending on their remit and scale, individual RIs can have a major influence on strategic directions and research choices in their own field and, by being open and providing services to new users, can support bottom-up research across multiple domains. Both direction and diversity in research are important for promoting transformative change and RIs can support both provided that they have the long-term strategic investment that enables them to extend their principle scientific missions to fully accommodate new users from science and beyond.

Besides their primary role as knowledge producers, most RIs also play a role in technology development and innovation. This can either be as a by-product of pursuing scientific goals – for which RIs often have to develop their own unique instruments and software – or a direct result of collaboration with industry and other partners to develop and test their products. In addition to experimental equipment and resources, RIs often have unique technical expertise, skills and know-how that can be applied beyond their immediate scientific goals. Many RIs are contributing to technological development and innovation in a range of areas, from energy to materials research, that are important for sustainable transformations. This often occurs in close collaboration with industry. Some have developed substantive initiatives that are specifically focused on leveraging in-house expertise to address green transitions and/or sustainable development. However, the funding for such activities remains limited and the incentives and mechanisms for engagement are relatively weak (OECD, 2025[37]).

RIs are increasingly co-operating with each other, exchanging know-how, and developing common protocols and practices to increase their efficiency and effectiveness. RI ecosystems, which support or co-ordinate services and/or activities across different facilities, are also emerging. These are dynamic and evolving entities that develop around shared strategic objectives, which are often related to socio-economic transformations and/or crisis preparedness and response (Table 4.1). They operate at different geographic scales from local to international. By combining resources and expertise they strengthen research systems' capacity to address shared challenges. Although there are mechanisms to support such ecosystems at a national or regional scale, there is an absence of effective tools or incentives to sustain effective global RI ecosystems, which are often dependent on short-term funding or subsidised by other member activities (OECD, 2025[37]).

Table 4.1. Examples of international research infrastructure ecosystems supporting research related to socio-economic transformation

Research infrastructure ecosystem	Geographical dimension	Composition and objectives
Analytical Research Infrastructures of Europe (ARIE)	Europe	ARIE is a consortium of seven networks of analytical research infrastructures (neutron sources, electron sources, photon sources, lasers, ion sources, proton sources and high magnetic fields) grouped in a consortium for multidisciplinary uses to respond to societal challenges. It is, for example, involved in a European project to design new materials for a circular economy.
German-Canadian Materials Acceleration Centre (GC-MAC)	Germany-Canada	GC-MAC is a collaborative partnership of research activities between Germany and Canada, funded by matching (mostly in-kind) resources from participating institutions. It aims at co-ordinating and integrating German and Canadian activities in accelerated materials research. It supports the United Nations Sustainable Development Goals, aligning its research and development strategy with the global transition towards a defossilised, decentralised, efficient and economically viable energy infrastructure.
Global Ecosystem Research Infrastructure (GERI)	International	GERI is an integrated network of site-based research infrastructures from Australia, the People's Republic of China, Europe, South Africa and the United States dedicated to better understanding the function and change of indicator ecosystems across global biomes. GERI aims to support excellent science that can also inform political and managerial decision making regarding grand societal challenges.
Integrated Services for Infectious Disease Outbreak Research (ISIDORe)	Europe	ISIDORe regroups major European life sciences research infrastructures and infectious disease networks. It provides access to facilities, cutting-edge services, advanced equipment and expertise in an integrated way to enhance Europe's capacity for controlling (re)emerging and epidemic infectious diseases.

Source: OECD (2025[37]).

Given that many RIs are inherently international and most provide open international access to data, they have an important role to play in promoting inclusion in research and access to scientific knowledge. International RIs, i.e. those with funding from multiple countries and international governance arrangements, can play a central role in socio-economic transformation in their host region or country. For example, the establishment of the Square Kilometre Array telescope in South Africa is premised on plans that this will stimulate the digital economy in South Africa and the region more broadly (Adams, Tiplady and Sgard, 2023[38]). However, the scientific requirements and political factors that inform the location of international RIs are complex and opportunities to exploit this transformative potential are rare. Distributed RIs, networks and the development of RI ecosystems provide more accessible opportunities for all countries to participate in research that can support socio-economic transformations. As yet, the global support and flexible governance mechanisms for such global infrastructure ecosystems are lacking but the need for a socio-economic transformation agenda can provide a stimulus for their development and vice versa.

Research infrastructures and trusted data

RIs are at the centre of the digital transition. They collect, produce and manage massive amounts of scientific data and information and have the professional expertise required to enable its robust analysis by a variety of users. These data have great societal value: they provide the basis for innovation and technological development and are also critical for informing sound evidence-based policies and decision making. Access to trustworthy data and information is crucial for industry, academia, policymakers and the public at large. Many RIs are at the forefront of AI and LLM development and deployment, mainly driven by their own research data management needs but with major spillovers for society (see the previous discussion on AI and Box 4.1).

Dedicated cyber-infrastructure, such as high-performance computers or GRID computing networks, support the entire public research enterprise (as well as much of private sector R&D). Research data are deposited in networks of data repositories that ensure their future stewardship and safe and secure access, in line with the FAIR principles (see Chapter 2). Many of these repositories also develop and provide access to a variety of data services and tools for different user communities (OECD, 2017[39]). In many cases they are leading efforts to develop the standards, protocols and tools that are necessary to ensure the interoperability of data from different fields, which is essential for generating the new knowledge needed to support societal transformations. For example, the social science and humanities RIs ODISSEI (Open Data Infrastructure for Social Science and Economic Innovations) and CLARIAH (Common Lab Research Infrastructure for the Arts and Humanities), together with SSHOC-NL (the Social Science and Humanities Open Cloud for the Netherlands, http://sshoc.nl), have developed a common initiative to create a secure digital infrastructure for linking and analysing diverse administrative and research data sets. This is enabling interdisciplinary research on "big" socio-economic issues, such as polarisation, social inequalities and the societal implications of environmental change.

At the international scale, the European Open Science Cloud – and similar data commons initiatives in other regions – aim to take advantage of the digitalisation of research by linking together trusted data sources and analytical tools and services, including AI algorithms and high-performance computing. These will be accessible, under safe and secure conditions, to both public and private sector researchers and promise to massively accelerate the interdisciplinary big data analysis necessary to inform socio-economic transformations. Supporting and maintaining the cyber-infrastructure and developing the open technical standards and protocols that enable the interoperability of data from different sources are significant challenges but rapidly building the human capacity and skills for rigorous data-intensive research is perhaps the toughest challenge of all (OECD, 2020[32]).

Research infrastructures, skills and training

The construction and operation of RIs depends on highly skilled and specialised human resources – scientists, engineers and professional support staff. Hence, RIs have the capacity to contribute significantly to the development of skills and capabilities needed in many areas of society. This can include many specialised skill sets, such as digital expertise or technology-intensive engineering, as well as broader skills required for managing the complex operations and collaborations of RIs, such as transversal or systemic thinking and complex project management. RIs devote considerable time and effort to meeting their own training needs, which can be facilitated by working together in networks or ecosystems. They are also increasingly being used by a broader range of non-expert user communities, including citizen science practitioners and transdisciplinary research teams, who require dedicated training. However, while RIs provide both formal and informal training for scientists, technical support staff and users, they are rarely integrated into or well-connected to national education systems. For example, RIs handle massive amounts of complex data and increasingly use AI for data mining and analysis (see above); however, the training they provide in these areas is typically restricted to their own personnel and primary scientific user communities. There are opportunities for RIs to work more closely with higher education institutes and other training service providers to build digital, and other, capacities that address their own needs and those of society more broadly.

The challenges for developing and retaining RI personnel are similar to those in academia more broadly, including precarity, uncompetitive salaries and unclear career paths. In addition, career options within the public research system are often severely limited for those with very specialised skills and the draw of the private sector can be strong in some areas, such as in AI or quantum sciences. Specialised research support and technical personnel are critical for the effective operation of RIs They play an essential role maintaining and adapting the functioning of RIs. This ensures their daily operations but also enables these facilities to be rapidly mobilised during crises, such as the COVID-19 pandemic, and potentially also to play a major role in catalysing solutions for socio-economic transformation.

While networking and RI ecosystems can help promote mutual learning and staff exchange, RIs need to be supported to work with universities and relevant private sector actors to improve career paths and intersectoral mobility. This can also ensure that the invaluable tacit knowledge embedded in professional research support staff is shared and disseminated across different socio-economic sectors.

Policy actions

1. Recognise the essential role that RIs can play in supporting crisis response and socio-economic transformation and adopt strategic funding approaches that enhance their sustainability and enable flexibility.[6]
2. Support the co-ordinated and collaborative development, operation and use of RIs – including the promotion of global RI ecosystems – to tackle complex and interconnected global challenges (see Table 4.1 for examples).
3. Mandate and support RIs as sites for the generation and secure stewardship of high-quality FAIR data for responding to societal challenges.[7]
4. Leverage RIs for training and education to help address skills scarcities and mismatch associated with transformations.[8]

Closing the gap between science and society

As witnessed during the COVID-19 pandemic, relevant scientific knowledge and social and technological innovations are essential for responding effectively to complex socio-economic challenges and crises. These, in turn, depend on having productive research environments and the right incentives. However, in a crisis situation, translating scientific knowledge into effective actions is absolutely dependent on the three-way relationship between science, policymakers and society (OECD, 2023[40]). Where trusted relationships exist, evidence-based policymaking can lead to effective crisis mitigation and adaptation strategies. Where there is a lack of trust between science and the public, crisis response is seriously compromised. Likewise, when relevant authorities are dismissive of science, their decisions and actions are likely to be ineffective. There are three critical areas for urgent attention if science is to effectively engage, and be trusted by, the public and policymakers: 1) integrity and science communication; 2) citizen engagement in research; and 3) the interface between science and policymaking. These are all closely linked to the implementation of open science in the broadest sense, i.e. embedding science in society (Dai, Shin and Smith, 2018[41]; UNESCO, 2021[42]; Wehn and Hepburn, 2022[43]).

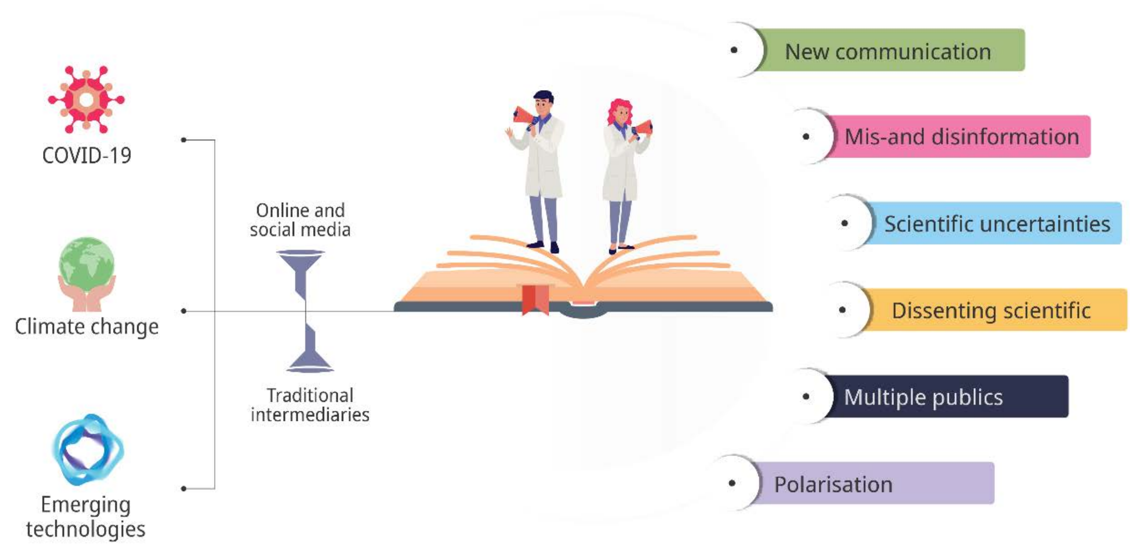
Research integrity and science communication

Scientific integrity, good ethical practice and responsible scientific communication are essential if science is to be trusted. Following a number of high-profile scandals related to fraudulent and/or unethical research practices in the early 2000s, strong measures have been taken to protect the integrity of scientific research – including the development of guidelines, training, and review and reporting procedures. Scientific publishers have been key players in this and the formal publication of scientific results in professional journals is subject to strict review procedures and "self-policing" by peers. Nevertheless, following a number of highly publicised breaches of research integrity and misleading publications during COVID-19, scientific authorities in some countries have recently declared that science needs to refocus on its core values.

Ensuring the rigour of science and the scientific record is a long-term challenge that also relates to incentive and reward structures (see below). Whatever mitigation measures are implemented, they will not always be 100% effective and honest human (and machine) errors will occur. Despite the attention devoted to a small number of fraudulent and erroneous publications, the self-correcting mechanisms of science continue to operate effectively (albeit, in some cases, slowly). Processes for the correction and/or retraction of articles, such as such as Retraction Watch, are increasingly transparent and routine and overall the integrity of the formal scientific record is high. At the same time, as discussed in Box 4.2, the rapid development of AI and LLMs is introducing new challenges and opportunities for producing and detecting fraudulent research publications.

The public communication of science has, until recently, received less attention than the formal publication process for scientific articles. Public communication has tended to focus on exciting scientific discoveries and delivering facts in a one-way process rather than engaging with the public and addressing their interests and concerns. The limitations of this approach were clearly illustrated during the COVID pandemic, when a lack of transparency about the gaps and uncertainties in scientific data and information contributed to distrust in science-based interventions for many population groups (OECD, 2023[40]; 2023[44]). Effective two-way dialogue between citizens and scientists will be important if science is to effectively inform socio-economic transformation.

Figure 4.5. The evolving science communication landscape



Notes: This figure is a simplified representation of the complex relationships between critical issues of societal concern and the challenges for science communication. These are not necessarily wholly new challenges, but they can manifest differently and are often magnified by social media.
Source: Based on OECD (2023[44]).

The science communication landscape is evolving, paving the way for a set of new actors (multiple publics, social media influencers, digital platforms, algorithms, etc.) who can create and share scientific content. There is a shift from traditional communication intermediaries (scientific journals, mainstream media) to online and social media, largely driven by the digital transformation. While this change provides a welcome opportunity to move beyond one-way communication, it can also enable misinformation and disinformation. In this new context, communicating science as it relates to critical issues of societal concern (public health, climate change, emerging tech) faces a number of significant challenges (Figure 4.5).

Poor or irresponsible science communication can seed fake news, which can be rapidly propagated via social media and facilitated by the use of AI. Fake news stories often promote alternative/non-credible scientific perspectives and are a major threat to science and to democratic processes. Ineffective science communication can undermine the credibility of scientific experts, scientific institutions and policymakers. During crises, confusing, contradictory and untargeted scientific messaging can lead to poor compliance with policy advice, putting individuals and communities at risk (OECD, 2023[40]). Responding effectively to misinformation and disinformation requires a multi-faceted approach in which the science community needs to play a leading role. This is partly about responsible science communication (Box 4.3) but also about promoting scientific and digital literacy so that people are able to distinguish between rigorous scientific information and opinion.

Box 4.3. Key principles for responsible science communication

1. Transparency
   - Providing access to data on which scientific conclusions depend.
   - Clearly describing the methods and data used to reach a conclusion.
   - Communicating uncertainties.
2. Inclusivity
   - Reaching out to diverse groups in society.
   - Making science communications accessible (e.g. taking into account digital infrastructure and language barriers).
3. Integrity
   - Adhering to ethical and professional standards in scientific research and communication.
   - Being intellectually honest (e.g. not hyping scientific results) and ensuring the rigour of the research that is being communicated.
4. Accountability
   - Making clear who is responsible for a scientific communication and in what capacity they are communicating (e.g. personal or institutional; subject expert or scientific commentator).
   - Being clear on the sources that underpin a scientific communication.
   - Openly declaring any potential conflicts of interest or commitment for those communicating or providing the content of scientific communications.
5. Freedom and autonomy
   - Communicating scientific research without being constrained by external interference (e.g. political, legal, religious).
   - Respecting the self-governance of academic research and the right of scientists to freely communicate (in accordance with Principles 1-4).
6. Timeliness. This is particularly relevant in emergency situations and includes:

- Delivering relevant and up-to-date information to citizens in a timely manner, with appropriate caveats where necessary.
- Not withholding or delaying the communication of relevant scientific information while ensuring that essential quality controls have been performed prior to its release.

Source: OECD (2023[44]).

Citizen engagement

While responsible and effective science communication is important, public engagement with science needs to go beyond this. Co-design and co-production of research, including the engagement of local and indigenous communities, is essential to achieve the Agenda for Transformative Science, Technology and Innovation Policies. Citizens are important contributors to environmental and health monitoring, e.g. for biodiversity assessments and pandemic alert mechanisms, and also have critical knowledge and perspectives that need to be integrated into transformative research agendas and practice. Citizen science – the active engagement of citizens in the production of scientific knowledge – needs to be widely embraced and incentivised (OECD, 2025[45]). Beyond this, there is a need to support transdisciplinary research that combines and integrates knowledge from different disciplines as well as different public and private sector stakeholders (OECD, 2020[5]). These, and other modes of research that bring together different stakeholders to co-produce scientific knowledge and/or innovations, are increasingly being deployed across many research fields, although they still represent a very small fraction of total research activity. Increasing this requires broad acceptance of the value of citizen engagement in research within both the academic and policy communities and tailored support and review mechanisms (Box 4.4). It also requires new incentive and reward structures to promote a shift in academic culture (see below).

Box 4.4. Key policy considerations for promoting citizen science

Why and when to promote citizen science?

1. Policy and decision makers across government should recognise the value of citizen science for science and society and embed citizen science into their considerations when formulating policies. From the research policy perspective, there are three main rationales for promoting citizen science:
   - increasing the scope of data collection and/or analysis and accelerating scientific discovery
   - addressing societal needs and challenges more effectively
   - promoting the democratisation, legitimacy and uptake of policies informed by scientific knowledge.

How to support citizen science?

2. Senior-level commitment (in ministries, research agencies and institutions) is critical to drive wider acceptance of the value of actively engaging citizens in research.
3. Top-down and bottom-up approaches need to be combined and supported effectively to promote citizen science, as it requires engagement from multiple actors and good interactions between them.
4. A variety of citizen science community groups and entities, including public and private intermediary agents, networks and associations, play important roles and should be supported accordingly.

Overcoming obstacles and challenges

5. The rigour and quality of citizen science, as well as the management of potential bias, must be ensured for citizen science to be widely accepted.
6. Throughout policy planning and implementation, recognition that citizens are a very heterogeneous group with different motivations, interests and barriers for getting involved with research is important.
7. Citizen science collaborations across countries can make a significant contribution to tackling global challenges.

Systemic change and assessing impact

8. The science community and its institutions need to embrace citizen science as a valuable mode of research that can complement and improve traditional research activities. This requires a shift in academic research culture that can be supported by providing appropriate career pathways and reward systems for citizen science practitioners.
9. Monitoring, evaluation and assessment of the impacts of citizen science should reflect the different rationales for its deployment and, in many cases, the most important impacts will not be fully reflected in traditional bibliometric performance measures.

Source: OECD (2025[45]).

Open science – including public access to scientific information and data – can be an important driver to promote responsible science communication and citizen engagement in research. Indeed, citizen science is increasingly viewed as the third pillar of open science (UNESCO, 2022[46]).[9] While opening up scientific data and information and the processes of science to the public at large could potentially encourage misuse, the potential benefits far outweigh the risks provided that appropriate safeguards can be put in place to limit misuse. This is the case, for example, with sensitive personal data for which safe and secure access protocols are being developed so that only legitimate parties can access and analyse the data. Integration of data from multiple sources, including administrative and research data and data collected by citizens, will be important to inform and monitor the impact of socio-economic transformations.

Science, decision making and policymaking

As discussed above, the main focus of STI policy in most countries has been on translating scientific knowledge into commercial products and growth. Until recently, much less attention has been devoted to translating scientific knowledge into effective policy and decision making. Yet in the context of transformations, this is a critical area for attention. Complex transformations are characterised by considerable scientific uncertainty and relevant scientific advice needs to be timely, yet rigorous and transparent (OECD, 2015[47]). Policies and decision making need to be informed by best available scientific evidence that draws on all relevant disciplines and explicitly acknowledges gaps in existing knowledge (Box 4.5). At the same time, the independence and autonomy of science must be protected. The frameworks, processes and incentives to enable well-functioning science advisory systems and the uptake of scientific knowledge in policy making are lacking in many countries and internationally (OECD, 2018[48]). The COVID-19 pandemic was revelatory in this regard and the lessons learnt from it are directly applicable to future crises and ongoing policy development to address complex socio-economic issues (OECD, 2023[36]; 2023[40]; 2023[6]).

Box 4.5. Principles for science advice

The following principles are important in building an effective and trustworthy science advisory process:

1. Have a clear remit, with defined roles and responsibilities for its various actors. This includes:

- a clear definition and demarcation of advisory versus decision-making functions and roles
- defined roles and responsibilities, and the necessary expertise for communication
- an ex ante definition of the legal role and potential liability for all individuals and institutions involved
- the necessary institutional, logistical and personnel support relative to its remit.

2. Involve the relevant actors, including scientists, policymakers and other stakeholders, as necessary. This involves:

- using a transparent process for participation and following strict procedures for declaring, verifying and addressing conflicts of interest
- engaging all the necessary scientific expertise across disciplines to address the issue at hand
- giving explicit consideration to whether and how to engage non-scientific experts and civil society stakeholders in framing and/or developing advice
- implementing effective procedures for the timely exchange of information and co-ordination with different national and international counterparts.

3. Produce advice that is sound, unbiased and legitimate. Such advice should:

- be based on the best available scientific evidence
- explicitly assess and communicate scientific uncertainties
- be preserved from political (and other vested-interest group) interference
- be generated and used in a transparent and accountable manner.

Source: OECD (2020[49]).

One of the principal lessons from the COVID-19 crisis is that no matter how good science advisory processes are, the effective uptake of rigorous scientific evidence by governments depends on the political willingness to consider this evidence. Policymaking is rarely determined by science alone and there are multiple sectoral perspectives that need to be considered and weighed according to different value judgements by policymakers (OECD, 2023[40]). However, consideration of best available scientific evidence (and the associated gaps and uncertainties) is critical for policies to effectively support inclusive socio-economic transformations. The absence of political support or acceptance can be a major challenge for science. In this regard, the three-way relationship between science, society and policymaking is critically important. In well-functioning democracies, governments are accountable to citizens, and public trust in science can reinforce both evidence-based policymaking and the implementation of these policies (OECD, 2024[50]). In the ideal situation, a virtuous triangle of trust can be established between governments, science and the public.

A cultural change within science is necessary to make it more open, inclusive and responsive to societal needs. In the face of urgent global challenges, scientific knowledge needs to inform policy development and decision making at different scales, from the international to the local level.

Policy actions

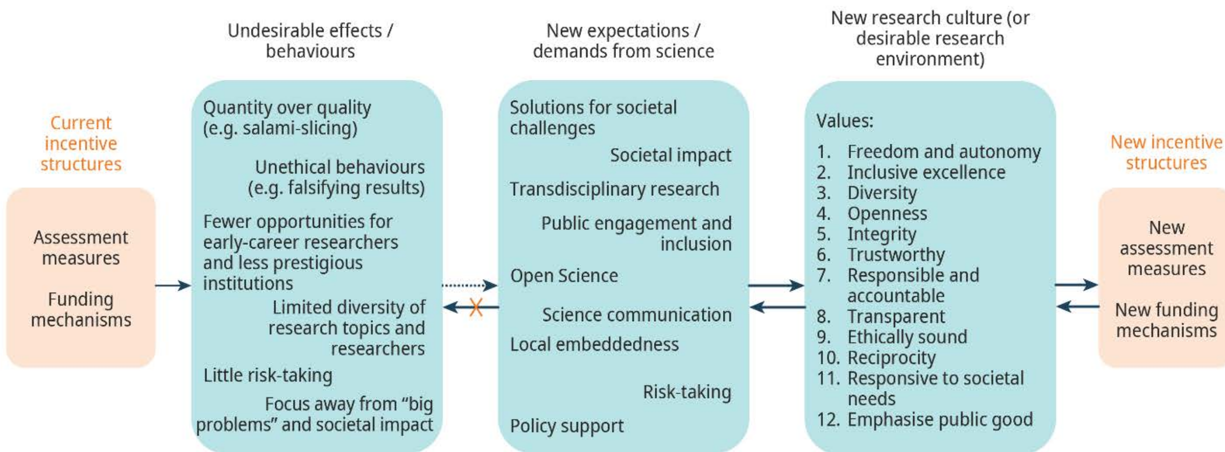
1. Strengthen scientific integrity and good research conduct by shifting the focus from the quantity of research outputs to the quality, transparency and rigour (see next section).
2. Prioritise and reward responsible science communication and societal engagement, including transdisciplinary and citizen science activities (see Boxes 4.3 and 4.4).[10]
3. Promote open science and public access to scientific data and information while ensuring the safety and security of sensitive information.[11]
4. Develop effective science advisory systems that can integrate insights from different disciplines and respond in a timely manner to policymakers' and citizens' needs (see Box 4.5).[12]
5. Promote scientific and digital literacy across society and reward scientists for contributing to related education and training activities.[13]

Leveraging research assessment and incentives

For science systems to significantly change the way that they operate, one or both of the following conditions are required: 1) there is a major crisis, such as a pandemic or a war, that science clearly has a role in addressing;[14] and 2) the incentive and reward structures for scientists and scientific institutions are shifted. Considering the latter, as described earlier, the incentive and reward structures in public research are heavily focused on a narrow definition of scientific excellence. Despite growing criticism and calls for change (see Box 4.6 for examples), bibliometric measures, such as citations, continue to be heavily used – often in isolation – to evaluate and reward scientific performance at the institutional and individual level and to benchmark national performance. This is what drives "the publish or perish culture", with its adverse effects on early career scientists, diversity in science and research choices. It discourages researchers from taking the risk of working across disciplines or sectors and addressing the "big issues" that underpin inclusive socio-economic transformations.

While formal research publications continue to be an important output from research, there are other activities and outputs that society expects and needs and which must be valued and incentivised if science is to support sustainable transformations. These include: public engagement, policy support, provision of trusted FAIR data and green innovations (Figure 4.6). Unlike publication outputs, none of these, with the possible exception of technological innovation, are easy to measure or assess in an objective or quantitative manner. While qualitative assessments and peer review can give some indication of performance in these areas, such approaches are resource-intensive, are not always feasible and have their own limitations (Wilsdon, 2015[51]). Nevertheless, it is important that science policymakers and academic leaders give clear signals in terms of incentives and funding that business as usual is not sufficient for science to support socio-economic transformation. Talented young scientists and scientific institutions must be encouraged and supported in pursuing inclusive excellence in research (see Box 4.1) and to support transformative change.

Figure 4.6. Relationship between research assessment/incentives, behaviour, scientific outputs and research culture



There is growing recognition of the need for change in research assessment processes (Box 4.6). While this has mainly been driven by concerns about the perverse effects that current processes have on individual and institutional behaviour, it also recognises the need for a broader framing of scientific excellence, or inclusive excellence (see Box 4.1), that values different scientific contributions, activities and outputs. A number of countries and institutions are responding to these calls for change and implementing reforms to their assessment systems. Many of these put a greater emphasis on qualitative assessment and peer review, although these approaches have their own drawbacks in terms of resource requirements and potential biases. AI and LLMs are also opening up new avenues, e.g. analysis of publications to identify high-risk innovative research outputs (Machado, 2021[52]). It will be important to harmonise these various initiatives across different scales – individual, institutional, national – and countries so that they do not inadvertently introduce barriers to mobility. Research assessment reforms are a critical tool for incentivising and monitoring different aspects of scientific performance in relation to socio-economic transformations.

Box 4.6. Examples of international initiatives promoting change in research assessment

- DORA (the San Francisco Declaration on Research Assessment) (2012): calls on research actors to avoid using journal-based metrics as a surrogate measure for the quality of scientists or their work, and considers a broad range of impact measures. Provides positive recommendations.
- Science in Transition (2013): a movement started in the Netherlands to develop principles for assessing scientists for hiring/promotion/tenure.
- Leiden Manifesto (2015): sets out principles and best practices for the use of quantitative indicators in research assessment.
- INORMS (International Network of Research Management Societies) (2018): brings together research managers to share good practices. Key outputs of the INORMS Research Evaluation Group – including the SCOPE Framework for Research Evaluation and More than Our Rank initiative – are aimed at all stakeholders in higher education and research.
- FOLEC-CLACSO (Latin American Forum on Research Assessment) (2019): a forum for exchange on research evaluation practices in Latin America, initiated by the Latin American

Council for Social Sciences (CLACSO). The forum provides regional-specific guidelines for research assessment. CLACSO-FOLEC's Research Assessment Academy trains reviewers and assessment specialists to support fairer and more situated evaluation processes.

- Room for Everyone's Talent (2019): an initiative by Dutch public knowledge institutions and funders of research. Advocating for change in the recognition and reward system, and more inclusive research culture.
- Honk Kong Principles for Assessing Researchers (2019): principles to help research institutions to minimise perverse incentives, recognise and reward trustworthy research, support the inclusion of behaviours that strengthen research integrity in frameworks for career appraisal and advancement.
- Science Europe (2020): produced a position statement and Recommendations on Research Assessment Processes.
- TARA (Tools to Advance Research Assessment) (2021): growing out of the DoRA community, this "bottom-up" initiative aims at developing practical tools to promote responsible research assessment in research-performing organisations.
- CoARA (Coalition for Advancing Research Assessment) (2022): an international initiative aimed at reforming research evaluation systems to emphasise quality, inclusivity and a diversity of contributions – moving beyond traditional metrics such as publication counts and journal impact factors.
- AGORRA (A Global Observatory for Responsible Research Assessment) (2023): part of the Research on Research Institute, this observatory generates evidence and analysis to support and accelerate responsible research assessment across 14 countries.
- Barcelona Declaration (2024): advocating for open research information.

Source: Adapted and updated from Curry et al. (2020[53]).

In addition to changes in performance assessment systems, many countries are implementing new research-funding initiatives to support the type of research and innovation required to address the "big questions" and support sustainable and inclusive socio-economic transformation. A number of new funding schemes support mission- and challenge-based research, high-risk/high return research (OECD, 2021[4]), citizen science (OECD, 2025[45]), transdisciplinary research (Kaiser and Gluckman, 2025[54]; OECD, 2020[5]), and other modes of participatory research. At the institutional level, interdisciplinary centres of excellence, some with a specific remit to inform policy, are relatively commonplace and some universities are restructuring their research around transversal missions and/or local societal needs rather than traditional academic disciplines (OECD, 2020[5]). New disciplines, such as sustainability research, that directly address key aspects of the Agenda for Transformative Science, Technology and Innovation Policies are emerging. However, all these initiatives and developments represent a very small proportion of the total public research effort. The large majority of academic research continues to be conducted in traditional disciplines and public and policy engagement activities are sideline activities rather than mainstream outputs. The challenge for science policymakers is to provide the right incentives – including funding – to mobilise a significant fraction of academic science to address the big questions and support society in making urgent socio-economic transformations.

Policy actions

1. Review research assessment processes at all levels to promote inclusive excellence and take full account of the variety of scientific activities and outputs required to support transformative change (see Box 4.6).

2. Recognise the value of citizen engagement, policy advice and FAIR data provision (even in the absence of rigorous quantitative measures) in individual recruitment and career progression.[15]
3. Recognise the value of teamwork, interdisciplinary and-transdisciplinary research, and citizen science approaches, which are all required to address sustainability transformations, and embed this into research assessments [16]
4. Provide the necessary funding support, via suitably adapted mechanisms, to scale-up the type of research and activities, including public and policy engagement, that can support transformations.[17]

Conclusions

Governments and research funders have an important role to play in investing in research that supports socio-economic transformation and supporting the communication and engagement activities necessary to translate research outcomes into effective action. However, investment alone is not sufficient, and the existing structures, operating frameworks and incentives that shape research choices, careers and practices need to be adjusted.

Many positive developments are already underway, but these tend to be small scale and peripheral to the mainstream of scientific activity. Traditional disciplinary research conducted by clever individuals must continue to be supported and serendipitous discoveries will surely contribute to positive transformations, but this alone will be insufficient. Significant structural change and new incentives are required to ensure that a diversity of bright minds are empowered and supported with the necessary infrastructure to work together and engage other stakeholders in producing and applying the scientific knowledge required to promote transformative change.

In the face of urgent global challenges, science should be a source of hope and optimism rather than scepticism and mistrust. Science has been a critical factor underpinning many countries' socio-economic development and prosperity. In fields like medical research or agriculture, it has made a huge contribution to improving human well-being. The understanding of the universe that comes from basic research in physics and astronomy has had an incalculable impact on human culture, beliefs and values. However, an important lesson from history is that scientific knowledge and the technologies that arise from it can be instrumentalised for both good and bad purposes.

Another lesson from history is that science advances best and benefits the most people when an appropriate balance between national competition and international co-operation is achieved. No one country has all the expertise necessary and infrastructure to address the complex global challenges we are already faced with, let alone the new crises that will surely emerge over the coming decades. As the COVID-19 pandemic illustrated, we live in a globally connected world, where crises can rapidly propagate with no respect for national borders. Achieving socio-economic transformations and sustainable prosperity for all requires both the adaptation of national science systems and a strengthening of the global research ecosystem.

The effectiveness of science in promoting transformative change is dependent on science being trustworthy and being trusted by policymakers and the public at large. Building and maintaining this trust, in an increasingly polarised geopolitical environment means upholding academic freedom and research integrity. It also means supporting open science and international co-operation while protecting scientists and scientific institutions from interference by state and non-state actors.

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Notes

[1] This chapter focuses mainly on public science or academic research systems. In most OECD countries, the majority of academic research is conducted in universities and supported by dedicated science funding agencies. In some countries, public research institutes, such as the CNRS in France, are the main public research provider. The distinction is made between science systems and broader concepts of innovation or STI systems, which also include government research conducted in research and technology organisations and dedicated innovation agencies, whose primary mission is to support industry. There is considerable variation across countries in the weight of different components that make up science and STI systems. Science policy and innovation policy can likewise be more or less integrated depending on the scope of different ministries and agencies.

[2] See OECD (2021[8]) for a detailed analysis on policy options and illustrative examples of what countries are doing to reduce precarity. These range from voluntary concordats and charters for research providers to the promotion of tenure track positions or legislative action on contractual status. In 2015, as part of its University Capacity Building Strategy, South Africa introduced a New Generation of Academics Programme with successful applicants being appointed into permanent posts firmly factored into long-term university staffing plans from the outset. France and Germany have introduced legislative measures to eliminate stipends and ensure that PhD and postdoctoral researchers are employed on standard employment contracts. They have also introduced junior chair and tenure track programmes to reduce uncertainty around future careers.

[3] Many countries are implementing a diversity of policies to: build a sound evidence base on diversity in research personnel; support accessibility to research careers for under-represented groups; reduce uncertainty in research careers; and ensure equitable access to funding opportunities. Germany has integrated gender equality as a core component of its Excellence Initiative (2007-2017), in the Excellence Strategy (since 2017) and related research funding strategies, aiming to foster a more equitable and inclusive research landscape. Canada introduced its Tri-Agency EDI Action Plan in 2018 as the foundation for a range of measures to support the equitable participation of students and researchers in the research system. UK Research and Innovation introduced the Equality, diversity and inclusion strategy in 2023, which encourages the nine UK research councils to use equality impact assessments, an evidence-based approach designed to help organisations ensure that their policies, practices, events, trainings and decision-making processes are fair and do not create disadvantages for any protected groups.

[4] See OECD (2023[7]) for a detailed analysis of policy options and examples of initiatives being implemented in different countries to diversify research career pathways. These range from capacity-building training and exchange partnerships between public research providers and other public and private sector actors with research capabilities to improving career guidance and mentorship for early career researchers. Recognition of new research roles, including "third space professionals", who operate at the interface between research and professional services, is also increasing. Japan has recently conducted a Survey of Japan Master's Human Resource Profiling, exploring the reasons why master's students choose non-academic careers instead of pursuing doctoral programmes.

France has created a postdoctoral contract in both public and private law to facilitate the professional transition of doctoral graduates to permanent positions in public or private research. Norway provides mobility grants (salary funds) for doctoral and postdoctoral fellows for internships in the public and voluntary sectors for up to six months.

[5] International mobility is a high priority for many OECD countries that wish to strengthen their research workforce. Most countries have dedicated funding schemes to attract foreign researchers, e.g. Brain Pool Korea is a specific scheme to attract outstanding overseas scientists, including Korean scientists living abroad, to work in all sectors of the economy. Japan is providing major funding to small number of selected universities to become global research leaders, with an emphasis on international recruitment at all levels, from PhD students through to principal investigators, including professional support staff. More broadly, the European Commission is supporting a number of regulatory and administrative initiatives to harmonise conditions, including pension rights, for early career researchers across Europe to facilitate mobility and exchange.

[6] An illustrative example of this is the importance that has been attached to strengthening the RI ecosystem, to ensure health emergency readiness, and to transform Canada's biomanufacturing and life sciences sector after the COVID-19 pandemic. As part of a comprehensive inter-ministerial strategy (Canada's Biomanufacturing and Life Sciences Strategy), the Canada Foundation for Innovation, in co-ordination with domestic funding counterparts, launched two sequential competitions under the Biosciences Research Infrastructure Fund. The first stand-alone competition focused on biocontainment and large-animal facilities to conduct infectious disease research safely. The second competition adopted a strategic ecosystem approach through an integrated biomedical research and RI competition, focused on accelerating the translation of promising research into commercially viable products and processes. The competitions were designed to strengthen research, RI and talent capacity in Canada for innovation-led growth; identify, leverage and boost existing networks of players and RI capabilities across sectors; and create meaningful, sustainable synergies within the pan-Canadian research ecosystem. Central to achieving this was a robust governance structure for design, decision making and oversight, which provided strategic guidance, flexibility and coherence throughout the different stages of programme development and merit review processes. This ensured that the final recommendations for the RI competitions were targeted, anchored in real needs and driven towards the core objectives of the strategy, ensuring alignment with other federal investments to achieve maximum impact.

[7] An illustrative example of this is the Open Data Infrastructure for Social Science and Economic Innovations (ODISSEI), a collaborative consortium in the Netherlands that aims to improve user access to social sciences and humanities (SSHs) RIs. It provides analytical tools, algorithms, a secure computing environment, and specialised services and expertise. ODISSEI regroups all SSH RIs in the Netherlands in a unique consortium. SSHs are traditionally a very scattered group of disciplines with very different data access policies and data standards. Not only has ODISSEI been able to regroup all research institutions on SSHs in the country but it also includes and provides secured access to SSH data from Statistics Netherlands. Secured access to the large diversity of SSH data has allowed the conduct of complex interdisciplinary studies of societal interest.

[8] The CERN Accelerator School (CAS) has been running for over 40 years. Initially focused on training directly related to particle accelerators, courses have progressively diversified to a wide range of domains, including data sciences and engineering, as innovation and technologies developed for scientific equipment proved to be invaluable to a vast array of potential users. CERN works closely with industry and accelerator technologies are transforming society in areas such as security scanning, cancer treatment, and food and materials sterilisation. It has been at the origin of many spin-offs and has recently developed a "CERN Entrepreneurship Student Programme" (CESP) that brings together graduate students from around the globe for practical and theoretical trainings. Under the supervision and coaching of CERN experts and knowledge transfer professionals, students explore, evaluate and exploit CERN technologies

with the aim of developing concepts for new ventures. CESP builds upon basic knowledge about entrepreneurship and venture creation.

[9] Open science is a policy priority for all OECD countries, and several are developing monitoring systems to track the openness of scientific information, data, and software. Despite these efforts, monitoring and evaluation of open science impact remains insufficient, with most current assessment models focusing on output-based measures such as publication counts, rather than real-world societal benefits, inclusivity, and sustainability. The EOSC Observatory data highlights this gap, as only 15 countries have national monitoring for open-access publications, while none have comprehensive monitoring systems for research data. In the meantime, the French government has made strides in developing a national indicator, called the "French Open Science Monitor", which is internationally recognised (see https://frenchopensciencemonitor.esr.gouv.fr/).

[10] A number of countries have introduced strategies for citizen engagement and communication linked with dedicated funding and reward schemes (OECD, 2025[45]; 2023[40]; 2020[5]). Several countries or funding agencies, such as The Research Council of Norway, have embedded citizen science and engagement in national open science strategies. Others, such as the German Federal Ministry of Research, Technology and Space; UK Research and Innovation; and the National Research Foundation in South Africa, have developed dedicated strategies for public engagement or participation in science. With respect to funding, an interesting example is the European Commission's Framework Programme, which has evolved from having a dedicated funding stream for science and society (2002) to science in society (2007) to science with and for society (2014). Since 2021, Horizon Europe has included a focus on widening participation and strengthening the European research area (2021), with societal engagement being mainstreamed across the programme, including in the dedicated funding for missions-driven research. This approach has been echoed in a number of countries which have a variety of dedicated and more generic funding schemes that support citizen engagement. In terms of recognition and rewards, there are also a variety of national initiatives, for example: the Flemmish Academy of Belgium has introduced annual Science Communication Awards; Germany has a Knowledge of the Many – Research Prize for Citizen Science sponsored by the Federal Ministry for Research, Technology and Space and the Natural History Museum; and France has a Prize for Participatory Research, sponsored by the Ministry of Research and Environmental and Agricultural Research's funding agency.

[11] Many countries are implementing a broad range of policies and actions to promote FAIR and open data (STI policies for Open Science portal). In 2021, the OECD Council adopted a revised Recommendation of the Council concerning Access to Research Data from Public Funding and a policy toolkit is being developed to support countries in the implementation of this Recommendation.

[12] Science advisory structures and processes differ from one jurisdiction to another (OECD, 2015[47]) and these proved to be variously effective during the COVID-19 pandemic, when a particular challenge was integrating data and knowledge across different sources (OECD, 2023[40]). The pandemic also highlighted the challenges in co-ordinating and sharing advice across federal and national boundaries (OECD, 2018[48]). Since the pandemic, a number of countries have revised their science advisory mechanisms to try to address these challenges.

[13] While promoting digital and scientific literacy falls largely under the remit of formal education, there a number of accompanying measures or actions that scientific agencies and institutions can also take. These range from support for science centres and museums to science festivals or open laboratories. The United Kingdom's Festival of Social Science takes place annually and includes a series of exhibitions,

lectures and public debates as well as performances, guided walks and workshops. A similar Science Festival is organised annually in different cities in Poland.

14 While climate change and biodiversity loss are widely regarded as major global crises, they are not at the top of the list of national priorities for many countries. This reflects the fact they are also not the immediate priority or concern for the majority of citizens in most countries. In the absence of strong societal and political pressure, the public scientific enterprise as a whole has not yet fully mobilised to support sustainability transitions and inclusive socio-economic renewal. The bottom-up mobilisation of the scientific community that characterised the COVID-19 pandemic is not happening spontaneously with regard to sustainability transitions, at least not at the necessary speed and scale.

15 One mechanism to ensure this is to adopt standardised academic CV templates that include only a small number of key publication outputs and support narrative accounts for other activities and outputs, e.g. in relation to science and society or science and policy. Going further, the Norwegian Career Assessment Matrix (NOR-CAM) is a framework for assessing and evaluating research(ers). Central to this framework is the move away from merely favouring quantitative measurements, for instance solely focusing on the number of publications or the ranking of the journal where the research is published, to a more comprehensive and flexible framework where multiple areas of expertise can be assessed more systematically than is currently the case.

16 The Dutch Recognition and Rewards programme, launched in 2020, brings together an alliance of research institutes and universities with support from the Ministry of Education, Culture and Science to promote cultural change in academia via changes in research assessment and incentives. It has five areas of focus: 1) diversifying and revitalising career paths; 2) achieving balance between individuals and the collective; 3) stimulating open science; 4) focusing on quality; and 5) stimulating academic leadership.

17 On behalf of the German federal government, the state of Brandenburg and several members of the Alliance of Science Organizations in Germany, the Federal Ministry of Education and Research (since May 2025 renamed to the Federal Ministry of Research, Technology and Space) established a new research institute in 2009 with the aim of acting as an intermediary between science, politics and society. In January 2023, the institute joined the Helmholtz Association of German Research Centres and was institutionalised as the Research Institute for Sustainability. The institute's goal is to act as an international platform for science and a link between research, politics and business in society and to contribute to the formation of public opinion. With its transdisciplinary research approach, the Research Institute for Sustainability brings together science, politics, economy and society in discourses on societal challenges. The Federal Ministry of Education and Research has also been funding "social-ecological junior research groups" since 2002. These groups explicitly implement interdisciplinary and transdisciplinary research approaches to tackle complex societal challenges.

5 Technology convergence: Trends, prospects and policies

The convergence of technologies is driving forward innovation, new approaches, new production methods, new applications and new governance challenges. Four important technology areas – synthetic biology, neurotechnology, quantum technologies and earth observation from space – illustrate these processes. While technology convergence can be understood in terms of products or technology applications, it can also be understood as a process of integration, not only across technologies, but also disciplines and communities. Policymakers around the world are enabling convergence by designing "convergence spaces": institutions and programmes that integrate scientific approaches, technical infrastructure and interdisciplinary skill sets. The intention is to unleash the generative potential of deep multidisciplinarity and interdisciplinary assets. The discussion of the four technology areas reveals the possibilities of convergence as a generative force in each domain and points to new challenges and opportunities for emerging technology policy.

Key messages

- Technology convergence can be understood in terms of products or technology applications, but also as a process of integration involving different disciplines and communities. Societal transformations will require harnessing the dynamism of technology convergence, a trend emerging with particular force in the contexts of artificial intelligence (AI), neurotechnology, synthetic biology, quantum technology and space observation.
- Convergence can be enhanced by designing "convergence spaces" – physical, digital and technological infrastructures and platforms that promote the integration of tools, fields and human expertise. Integrating considerations of a regulatory, ethical, legal and social nature can also help shape the outcomes of convergence so that innovation accords with existing regulations and societal values and is sensitive to concerns and risks.
- In the interest of promoting technology convergence to drive transformative change in the economy, governments could:
    - Design convergence spaces through good institutional and programme design to foster deeper forms of interdisciplinary research, engineering and innovation.
    - Simultaneously consider technological and regulatory developments, since the often-complex regulatory implications of convergence calls for including ethical, legal and social analysis in the interdisciplinary mix of the convergence space.
    - Analyse the feasibility and potential effects of technological convergence on key sectors, with input from labour and business stakeholders and other representatives of civil society.
    - Leverage different funding models, access rules and technology transfer structures to shape the technological and collaborative platforms necessary for convergence.
    - Find agile regulatory approaches and promote strategic intelligence to better anticipate and engage the drivers and impacts of convergence, drawing on the OECD Framework for Anticipatory Governance of Emerging Technologies.

Introduction

Societal transformations will require harnessing the dynamism of technological convergence, a trend long noted across science and technology policy communities but emerging with particular force in the contexts of AI and the digital transformation, advanced biotechnologies, and materials science. In many analyses, technology convergence promises powerful synergies to enhance the speed and functionality of technologies, tools and products. The phenomenon is seen across academia and industry. Indeed, seeking to expand their existing knowledge domains, many industrial actors are moving beyond traditional single-technology development models in favour of more multivalent cross-disciplinary technology convergence (Ma and Wu, 2024[1]). In particular, AI, as a broadly enabling technology, promises to supercharge the large-scale integration of digital technologies. Driven particularly by the digital transformation and AI, but not only so, many key areas of emerging technology like robots that learn, biotechnology, quantum science and technology, or satellite systems have become the loci of powerful integration of tools, approaches, disciplines and technologies.

Perhaps because convergence presents special opportunities and challenges for innovation policy that arise with the synergy of hitherto separate domains, it has become one of the central themes of technology and innovation strategies (Sick and Bröring, 2022[2]). Technological integration is giving rise to unique policy dimensions and governance challenges that must be addressed should technologies achieve their full potential, but the empirical basis for policy approaches, while growing, is arguably still limited.

This chapter examines the phenomenon of technology convergence in the context of four important emerging technological areas: synthetic biology, neurotechnology, quantum technologies and space-based earth observation (EO). The combination of technologies previously understood as distinct are driving forward innovation, new approaches, new production methods, new applications and new governance challenges. This chapter argues that while technology convergence can be understood in terms of products or technology applications, it can also be understood as *a* process of integration not only across technologies but across disciplines and communities. This process has internal logics and technological drivers. Nevertheless, policymakers are enabling convergence by constructing what might be called “convergence spaces”: institutions and programmes that integrate scientific approaches, technical infrastructure and interdisciplinary skill sets. Through its discussion of convergence in the four emerging technology areas, the chapter illustrates the diverse products that are arising at the intersection of multiple technologies, as well as the role of convergence spaces. Convergence phenomena occurring through and around these four technologies are giving rise to new challenges and opportunities for emerging technologies’ policy.

Understanding convergence

Convergence as a product

Technological convergence is an umbrella term whose definition has grown since its first popularisation in the early 2000s. “Technological convergence” was first used to describe the combination of nanotechnology, biotechnology, information and communication technologies, and cognitive technologies, leading to products such as micro-electro-mechanical systems (used in sensors and actuators from automobiles to electronic game consoles and cellphones), computerised genomics and nanoelectronics. In this usage, technology convergence can be understood in terms of the combination or hybridisation of one or more technologies (OECD, 2014[3]). Today, key convergence products include brain-computer interfaces (BCIs), quantum-enhanced biosensors and space-based biomanufacturing devices, all emerging from the interaction of synthetic biology, neurotechnology, quantum technologies, space technologies and AI. In this sense of the concept, convergence is primarily located in products, i.e. the resulting technologies themselves. These convergence products are conceived for immediate customer, consumer and patient use or as research tools.

Convergence as a process

Although convergence as tool is a familiar framing that captures key aspects of the phenomenon, convergence can also be understood as a process – dependent on human agency, technologies and systems – that can result in new products, industries, and fields of research and development (R&D). The creation of convergence products results from various cross-disciplinary and cross-sectoral integration efforts. In this sense, technological convergence refers to a set of processes, typically subdivided into co-evolution and fusion. Co-evolution is the process by which various technologies develop in tandem, each propelling the other's advancement. For example, AI is made increasingly powerful with advances in computing hardware, while 5G networks amplify the scale and speed at which AI-driven services can be delivered.

Fusion goes beyond combination and refers to the full integration of scientific knowledge and tools leading to entirely new fields of innovation. In 2014, experts working through the US National Academies defined the concept in terms of combining disciplines to create new fields (US National Academies, 2014[4]). In other words, it "comprises the merging of ideas, approaches, and technologies from widely diverse fields of knowledge at a high level of integration. [This constitutes] one crucial strategy for solving complex problems and addressing complex intellectual questions under emerging disciplines" (US National Academies, 2014, p. 20[4]).

The process has been described not as two parts creating a single whole but rather as Brew describes, "disciplines are more like water than land in that they can be separated yet come together, can combine, merge and recombine in an almost infinite number of ways" (Brew, 2007[5]). Fusion can happen at varying degrees of depth, from full communication infrastructure and networks to data sets and analytics to down-the-line user-facing products and services.

The human element of convergence figures in the design, application of expertise and judgment, institutional context, and framework conditions for enabling development and diffusion. In perhaps its most expansive view, the convergence process has been understood as a phenomenon of "escalating and transformative interaction among seemingly distinct scientific disciplines, technologies, communities, and domains of human activity" (Roco et al., 2013[6]). In this sense, convergence is a true collaboration between human creativity and technological logics (Bijker, Hughes and Pinch, 1987[7]). In addition to reminding us of the inherent social nature of technological change, this conception also creates the possibility for normative integration that crosses over the technology and social divide. For instance, convergence can help embed norms like "privacy-by-design" in technologies and drive responsible innovation.

Convergence spaces and interdisciplinary assets

On some level, technology convergence seems to happen organically and be determined by purely technological logic. But sociologists of science and technology have demonstrated the role of human agency in science and innovation for decades (Latour, 2005[8]). How can governments and other funders help create good conditions to help drive convergence and direct it towards key science, engineering and societal problems?

Creating the right conditions for convergence can depend on the creation of the optimal conditions for R&D institutions, infrastructural assets, human skill sets, and networks to create synergies and novel sciences and technologies – i.e. "convergence spaces". The OECD has defined convergence spaces as physical and/or material loci that bring together diverse elements – actors, disciplines and technology – in ways that foster convergence (Winickoff et al., 2021[9]). Convergence spaces are akin to "innovation ecosystems". However, whereas the notion of innovation ecosystem focuses on networks of institutions, the notion of convergence spaces emphasises the goal of integrating scientific and engineering approaches, skills and understandings to draw on and create deep interdisciplinarity. Here the intention is to unleash the generative potential of interdisciplinary assets convened in convergence spaces. In doing so, convergence spaces can produce new kinds of value, products, technologies, training and approaches to regulation. If designed correctly, these can help optimise tangible and intangible value, realise sustainability models, foment collaboration, and promote technological integration. Box 5.1 describes one example of this intent.

Box 5.1. The Israeli Bioconvergence Program: A prototypical convergence space

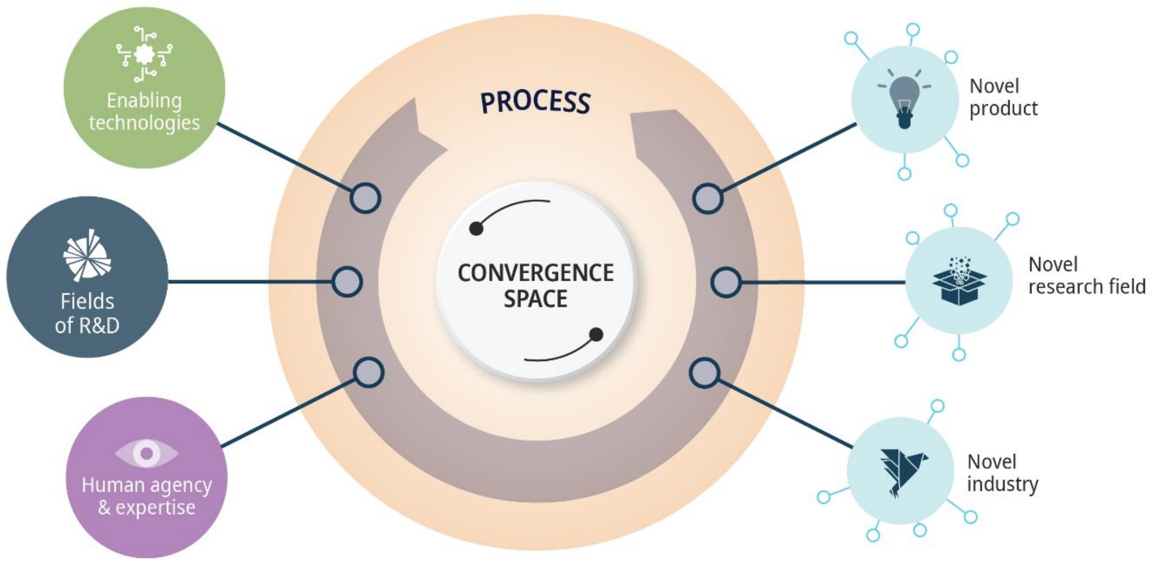
Israel's National Bioconvergence Program is strategically designed to cut across sectors and disciplines bringing together biology, engineering and computational science, and driving innovation in health, agri-food, manufacturing and the environment. Launched in 2022, the initiative combines multiple public offices spanning science, technology and innovation; health; finance; defence; and academia – broadly aligning policy and ecosystem support. Planned public investment in the programme is ~USD 400 million over a decade, attracting ~USD 200 million more through private sector leverage, including international partnerships (e.g. an international bioconvergence challenges programme). The programme has a five-pillar structure:

1. **Research:** National funds invest in multidisciplinary applicative research, supported by high-end research infrastructure and services.
2. **Interdisciplinary research and development (R&D):** Over USD 80 million publicly invested in industrial R&D, start-ups and consortia, closing funding gaps and growing the ecosystems with dozens of new companies. Key themes include biochips, engineered tissues, bioplastics and circular bioeconomy solutions.
3. **Infrastructure:** Significant public investments to establish self-sustained R&D service labs supporting innovation in SynBio, precision fermentation and scale-up, and prototyping and small-scale production of biochips/devices.
4. **Human assets:** Over USD 2 million allocated to various programmes for multidisciplinary training, upskilling and team-building across the academic and industrial pipeline, reaching more than 1 000 people.
5. **Enabling regulation:** A facilitative regulatory environment developed with the Ministry of Health to guide companies through regulatory pathways for complex bioconvergence health and food technologies, resulting in the world's first approvals for alternative milk and cultured beef.

Source: Israel Innovation Authority, https://innovationisrael.org.il/en/article/bio-convergence-israels-next-growth-engine.

As a simplified model of the process, three aspects of technological convergence (enabling technologies, fields of R&D, and diverse technical expertise) can be thought of as working through a churning wheel (Figure 5.1), where the process of integrating multiple disciplines and knowledge infrastructures takes place through spaces of collaboration and exchange. Technology convergence can respond to defined market or societal needs to enable the emergence of new industries or research domains. This process can help produce new and hybrid products, open novel research fields, and create new industrial opportunities.

Figure 5.1. The technology convergence process



Convergence spaces: physical and digital platforms that bring together technological, human, governance and scientific elements in a process that generates new products, fields and industries. These new products, fields and industries feed back into the convergence process making a virtuous cycle.

Note: R&D: research and development.

Cases of convergence

This section examines convergence in the context of four important technological areas: 1) synthetic biology; 2) neurotechnology; 3) quantum technologies; and 4) EO from space. The discussion of the four technology cases reveals the rich possibilities of convergence as a generative force in each domain. In doing so, the chapter illustrates convergence in both its forms: the diverse products that are arising at the intersection of multiple technologies and examples of convergence spaces illustrated in the boxes below.

Convergence in synthetic biology

Synthetic biology brings an interdisciplinary engineering approach to biotechnology, associating biology, digitalisation, engineering, AI and automation. While there is no internationally recognised definition, synthetic biology designs, fabricates, scales and embeds biological components and systems – especially stretches of DNA – into useful applications.[1] Synthetic biology has an overarching perspective of harnessing living systems in research, product development and commercial solutions. It involves engineering living systems at multiple scales, from molecules to organisms, to enable research and product development in areas such as chemical, new materials and bio-based fuels. Synthetic biology draws on an array of scientific and technological approaches and tools, as described below, and its convergence finds the most tangible expression in the pieces of infrastructure known as biofoundries, which are interdisciplinary assets *par excellence*.

Understanding and designing biological systems and protein structure

While synthetic biology has been an important field of science and engineering that predates the rise of AI, its convergence with AI tools and accompanying digital technologies and automation is accelerating the pace of innovation in the field. The combination of synthetic biology and AI, and in particular machine learning, is proving to be a powerful tool for the design and optimisation of biological systems. Machine learning algorithms can be used to analyse vast amounts of experimental data, such as gene expression profiles and metabolic fluxes, to identify patterns and predict the behaviour of biological systems (Vindman et al., 2024[10]). By training deep neural networks on large data sets of genotype-phenotype relationships, researchers can create models that accurately predict the outcomes of genetic modifications, such as gene knockouts or mutations. These models can then be used to guide the rational design of engineered organisms, reducing the need for trial-and-error experimentation and guiding the design of new genetic circuits, metabolic pathways and synthetic organisms with desired properties (Iram, Dong and Ignea, 2024[11]). These approaches have a wide range of applications across both research and economic sectors, including the use of computational prediction tools.

Computational prediction tools can provide new or faster information to researchers to help accelerate research. Understanding protein structures at the molecular level is a foundational biotechnology innovation, particularly in the development of new therapies. Recently, AI tools like deep learning have been shown to help predict protein structure with the same accuracy as experimental methods. Google DeepMind's AlphaFold, which contributed to the awarding of a shared Nobel Prize in Chemistry, is a prominent example of how convergence is being successfully applied in synthetic biology today. By leveraging publicly available data on known protein sequences and structures (obtained experimentally), the AI model can accurately and efficiently predict the 3D structure of proteins based solely on their amino acid sequence. Their latest model, AlphaFold 3, can go further and predict the interactions and structures between proteins and other biomolecules, like DNA and RNA. Traditionally, these analyses of proteins were time-consuming and expensive, a major bottleneck to innovation.

Chemicals and materials

AI-augmented synthetic biology is also poised to transform the production of materials and chemicals, enabling the sustainable and scalable synthesis of a wide range of products. By engineering microorganisms to produce desired compounds, synthetic biology is providing an alternative to traditional chemical synthesis methods that often rely on fossil fuels and generate harmful byproducts.

- **High-value chemicals, e.g. flavours, fragrances and pharmaceuticals, using microbial fermentation.** By engineering the metabolic pathways of microorganisms, researchers can create efficient and sustainable production platforms for these compounds. AI tools can aid throughout this process from the design to the extraction stages, by helping design the genetic sequences used or optimising and scaling production systems (García Martín, Mazurenko and Zhao, 2024[12]).
- **Bioplastics and resins.** Researchers have developed synthetic pathways in bacteria and yeast that can convert renewable feedstocks, such as sugars and plant oils, into monomers that can be polymerised into biodegradable plastics. These bio-based plastics have the potential to replace petroleum-derived plastics, reducing our reliance on fossil fuels and developing safe-by-design materials mitigating the environmental impact of plastic waste (Adkins et al., 2012[13]). AI neural networks are being used to predict these bioplastics' characteristics and find viable replacements to non-biodegradable products on the market, which could then be produced via microbial synthesis (Kuenneth et al., 2022[14]).
- **Self-assembling and repairing advanced materials.** Scientists have engineered bacteria to produce biofilms that can be used as living materials for applications such as water filtration and bioremediation. These living materials can be programmed to perform specific functions, such as selectively binding to contaminants or degrading pollutants. The unintended release or escape of such living organisms into the environment could, however, also pose a risk for natural microbial communities.

Biofoundries as interdisciplinary spaces

Converging technologies tend to co-emerge with other infrastructure that leverages, enables and drives convergence. In synthetic biology, this process can be seen in the so-called “biofoundry”: an advanced, automated facility designed to accelerate synthetic biology research and biomanufacturing by integrating high-throughput robotics, automation and AI-aided design tools. In the field of synthetic biology, biofoundries, and the institutions, disciplines and skill sets assembled around them, operate as powerful convergence spaces. Catalysing the development of potential products, biofoundries can improve and produce novel knowledge and products. In the field of biotechnology, convergence with AI is just gearing up.

The biofoundry referenced above leverages machine learning and large language models to accelerate the design and production of bio-based products and reduce labour costs via automation. A study at the University of Wisconsin-Madison demonstrated that AI-driven autonomous protein engineering could achieve results three to six times faster than the speed of the (human) researchers at the university (Rapp, Bremer and Romero, 2024[15]). Biofoundries require significant upfront investment, but their long-term operational costs, such as staffing and equipment maintenance, pose a greater challenge to sustainability. In particular, the need for a skilled workforce that can combine knowledge of AI, automation and molecular biology is a serious bottleneck. While technologies and tools are converging, training programmes for researchers and technicians still remain mostly mono-disciplinary.

Policy opportunities and challenges

Some policy issues arising from the convergence of synthetic biology, AI and automation include:

- **Optimising the regulatory environment.** Technology developments can pose challenges for regulatory systems which may become less fit-for-purpose as technologies converge. For AI-enabled synthetic biology, these challenges are exacerbated not only by the speed of technological development but also by the complexity of combinations of AI, synthetic biology, automation, etc. In this convergence, a variety of regulatory regimes apply that encompass R&D in the design of new bioproducts, the use of AI in that context, and the regulation on the safety of the products themselves. This calls for the simultaneous consideration of technological development and regulatory considerations, and supports the need for including ethical, legal and social analysis into the interdisciplinary mix of the convergence space.
- **Access and freedom to operate.** The trade-off between open science and security is key in AI-enabled synthetic biology given the potential biosecurity implications of some applications, as well as open access and commercial application, since fostering trust in the biodata used and the algorithms mobilised is key but so is protecting intellectual property and ensuring economic competitiveness. How can innovators be transparent and build trust while being secure and profitable?
- **Biodata harmonisation and sharing.** AI-enabled synthetic biology relies on the mobilisation of vast amounts of biodata that can then be processed using algorithms. However, the nature of the data infrastructures – both their form and who controls them – is not yet clear. With the potential of industrial monopolies on biodata, and the lack of standards for quality control, interoperability and rules for sharing data, there is a clear challenge for governance. In a similar vein, there is often little transparency on the construction of (bio)databases (what is in the data set and how did they get it?), the means of storing the data (who owns it and how is it managed?) and the quality of the algorithms (what does the outcome from the algorithms actually mean?). This poses a great challenge for governance.
- **Challenges of oversight with humans out of the loop.** Replacing humans with AI, automation and robotics means that increasingly complex and time-consuming processes of synthetic biology

development are possible. However, ensuring that human agency has a meaningful place in workflow preserves opportunities for value judgements to be made during the R&D processes as well as quality control, assurance, cybersecurity, and even legal and moral accountability. It is also critical to consider workers' rights to consultation, participation and protection against unemployment. With the promise of increasingly autonomous design, build, test and learn cycles, what is the best balance between autonomous and human-in-the-loop systems?

- **Supply chain access and resilience.** The COVID-19 pandemic revealed pressures on key supply chains for synthetic biology R&D. With an increased interest in technological sovereignty and rising geopolitical tensions, building resilience in global synthetic biology supply chains is a key challenge going forward. This is particularly key for realising the promise of distributed manufacturing through AI-enabled synthetic biology, where the need for specific chemical reagents to undertake R&D is key, and is dictated by local resources, demographic pressures and sustainability impact. Beyond the supply risks observed during health crises with border closures, the challenges of synthetic biology on supply chains stem also from the replacement of oil with plant-based or waste-derived sugars as raw materials. Beyond the risks of border closures, it will, therefore, be essential to rethink raw material supply networks to make this industry sustainable.
- **Cyberbiosecurity as a key issue for research security.** The increasing integration of biological research and automation has elevated the significance of cyberbiosecurity – the intersection of cybersecurity and biological sciences. Cyberattacks such as ransomware and distributed denial-of-service attacks on biological research and biomanufacturing facilities pose substantial risks, including economic disruptions (e.g. operational delays, industrial espionage), environmental hazards (e.g. accidental explosions, release of hazardous substances) and public health threats (e.g. unintentional dissemination of infectious agents). However, much of the existing infrastructure supporting biological research and bioproduction was not originally designed with resilience to cyberthreats in mind. This vulnerability is particularly pronounced in under-resourced communities, which frequently rely on secondary markets where older, and potentially less secure, equipment is more prevalent. As a consequence, enhanced oversight and control mechanisms to systematically assess these vulnerabilities and develop effective mitigation strategies might be required (Robinson and Nadal, 2025[16]). Further interdisciplinary research and policy initiatives are essential to strengthen cyberbiosecurity frameworks and ensure the resilience of biological research and biomanufacturing infrastructures against evolving cyberthreats.
- **Lack of ecological data for applications that are intended for release.** With the great pace of innovative and new synthetic biology applications that are intended for release more cases will arise, where a sound risk assessment will be hampered by a lack of ecological data of the receiving environment. A parallel strengthening of biodiversity research will prevent this obstacle and help to make use of these technologies.

Convergence in neurotechnology

Neurotechnology has been defined as "devices and procedures used to access, monitor, investigate, assess, manipulate, and/or emulate the structure and function of the neural systems of natural persons" (OECD, 2019[17]). Neurotechnology is marked by increasing confluence of component technologies, scientific understandings and know-how, particularly AI and BCIs and even new immersive technologies. These technologies and approaches are converging in both the sense of "co-evolution" and "fusion" noted above, and present opportunities for the repair and enhancement of neural functioning (García and Winickoff, 2022[18]). The same confluence also raises new ethical, legal and social implications or exacerbates existing ones (García and Winickoff, 2022[18]).

Assembling institutions, actors and tools around the human brain

The complexity and importance of the human brain – as a terrain of study, engineering, diverse skill sets and disciplines – is opening up forms of innovation that are deeply interdisciplinary, translational and transformational. Indeed, it is actively assembling a broad range of actors, approaches and institutions to the project of generating new therapies, applications and solutions. New institutions devoted to neurotechnology are taking advantage of the convening power of the human brain to generate new kinds of understandings and interventions of neural processes. An excellent example of this is the Wyss Center in Geneva (Box 5.2).

Box 5.2. The Wyss Center: Neurotechnology convergence in Switzerland

The Wyss Center for Bio and Neuroengineering is an independent not-for-profit translational research centre and "venture builder" dedicated to advancing disruptive innovations in the convergence arena of neurotechnologies. A prototypical convergence space, the centre assembles the skills and knowledge of its personnel, state-of-the-art infrastructure, and business innovation partnerships to generate new solutions for mental and brain health.

Founded in 2014 with the support of Swiss entrepreneur and philanthropist Hansjörg Wyss, the Wyss Center convenes experts from diverse fields such as neuroscience, engineering, software and data analytics, neurosurgery, regulatory and clinical affairs, quality assurance, manufacturing, and business development. Together they pursue challenge-driven research and engineering approaches to the human brain, also engaging in patient-based translation, business activities such as spin-off formation, licensing, joint ventures and asset transactions. The Wyss Center's diverse portfolio includes brain-computer interfaces, advancements in neurosurgery, artificial intelligence-driven neuromodulation, breakthroughs in neural imaging, studies on the gut-brain axis, epilepsy management, and clinical applications of optogenetics.

One example of a programme is the USD 23 million "Campus Biotech Lighthouse Partnership for AI-Guided Neuromodulation", an inter-institutional collaboration aimed at accelerating translational research and development in the field of neurotechnology and artificial intelligence (AI). The programme seeks to leverage interdisciplinary excellence to explore new implantable neurotechnologies for brain recording, on-chip AI-guided decoding of neural activity into electrical patterns, and precise stimulation of the spinal cord.

Source: Based on information from the Wyss Center (personal communication and website).

BCIs are technological mechanisms enabling direct communication between the brain and external devices. These techniques show potential for cognitive enhancement by influencing neural activity like attention, memory and executive functions without surgery. AI systems are machine-based systems that, for explicit or implicit objectives, infer, from the input they receive, how to generate outputs such as predictions, content, recommendations or decisions that can influence physical or virtual environments (OECD, 2024[19]). Immersive technologies, often referred to as "extended reality", create environments that blend digital and physical realities to various degrees (OECD, 2025[20]). Key elements of these immersive technologies include: fully immersive technology digital environments that replace the user's physical surroundings, i.e. virtual reality (Turan and Karabey, 2023[21]); digital overlays on the physical world, enhancing real-world experiences with digital information, i.e. augmented reality (Samuel, 2022[22]); and a combination of the two, with digital overlays that are affected by the physical features like lighting, i.e. mixed reality (OECD, 2025[20]).

The three fields are helping each other accelerate their individual trajectories and integrating to form new applications. AI can enhance immersive technology experiences by providing intelligent responses, personalised content and adaptive environments based on user behaviour and preferences. BCI enables direct communication between the brain and external devices or software, allowing users to control computers or devices using their thoughts. It can lead to more natural and intuitive interactions within immersive technology environments, such as controlling virtual objects or environments through mental commands. In the future, immersive technology might provide a platform for integrating AI and BCI, offering users experiences that respond intelligently to their inputs and cognitive states. But these very same convergences can raise concerns around human autonomy and privacy.

For example, Forsland et al. (2021[23]) describe a BCI system for augmented reality that demonstrates the potential for seamless integration of neural inputs with immersive technology environments. This convergence enables more natural and intuitive interactions within immersive technology environments, such as controlling virtual objects or navigating digital spaces through mental commands. Mental commands can replace or supplement traditional input methods, particularly valuable in situations where physical movement is limited or undesirable (Forsland et al., 2021[23]).

The neuro-AI convergence produces new products and opens research avenues. Some estimates suggest that the global market for BCI will increase to USD 6.2 billion by 2030.[2] Implications for healthcare and consumers' use are profound, therefore requiring ethical reflection and policy consideration. This section illustrates AI-BCI-immersive technology's key developments, discusses its most critical ethical considerations and identifies salient policy challenges.

Converging medical technologies

More than 3 billion people worldwide (i.e. over 40% of the global population) were living with a neurological condition in 2021 (Steinmetz et al., 2024[24]). Healthcare is undergoing a digital transformation, integrating AI into many aspects of the care, which promises to reduce costs and risks of therapies (Al Kuwaiti et al., 2023[25]). In the area of brain health, AI is creating a paradigm shift in delivery, patient outcomes and medical research. Convergence around neurotechnology can be found in diverse areas of medicine, such as:

- **Precision medicine:** AI algorithms analyse vast amounts of patient data, including genetic information, to tailor treatments to individual patients. When combined with BCI technology, this allows for real-time monitoring and adjustment of therapies based on neural feedback. For example, in the treatment of Parkinson's disease, AI-powered closed-loop deep brain stimulation systems can adjust stimulation parameters in real time based on neural signals, providing more effective symptom management (Denison and Morrell, 2022[26]).
- **Robotic surgery:** AI-powered surgical robots are becoming increasingly sophisticated, with immersive technology interfaces providing surgeons with enhanced visualisation and control. BCIs are being explored to allow surgeons to control these robots more intuitively, potentially improving surgical precision and reducing fatigue. Recent advancements include the integration of haptic feedback in robotic surgical systems, allowing surgeons to "feel" tissue properties through BCIs, significantly enhancing precision in minimally invasive procedures (Qu et al., 2022[27]).
- **Neurological rehabilitation:** Combining BCI-controlled virtual environments with immersive technology can create highly engaging and effective rehabilitation programmes for patients with motor impairments. Using AI, these systems adapt in real time based on neural feedback, optimising the rehabilitation process (Vourvopoulos et al., 2019[28]). Recent studies have shown that BCI-virtual reality rehabilitation systems induce greater neuroplasticity compared to traditional therapies, leading to improved functional outcomes in stroke patients (Aderinto et al., 2023[29]). A notable example is the use of BCI-controlled virtual reality systems for upper limb rehabilitation in stroke patients, which have shown promising results in improving motor function beyond traditional therapies (Zhang et al., 2020[30]).

- **Cognitive training:** For patients with cognitive impairments, BCI-immersive systems provide personalised cognitive training exercises that adjust difficulty based on real-time neural activity, potentially enhancing the effectiveness of cognitive rehabilitation. AI algorithms analyse patterns of cognitive performance and neural activity to tailor training programmes that target specific cognitive domains, maximising therapeutic efficacy (Maggio et al., 2023[31]).

Consumer markets

Neurotechnology convergence in the consumer space is significant due to its potential for rapid, widespread adoption and its intimate integration into daily life. Unlike specialised or industrial applications, consumer-focused convergence has the power to reshape social norms, personal habits and even cognitive processes on a massive scale. The consumer market for converging technologies evolves rapidly, with products ranging from electroencephalogram (EEG)-based meditation headsets to advanced augmented reality glasses with neural interfaces. These technologies find applications in gaming, entertainment and education which, together, represent significant economic potential.

The consumer neurotechnology market is rapidly expanding, with a focus on enhancing cognitive performance, emotional regulation and overall well-being. Many companies are pushing towards non-invasive and minimally invasive BCIs for consumer use. These technologies are increasingly moving beyond niche markets and entering mainstream consumer consciousness, driven by advancements in miniaturisation, AI algorithms and user experience design. Other companies are exploring different approaches to consumer BCIs. The patent awarded to Cognixion (Forsland et al., 2021[23]) describes a BCI system for augmented reality that aims to overcome the limitations of wired connections and expand beyond medical lab usage. Their emphasis on offline AI processing and the potential for smart glasses or contact lens integration points to a future where BCIs could become as ubiquitous and unobtrusive as today's smartphones. Notable examples include Neurable's brain-sensing headphones, which use EEG to measure focus and provide a personalised audio experience as well as NextMind's dev kit, which allows users to control digital interfaces using their thoughts.

The integration of EEG technology into everyday wearables, exemplified by Apple's patent for EEG-capable earbuds (Azemi et al., 2023[32]), represents a significant step towards ubiquitous neurotechnology. This trend towards unobtrusive, consumer-friendly neurotechnology is further exemplified by companies like Sens.AI, whose patent (Telfer, Julihn and Sokhadze, 2023[33]) describes a wearable device for closed-loop transcranial photo biomodulation, which uses light applications to improve processes in the brain and treat mental disorders such as depression. Such technologies blur the line between consumer wellness products and medical devices, potentially offering cognitive enhancement capabilities to the public.

Consumer technologies in the context of the AI-BCI-immersive convergence refer to products and services designed for personal use by the general public, as opposed to medical or industrial applications. These technologies aim to enhance everyday experiences, productivity, entertainment and personal development. Key areas of application include:

- **Entertainment and gaming:** The AI-BCI-immersive convergence in gaming is spawning unprecedentedly immersive technology and responsive entertainment experiences. Forsland et al. describe a BCI system for augmented reality that demonstrates the potential for seamless integration of neural inputs with augmented reality environments (Forsland et al., 2021[23]). The ability of AI to adapt game environments in real time based on a player's neural and physiological responses could create experiences earmarked for each individual.
- **Productivity and work:** The integration of BCI-controlled interfaces with AI assistants in immersive technology environments promises to revolutionise remote work and collaborative virtual spaces. The Internet of Things may have the potential to bridge physical and digital realities in the "metaverse", enabling seamless control of work environments (Li et al., 2023[34]). This convergence could enhance productivity and collaboration, allowing for more intuitive and efficient

interactions with digital tools and remote colleagues. For instance, the ability to manipulate data visualisations through thought alone, or to instantly access and share information through neural interfaces, could transform the nature of work.

- **Education and skill acquisition:** AI-powered adaptive learning systems, combined with immersive technology environments and BCI inputs, will enable highly personalised and efficient educational experiences. AI systems might be able to analyse a learner's cognitive states through BCI inputs, adapting the pace, style and content of instruction in real time within immersive technology environments.
- **Social interaction:** AI-mediated social platforms in immersive technology environments, enhanced by BCI inputs, could enable more nuanced and empathetic digital communication.
- **Personal development and wellness:** The AI-BCI-immersive technology convergence enables new approaches to mental health and cognitive enhancement. For example, a closed-loop transcranial photobiomodulation system using cognitive testing demonstrated how AI can be used to optimise non-invasive neuromodulation in real time (Telfer, Julihn and Sokhadze, 2023[33]). These technologies offer the potential for personalised interventions for mental health and cognitive enhancement. AI could analyse patterns in neural activity, behavioural data and environmental factors to provide tailored interventions through BCI.

Policy opportunities and challenges

The convergence of neurotechnology and AI carries promises for human enhancement, provided that policymakers address ethical considerations through adequate governance strategies. Immersive technologies rely on technological enablers (such as machine learning models, data, computational power, etc.) and, if developed and used responsibly, offer significant potential advances. At the same time, integrating neurotechnology and AI raises new ethical questions while exacerbating existing ones. Most urgently, these new research areas and resulting technological products cause risks to individual privacy and mental integrity; informed consent procedures must be updated adequately and ambiguous protection frameworks need to explicitly extend to neural data to avoid unauthorised access to a new kind of data that could reveal personal thoughts and emotions. Such access could then lead to manipulation and control serving marketing or political purposes, depriving individuals of their autonomy and freedom of thought, or giving rise to cyberbullying or harassment. In parallel, like many advanced technological developments, neuro-AI innovation might not be equitably accessible. The high cost and limited availability of products could also make access to innovation highly inequitable, depending on whether health systems cover new applications. Products aimed to enhance cognitive capacities in consumer markets could also heighten equity concerns.

The prospect of cognitive enhancement revives the question of the definition of humanity – its purpose and limits – which can only be tackled through dialogue and deliberation from a broad range of perspectives. Identity, personhood, society and culture are uniquely human concepts whose definitions may vary from one tradition to the next and, hence, deserve careful and pluralistic consideration before picking one technological direction.

In general, policymakers should consider reinforcing agile regulatory oversight mechanisms (with particular attention to the potential for dual use), expand data protection, develop standards across sectors and countries, deploy strategies for broad and fair access, and organise regular opportunities for public engagement. The neuro-AI convergence also foregrounds particular policy needs, including:

- **Rethinking responsibility:** Neuro-AI products raise questions about individual agency and responsibility, especially when AI systems are involved in decision-making processes through neural interfaces. Policymakers must address how to attribute responsibility in such scenarios.

- **Deploying anticipatory governance strategies:** The rapid evolution of neuro-AI convergence requires flexible and adaptive regulatory approaches. To keep pace with technological advancements, regulatory bodies could explore models such as "regulatory sandboxes", controlled environments where businesses can test products under relaxed regulatory conditions and close supervision by regulators. Iterative review processes that can quickly incorporate new scientific findings and technological developments are also effective.
- **Adapting funding, insurance and regulatory categories:** Neuro-AI products such as AI-enhanced neural implants combine hardware, software and AI components. These hybrid technologies often span multiple regulatory categories, making it difficult to determine appropriate oversight. Policymakers could consider:
    - Providing a new organisational funding structure to leverage and combine existing programmes, which may lead to the discovery of funding or goal synergies to enhance funding allocation.
    - Getting insurance companies to support tech companies with reimbursement and patient accessibility. With a strong relationship with insurance agencies, such companies would attract more investment opportunities as the development and rollout of products would stabilise. On the patient side, a more substantial insurance plan would ensure wider access.
    - Rethinking the medical/consumer dichotomy and instead privileging a risk-based classification or purpose-agnostic approach, for example.
- **Cross-border data platforms:** As AI-enhanced neurotechnologies generate vast amounts of data, policymakers should co-ordinate internationally to create data-sharing platforms and establish governing frameworks. This process will require the consideration of diverse cultural perspectives on data protection, research practices and technological use.

As neuro-AI convergence keeps on advancing, addressing these policy challenges is critical to innovating in a way that protects and advances core values. In this vein, the OECD Recommendation of the Council on Responsible Innovation in Neurotechnology (OECD, 2019[35]), the first international standard in this domain, guides governments and innovators to anticipate and address the ethical, legal and social challenges raised by novel neurotechnologies while promoting innovation in the field.

Convergence in quantum technologies

Quantum science originated in the early and mid-20th century as physicists tried to understand phenomena that classical physics had not been able to explain. The initial breakthroughs – often described as the first quantum revolution – are associated with such scientific luminaries as Niels Bohr, Albert Einstein and Erwin Schrödinger, among many others. These discoveries depicted a quantum world that contrasts sharply with classical physics and everyday experience. It revealed a reality where, among other features: the act of measurement influences outcomes; quantum particles can be correlated or entangled such that the state of one instantly influences the state of another, no matter the distance between them; quantum systems can exist in multiple states simultaneously until measured ("superposition"); and particles pass through objects unhindered ("quantum tunnelling"). The first quantum revolution also gave rise to the creation of a first generation of quantum-based technologies, many of which are central to contemporary science and society, ranging from transistors and semiconductors to lasers, light-emitting diodes and magnetic resonance imagers.

The term "second quantum revolution" refers to the current phase of technological progress that builds on the initial breakthroughs to harness quantum phenomena like superposition, entanglement, and quantum tunnelling for novel and more powerful technologies (OECD, 2025[36]; OECD, Forthcoming[37]).

Three key technologies of the second quantum revolution

The key technologies of the second quantum revolution include quantum computing, quantum sensors and quantum communication devices (OECD, 2025[36]).

- **Quantum computing** holds the promise of advancing high-performance computing in the medium to long term, pushing the boundaries of what is currently considered "computable". A conventional transistor flips between on and off, representing 1s and 0s. However, a quantum computer uses quantum bits (qubits), which can be in a state of 0, 1 or any probabilistic combination of both 0 and 1 (for instance, 0 with 20% and 1 with 80% probability). Qubits can also interact with other qubits through so-called quantum entanglement, enabling parallel processing. Algorithms designed to run on quantum computers can, in principle, excel at specific problems like factoring large numbers (Shor's algorithm), database searching (Grover's algorithm) and simulating systems where quantum effects are important.
- **Quantum sensing** has the potential to significantly advance measurement capabilities, enabling sensitivity and precision on a par with the smallest perturbations found in nature (Degen, Reinhard and Cappellaro, 2017[38]). As their performance improves, these sensors could enable the measurement of phenomena such as time, gravity, magnetism, temperature and electromagnetic spectrum analysis at scales and levels of accuracy unattainable with classical methods (Ezratty, 2023[39]). Applications range from better medical imaging (as next-generation atomic clocks synchronise imaging processes); easier mapping of the ocean bed and detection of subsoil features on land (thanks to gravimeters) as also seen in the next section on satellite earth observations; and new means of navigation (using ultra-accurate measurements of the earth's magnetic field).
- **Quantum communication** is an emerging technology that uses the properties of quantum systems to enable transmission and manipulation of information through quantum networks. The best-known application of quantum communication is quantum key distribution (QKD), which uses quantum states (typically photons) to enable two parties to generate a shared, secret random key. The source of the security is physical law, because measuring a quantum state alters it irrevocably. The quantum-secured keys cannot be intercepted without detection. This is different from classical encryption, which can potentially be broken with enough computing power (Wikipedia, 2025[40]).

These three technologies are emerging. Among the three, quantum computing is the least advanced and quantum sensing the most advanced. Significant technical and research challenges still need to be solved. However, achieving technically and commercially viable systems could disrupt many sectors of economic and social life. The following sections describe three areas of science and technology that have converged, or are in the process of converging, with quantum technologies: AI, biology and engineering.

Quantum technologies converging with artificial intelligence

AI is being used in every domain of science and across all stages of the scientific process (OECD, 2023[41]). Quantum science is benefiting as much as any other branch of research, from automated scientific literature review to machine-assisted design of experiments.

AI is also contributing to quantum science and technology in a variety of specific ways. For example, machine learning techniques are being employed to decode and correct errors in qubits (Usman, 2024[42]). Reinforcement learning can help to design optimal control of qubit operations (Wolf, 2024[43]). In addition, given that every quantum device is slightly different, reinforcement learning can analyse a machine and its patterns to help fit algorithms specifically to that device (Padavic-Callaghan, 2024[44]; Vicentini, 2024[45]). In addition, AI is likely to support quantum sensing, distinguishing noise from feint sensor signals, and helping to understand sensor data.

Much attention has also been paid to the possibility that quantum computers could enhance AI systems. To date, this possibility is largely theoretical. Hybrid quantum-AI algorithms have been tested on small problems, and companies are exploring quantum neural networks for tasks like natural language processing (Quantinuum, 2025[46]). A key research topic focuses on using quantum computers to reduce the complexity and cost of using AI models. This might be achieved by having quantum computers describe complex features of a system of interest, such as a chemical reaction, more simply (i.e. with fewer parameters) than classical systems, before applying AI (Brooks, 2023[47]).

Vicentini (2024[45]) reports a recent lowering of expectations among researchers regarding quantum AI. He holds that quantum computers may not greatly advance AI because they struggle to process large-volume data from neural networks. To date, it has only been possible to maintain coherence across qubits for tiny fractions of a second, meaning that only very short calculations are possible. He considers that quantum computers will have ongoing problems in executing AI algorithms on large data sets because of such short coherence times. Trying to increase the rate at which data are input and output is written will introduce more calculation errors. However, he and others are optimistic that quantum computers will be very useful for applications that require limited input and output data, but much processing power.

Progress in harnessing quantum effects for AI faces several challenges. New algorithms are required. Quantum computers output probabilistic results – an answer to the same problem may differ every time a machine computes – not directly compatible with classical data pipelines, and quantum sensors produce novel data types requiring new AI processing techniques. Interdisciplinary expertise is also scarce. Computer scientists often know little about, or struggle to keep up with, theoretical developments in quantum computing. Effective integration of quantum and AI technologies demands close collaboration between quantum physicists and AI researchers.

Quantum technologies converging with biology

Recent years have seen rapid growth in a field of science known as “quantum biology”. Quantum biology studies the convergence of quantum physics principles with biological systems, exploring how life’s mechanisms may function at the quantum scale, and how natural selection has found quantum-based solutions suited for different ecological niches (Al-Khalili and McFadden, 2014[48]).

Quantum biology has its origins in a lecture given by Niels Bohr in 1932, entitled “Light and Life”, where, among other things, he discussed the atomic-level sensitivity of retinal cells (Bohr, 1933[49]). More recently, science has discovered evidence that quantum mechanical mechanisms likely underpin processes and functions such as photosynthesis, navigation in birds and the sense of smell (Al-Khalili and McFadden, 2014[48]).

In addition to helping explain the natural world, quantum biology is yielding technologically useful knowledge. For example, the speed with which plants convert sunlight into carbohydrates – one million billionths of a second – minimises energy loss in the form of heat. How plants achieve this remained a mystery until 2007 when biophysicists showed that plants use a form of quantum computation (Biello, 2007[50]). Scientists reasoned that the mechanisms plants employ to achieve near-perfect efficiency in harvesting energy might be mimicked in artificial systems for energy generation and capture. Indeed, experimental chemists have used this knowledge to build plant-like light-harvesting arrays (Romero, Novoderezhkin and van Grondelle, 2017[51]). Another area where quantum biology may yield technologically useful insights is in quantum biosensing (Box 5.3).

Box 5.3. Quantum sensing with biological materials

Scientists are exploring quantum sensors built from biological materials. For example, researchers recently engineered a fluorescent protein from a luminescent jellyfish. This glowing protein can be produced inside living cells and detect tiny changes in its environment with much greater sensitivity than standard sensors (Wilkins, 2025[52]). Potential applications include tracking biochemical signals or early disease markers from inside the cell.

In another laboratory experiment, a natural protein found in robins' eyes was shown to function as a magnetoreceptor, sensitive to Earth-strength magnetic fields. This suggests that such birds might use what is essentially a biological quantum sensor to aid navigation (Offord, 2021[53]). Indeed, recent research shows that biological magnetic sensing operates at near the limit of what is physically possible in terms of sensor volume, measurement time and measurement certainty (Wright, 2025[54]). While there are not yet any commercial biomimetic quantum devices, such discoveries are guiding research on the design of lab-made quantum magnetometers, potentially enabling ultra-sensitive compasses or biology-based medical imaging.

Sources: Wilkins (2025[52]); Offord (2021[53]); Wright (2025[54]).

Protein-based quantum systems

Quantum phenomena have long been observed in proteins (such as enzyme reactions involving tunnelling and light-absorbing proteins showing coherence). However, using proteins as quantum devices is a recent development. In the past decade, researchers began exploring protein-based quantum systems, where the proteins themselves serve as carriers of quantum information. Research on protein-based computing is exploratory, and practical applications are still far off. However, a few key advances demonstrate the concept's potential. For example, researchers at the University of Peking recently showed that DNA could act as storage and computing elements in quantum devices (SciTech, 2025[55]).

Convergence between quantum research and engineering

Beyond quantum technologies proper, progress in the quantum revolution relies on progress in several enabling fields of technology. Many of these have uses outside the quantum realm. Their progress relies in large part on the ingenuity of chemical, electrical and mechanical engineers (for an example, see Box 5.3). Two lesser-known examples are vacuum tubes and cables.

Box 5.4. Argonne National Laboratory's Q-NEXT/Argonne Quantum Institute

The Argonne National Laboratory near Chicago (Illinois) in the United States is a pre-eminent and interdisciplinary science and engineering research centre founded in 1946. The Argonne Quantum Institute combines expertise in quantum computing, sensing, photonics, communications, materials science and high-performance computing. Argonne enjoys an integrated interdisciplinary ecosystem, including national facilities like the Advanced Photon Source and the Center for Nanoscale Materials.

In June 2025, Argonne celebrated multiple quantum milestones in computing, communication, sensing and materials improvements. These included creating and characterising qubit materials, harnessing supercomputing to advance quantum computing, building quantum networks over a range of distances, developing sensors for science, strengthening the supply chain of materials for quantum devices and systems, and supporting the quantum ecosystem through partnerships (Argonne National Laboratory, 2025[56]).

Argonne also leads the Department of Energy's Q-NEXT Center, established in 2020. Q-NEXT brings together leading experts from the national laboratories, universities and technology companies to solve cutting-edge challenges in quantum information science. Q-NEXT's industry partnerships accelerate translation from lab to marketplace. The Argonne National Laboratory is also a founding partner of Duality, the first programme in the United States dedicated to accelerating start-up companies focused on quantum science and technology (Argonne National Laboratory, 2021[57]).

Several factors help to explain the Argonne Institute's success. One is national-level co-ordination and funding. The Department of Energy has supported five National Quantum Information Science Research Centers across the United States, including Q-NEXT, supporting fundamental research and applied translation in complementary ways. The Department of Energy's Office of Science recently announced the availability of USD 625 million to support the centres (Trueman, 2025[58]). Another reason for the institute's success is access to world-class user facilities: photon sources, nanoscale materials centres, multi-purpose quantum foundries and high-performance computing environments, among others, all enable cutting-edge quantum experiments. Argonne is also characterised by well-structured industry-academic-lab pipelines: it drives collaborative ecosystems across universities, laboratories and the private sector, nurturing spin-outs, training researchers and helping bring prototypes to commercial readiness.

Sources: Argonne National Laboratory (2021[57]; 2025[56]); Trueman (2025[58]).

- **Vacuum components:** To reduce disturbance of qubits, vacuum technologies are key to some forms of quantum computing. Recent theoretical work suggests that vacuum tubes, if designed and arranged properly, might also be able to carry photons – containing quantum data – for thousands of kilometres without attenuation (Williams, 2024[59]).
- **Cabling:** Cabling plays a key role, particularly with solid-state qubits. The cables used need to carry delicate quantum information between different parts of a quantum computer or between nodes in a quantum network, all while shielding the quantum information from disturbances from external sources such as heat, electromagnetic radiation, vibrations and extreme cold. Superconducting cables are expensive at around EUR 3 000 per metre and come from a single vendor from Japan (Ezratty, 2023[39]).

Bringing the cold of deep space to computing

One of the most important technologies in the quantum realm is cryogenics. Cryogenics is a branch of physics that studies the behaviour of materials at extremely low temperatures, typically below -150°C (-238°F). Cryogenics is critical to progress across multiple industries and domains of science, including space exploration, medicine and energy technologies. For instance, the James Webb Space Telescope uses cryogenic cooling to detect weak infrared signals from space. In medicine, cryogenics helps to preserve cells, tissues, embryos and organs. And hydrogen fuel cells and storage systems rely on cryogenic hydrogen (Connor, 2010[60]).

Cryogenics draws from several scientific disciplines, particularly physics and materials science. Engineering disciplines – particularly mechanical, electrical and chemical engineering – are also essential for designing practical cryogenic system. Cryogenics is critical to the operation of superconducting quantum computing, an architecture used by companies like IBM and Google (Pakin and Coles, 2019[61]). At ultra-low temperatures, electrons can flow in metal circuits with zero resistance, enabling the precise quantum states needed for computation. The extreme cold also helps isolate the quantum system from its environment, extending the time during which qubits maintain their quantum states, allowing the execution of more complex quantum algorithms.

Achieving these ultra-low temperatures presents significant engineering challenges (Gainey, 2019[62]). An additional challenge is to integrate cryogenic environments with electronic control systems, which necessitates materials and designs that can operate reliably under such extreme conditions.

While cryogenics is a mature field of science and technology, several areas of progress are needed, and research on these is active. For instance, more energy-efficient systems are required, as current methods for achieving ultra-low temperatures requires significant energy. Breakthroughs in miniaturising cooling systems will also make cryogenic technology more practical for quantum computing applications while enhancing efficiency and reliability.

Policy opportunities and challenges

The preceding section underscored the close relationship between research, engineering and experimentation. Institutions that can enhance such interactions are likely to be particularly effective in driving progress in quantum science and technology. Indeed, at least one recently announced private sector breakthrough in quantum chip development has been attributed, in part, to the large tech company in question having brought the manufacturing process in-house, thereby facilitating the needed interactions (Waters, 2024[63]).

Several research institutions and large companies have sought to facilitate close iteration between theoreticians, applied researchers and research engineers. An example is the Princeton Quantum Initiative, an interdisciplinary programme at Princeton University, described as "providing an integrated research environment at Princeton where experimentalists, engineers, and theorists work closely together." The Princeton website continues "This interdisciplinary collaboration accelerates development of next-generation quantum computing and quantum sensing technologies by linking theory, materials engineering, and device measurements in a single loop" (Princeton Quantum Initiative, n.d.[64]).

In the private sector, one of the world's largest quantum computing companies, Quantinuum, was formed in late 2021 from the merger of a quantum software and operating systems company, Cambridge Quantum, and Honeywell Quantum Solutions, a developer of quantum hardware. The merger integrated more than 370 scientists and engineers into the same organisation. In an example of the sort of convergence space referred to at the start of this chapter, the announcement of Quantinuum's creation emphasised the value of bringing together a unified team of hardware engineers, software experts and scientists.

Policy can help to increase opportunities for the sorts of exchanges described above. For example, both Japan and the United Kingdom have organised part of their national quantum strategies around funding quantum innovation hubs specifically intended to facilitate collaboration between academia and the private sector. This is not exactly the same as bringing all relevant competencies under the same roof, but fostering nuclei of institutions housing mixed-discipline expertise is a step in the right direction.

As referred to throughout this chapter, policies that support inter-disciplinary education are essential. Demand is growing for professionals who have some proficiency in quantum science and technology, but not necessarily specialists, as well as for science, technology, engineering and mathematics graduates with complementary skills suited to the quantum industry (White House Office of Science and Technology Policy, 2022[65]). The interdisciplinary nature of quantum technologies – encompassing fields such as mechanical engineering, optical engineering, systems engineering and application development – has underscored the need for academic institutions to offer master's programmes that align with industry requirements. In addition, there is scope for universities to develop shorter postgraduate certificates or continuing education programmes with quantum curricula. These could help to meet the growing demand for skills upgrading and diversification among adult learners (Goorney et al., 2024[66]).

Convergence in space-based earth observation

Space-based observation is the collection of information about the earth's surface, atmosphere and ocean from satellites equipped with sensors that detect reflected or emitted energy across various parts of the electromagnetic spectrum. Earth observation products provide intelligence, supporting decision making in many sectors, and economic, security and environmental policies. Data are collected by both public and commercial satellites, with US and European government programmes providing often open data with national and global coverage while commercial providers, working closely with government agencies, focus on more specialised imagery with higher resolution or revisit times.[3]

The increasing need to provide timely, accurate and actionable insights for policy, security and economic decision making is driving the convergence of different EO technologies. Convergence can be seen in the integration of multiple systems and disciplines. New EO systems no longer rely solely on satellite engineering progress but increasingly combine advances in optics, lasers, cloud and edge computing, AI, quantum technologies, robotics, and *in situ* sensor networks. This integration enables near real-time data collection, processing and dissemination while supporting applications like weather monitoring, disaster response and strategic intelligence (OECD, 2023[67]). As these domains co-evolve, EO becomes part of a broader, interconnected technological ecosystem where innovation in one area – such as AI-driven analytics – directly accelerates capabilities across others.

Interdisciplinary innovation centres and data platforms as convergence spaces

Interdisciplinary innovation spaces and advanced data platforms are now central to the technological convergence driving modern EO (OECD, 2020[68]). Innovation hubs in the space community, such as the European Space Agency's Φ-lab and the United States' National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory, foster collaboration between EO specialists, AI researchers, optics, robotics and quantum experts from industry, generating new space systems and applications that could not emerge in isolation.

This convergence is strengthened by collaborative platforms focused on data analytics and sharing, such as the European Union's Destination Earth, NASA's Earth System Observatory, the United States' National Oceanic and Atmospheric Administration's Open Data Dissemination programme, Digital Earth in Australia, satellittdata.no in Norway, Satellite Data Portal in the Netherlands, and Europe's Copernicus Data Space Ecosystem (T Systems, 2024[69]). Acting as operational interfaces, these initiatives increasingly rely on cloud-based platforms and digital twins to merge satellite imagery with open data from *in situ* sensors, Internet-of-Things networks and meteorological models. Supported by high-performance computing and AI, they can transform massive and complex data sets into timely, actionable insights that are then used and transformed further by public and private stakeholders (e.g. Google Maps).

These interdisciplinary innovation spaces and advanced public data platforms are becoming not only technical enablers but also strategic assets for convergence, supporting data sharing while also accelerating digital innovation across sectors that depend on reliable earth intelligence.

Convergence with optical systems and laser technologies

Optical systems for space-based EO largely originate from advances in fields such as astronomy, defence and precision manufacturing, including in medical fields. Technologies initially developed for telescopes, deep-space imaging and military reconnaissance have been adapted to create lightweight, high-resolution and multispectral satellite instruments. Laser systems, including light detection and ranging (LiDAR) and laser altimeters, similarly draw on progress in photonics, quantum optics and high-stability laser sources from scientific research and industrial applications.

However, this convergence presents several challenges. Optical and laser instruments require extreme precision and stability to function in the harsh conditions of space, demanding advanced thermal control, vibration mitigation and radiation-hardened components. Integrating cutting-edge optics with satellite platforms also raises issues of size, weight and power constraints, which can limit the deployment of the most advanced sensors on smaller satellites. Moreover, the rapid pace of innovation in optical and laser technologies outpaces traditional satellite development cycles, making it difficult to continuously leverage the latest advances without redesigning mission architectures. Despite these challenges, the convergence of EO with optics and lasers continues to drive transformative improvements in spatial resolution, accuracy and the range of measurable environmental variables.

Convergence with artificial intelligence

Space-based EO technologies are also converging with advances in AI. The scope and impact have evolved significantly over time, moving from experimental applications to mainstream operational use, from inputs to satellite engineering and manufacturing (including very small satellites and sensors), and improved data processing.

- In the late 1990s and 2000s, the revolution of small satellites was accompanied by the rise of AI in EO, through new space subsystems manufacturing processes, machine learning techniques like neural networks, and support vector machines for improved land cover classification and cloud detection in EO applications.
- In the 2010s, the surge in high-frequency data from satellites like the European Sentinel and American Landsat programmes, combined with cloud computing, enabled operational AI applications for large-scale environmental monitoring and change detection. For example, the Global Agriculture Monitoring initiative by the Group on Earth Observations combined EO data, weather information and AI-trained models to predict where, when and what crops were growing worldwide, in support of market transparency and early warning of production shortfalls (GEO, 2024[70]).
- Since the early 2020s, the combination of satellite sensors based on new optics, deep learning and onboard AI have driven a new era of autonomous EO, allowing satellites to pre-process, prioritise and react to observations in real time in orbit, supporting disaster response and multi-domain data fusion. As an example, the European Space Agency satellite Φ-sat-1 uses AI as part of its onboard processing to discard cloudy images, reducing downlink needs (ESA, 2024[71]).

The emergence of foundation models based on EO data may represent a turning point for further use of satellite imagery data, as they lower barriers of access such as advanced technical expertise and access to training data sets while strengthening analytical capability. A NASA and IBM-led partnership had by 2023-2024 created the Prithvi models for EO and weather and climate (Hugging Face, 2024[72]). The NASA/IBM Prithvi-EO 2.0 model is pretrained on some 4.2 million data points from the global harmonised Landsat and Sentinel-2 data set[4] and propose applications for carbon flux estimation, landslide detection, burn intensity estimation, crop pattern identification, flood mapping, etc. An important functionality is the Multi-Temporal Cloud Gap Imputation, which fills gaps in satellite imagery caused by cloud cover, a regular problem with satellite observations (NASA, 2024[73]; IBM, 2024[74]).

Convergence with quantum technologies

As seen in previous sections, one key application of quantum technologies is improved remote sensing. Future advances in space-based EO are increasingly tied to convergence with quantum technologies, which promise breakthroughs in sensing, communications and navigation.

Quantum gravimeters and magnetometers could allow satellites to detect minute changes in the Earth's gravity and magnetic fields, enabling more precise monitoring of groundwater, ice mass loss and subsurface structures. One technology being studied for these different types of gravity field measurement is cold atom interferometry, which has been tested in the NASA-funded Cold Atom Lab on the International Space Station. The Horizon Europe research programme is also funding technology development in this area. Quantum clocks and communication systems offer as well ultra-precise timing and secure data transmission, enhancing the reliability of EO networks and global positioning integration. NASA established the Quantum Artificial Intelligence Laboratory in 2012 to advance the development of quantum computing hardware and to learn where and how the application of quantum computing could be beneficial (NASA, 2024[75]).

However, this convergence faces significant challenges: quantum sensors are highly sensitive to environmental disturbances such as temperature fluctuations and radiation, making space qualification complex; their miniaturisation for satellite deployment is still a work in progress; and integrating these cutting-edge instruments into operational EO missions requires rethinking satellite architectures and data-processing pipelines. Despite these hurdles, the fusion of quantum technologies with EO holds the potential to transform global monitoring capabilities for earth and ocean science, security, and resource management.

Policy opportunities and challenges

The use of satellite imagery is associated with productivity gains and improved product quality in the public and private sectors (OECD, 2023[67]; 2024[76]). Convergence with optics and laser technologies, AI, quantum, and other technologies via interdisciplinary innovation centres and data platforms as convergence spaces are enabling OECD governments to diffuse public satellite imagery to foster innovation and economic benefits.

However, the convergence of these technologies, which is amplifying the value and global reach of space-based EO, carries significant policy implications that will require careful attention from policymakers:

- **Magnified security challenges:** Increased availability of higher resolution data magnifies security challenges linked to the malicious exploitation of information on military movements, physical infrastructures, forest fires, etc. A small number of OECD countries have explicit EO data regulations in place (Canada, France, Germany, Japan and the United States) (Harris and Baumann, 2021[77]). These frameworks regulate the conditions for reporting and/or disseminating private sector data for national security purposes, typically addressing technical characteristics such as temporal, spatial and spectral resolution, frequency domains, etc. In Japan, for instance, there are licensing thresholds linked to “distinguishing accuracy of target”, such as vehicles and ships – for optical sensors this accuracy should not exceed 2 metres. In 2020, the United States introduced a new tiered licensing approach for private EO systems, linking stringency to the existence and technological capabilities of foreign competition (Harris and Baumann, 2021[77])
- **Ethical use of satellite imagery:** There is also growing reflection on the ethical use of EO data related to data collection, sharing and ownership. The main issue is not necessarily individual data privacy (other technologies are generally less expensive), but challenges linked to broader scale physical phenomena. For example, asymmetric access to information on physical environmental characteristics (e.g. water levels) could create unfair economic advantages in land transactions. (NSpC UAG Climate and Societal Benefits Subcommittee, 2023[78]).
- **AI and trust:** Uptake of earth observation data beyond government agencies has so far proven difficult for multiple reasons, including, for instance, high investment costs (OECD, 2024[76]), the need to process and calibrate EO data against other data sets (UNECE, 2019[79]), and lacking or poor quality reference data sets (e.g. economic surveys in low-income countries) for satellite-based model validation (Burke et al., 2021[80]). As a result, potential users do not trust the technology because they lack the means, know-how or reference data to properly test predictions. The introduction of AI models could further deepen distrust in these technologies, in particular because

there seems to be widespread use in the EO field of AI methods that require random iterative searches and that are not fully repeatable (Pesaresi et al., 2024[81]; Gevaert, 2022[82]). Efforts to use interpretable models, such as those employed by the EU Joint Research Centre to develop the Global Human Settlement Layer, are, therefore, particularly important.

Conclusion

Societal transformations will require harnessing the dynamism of technological convergence, a trend emerging with particular force in the context of AI and digitalisation, synthetic biology, quantum technology, and space-based earth observation. This chapter has laid out a definition and conceptual model of convergence: it can describe the confluence of technologies but also be a process. Convergence can be enhanced by fostering "convergence spaces", i.e. physical, digital and technological infrastructures and platforms that promote the integration of tools, fields and skilled workers. If designed correctly, these can help optimise tangible and intangible value, foment collaboration, and promote technological integration, for example to enhance sustainability. The creation of convergence applications results from various cross-disciplinary and cross-sectoral integration efforts throughout the development process, resulting in new applications, industries, and fields of research and development.

The assemblage of interdisciplinary assets sometimes requires forces and incentives to stay together, whether they are financial, institutional or governance-related. This chapter focused on the ways that common technical challenges can also help create convergence spaces, in particular in four areas: the genome, the brain, the atom and space. Each of these terrains – and their associated challenges for their understanding, engagement and design – are being perceived as requiring interdisciplinary assets to open them up to view, to intervention and to exploitation. These four areas help carve out the convergence spaces and trading zones where parties can contract around access to resources, current discoveries and downstream inventions. Ultimately outputs like new knowledge, approaches and partnerships can feed back into the platforms, enhancing their value.

These four key areas of technology exhibit different facets, challenges and opportunities of convergence:

- In the field of **synthetic biology**, AI-powered protein design can create molecules with novel properties and reduce research time and costs with the potential to enable personalised therapies while at the same time posing new challenges. For example, the very same efficiency achievable through convergence has made the potential nefarious misuse more concerning, i.e. the potential engineering of viruses.
- In **neurotechnology**, convergence with immersive technologies and AI present opportunities for, for example, the treatment of mental illness and the enhancement of well-being, but the new powers to mine large data sets are raising critical questions of safety, societal trust, privacy, equity and discrimination.
- In **quantum technologies**, research is expanding on potentially valuable synergies between quantum science and technology and AI, and even biology, among other fields. Engineering innovations relevant to many sectors, such as vacuum components and cabling, are helping to drive progress in quantum technologies, but as yet the tangible impact of these interactions, in terms of market-ready technologies, has still to be felt.
- In **space-based earth observation**, the convergence of AI and digital technologies and satellite imagery technologies has led to multiple new applications ranging from food security monitoring to methane emissions alerts. But it also creates challenges that need to be addressed, such as potential malicious use and risks to national security, trust and asymmetric access to information.

The case studies make clear that AI is a critical – but not the only – driver of convergence today, both in terms of products (the additive factor of AI to existing and emerging technologies) and processes (the engagement of technological development itself). Hand in hand with the digitalisation of science, technology, innovation and society has come the influence of AI in these domains. AI promises to leverage data-rich innovation environments with new and powerful capabilities to learn, optimise and generate new content and processes. Many commentators draw a direct line between the rise of AI in science, technology and innovation and processes of convergence, noting how AI has brought together heretofore unrelated technological domains in ways that promote faster and deeper convergence (Ma and Wu, 2024[1]). This process can be seen in industrial processes as much as in science, although the diffusion of AI in industry is patchy and concentrated. Furthermore, convergence between AI and other fields of technology is likely to accelerate as AI is developed that can work on smaller data sets, opening it up to more potential niche applications. While it remains a frontier of research to better understand AI as a driver of technology convergence, the logic and early experience support this conclusion.

At the same time, the convergence of technologies is giving rise to unique policy dimensions and governance challenges that must be addressed should technologies achieve their full potential. In synthetic biology and AI convergence, for example, different regulatory regimes have different requirements. Synthetic biology is relatively heavily regulated as a legacy with a long history, whereas AI is much less regulated with compulsory legal provisions but codes of practice and self-regulation playing a much bigger part of its governance approach in many OECD countries. As a consequence, entrepreneurship in the AI-biology space may face more pronounced regulations since AI-synthetic biology products are subject to multiple regulatory regimes. Indeed, the hybrid nature of converging technologies raises specific ethical questions and policy challenges insofar as they may fit uneasily into traditional ethical and legal categories such as medical vs. consumer use and therapy vs. enhancement. In these cases, adapting governance to facilitate research use, clinical applications and market diffusion is needed while mitigating associated new risks to privacy, safety and autonomy.

While many governance approaches emphasise the need to mitigate risks, intentional and unintentional harms, and safety and consumer protection, it is also important to account for potential benefits in risk analysis and technology appraisal. In times of polycrises, directing technologies towards areas with the maximum positive impact is desirable. How can this be hardwired the best into agile and anticipatory governance frameworks? One approach can be found in the Framework for Anticipatory Governance of Emerging Technologies (OECD, 2024[19]), by shaping agenda-setting, helping draw "red lines" and influencing deployment practices – but it requires identifying a set of starting values to be deliberated in inclusive multistakeholder fora.

What can governments do?

In the face of these trends and future prospects around the general phenomenon of technology convergence, governments could take a number of steps to help maximise the positive impacts of convergence while minimising potential risks. These include:

- **Invest in deeper forms of interdisciplinary research.** Support approaches that synthesise diverse knowledge, technological methods and approaches, and academic cultures from, *inter alia*, life sciences, ecology, physics, humanities, computational sciences, mathematics, engineering disciplines and technology assessment research.
- **Build convergence spaces with technological and collaborative platforms.** Leverage different funding models, access rules and technology transfer structures to shape the technological and collaborative platforms that are conducive to convergent technologies. Invest in shared databases and other infrastructure that can leverage AI and other enabling technologies. There is no one-size-fits all approach, but institutional policies can shape the convergence space to optimise for innovation.

- **Deploy anticipatory governance.** Use the OECD Framework for Anticipatory Governance of Emerging Technologies, launched at the 2024 OECD Science and Technology Policy Ministerial meeting. Tools include:
  - **Strategic intelligence.** Converging technology policies should foster shared forms of strategic intelligence, involving the comprehensive analysis of technology's potential directions, economic stakes and societal implications. Recognising the unpredictable nature of converging technologies, robust tools like horizon scanning, foresight and technology assessment should be employed to anticipate future challenges, inform governance strategies and aid strategy formation (see Chapter 7).
  - **Agile regulation.** To leverage the vast potential of convergence, policymakers should develop adaptive systems that can keep pace with rapid technological change. These adaptive systems should embed policy experimentation that makes greater use of, for example, policy innovation labs and regulatory sandboxes (see Chapter 7).

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Notes

[1] The Convention on Biology Diversity's new ad hoc technical expert group developed an operational definition of synthetic biology, which describes it as "a further development and new dimension of modern biotechnology that combines science, technology and engineering to facilitate and accelerate the understanding, design, redesign, manufacture and/or modification of genetic materials, living organisms and biological systems".

[2]. See https://www.weforum.org/stories/2024/06/the-brain-computer-interface-market-is-growing-but-what-are-the-risks.

[3] Revisit time refers to the time elapsed between observations of the same ground point.

[4] Free and open data sets from the US and European Landsat and Copernicus programmes are the backbone of digitally enabled data analysis. They provide *de facto* standards of geometric (time and location), spectral (colour) and radiometric (colour intensity) calibration, allowing an accurate detection of change (NGAC, 2020[83]). These data sets have furthermore spurred the current wave of AI-fueled innovation in applications and foundation models.

6 An ecosystems approach to industrial policy

Industrial policies have regained importance in recent years and are now a crucial element of science, technology and innovation policy portfolios. Adopting an industrial ecosystem perspective – namely going beyond sectoral boundaries to consider both upstream and downstream industries, as well as the diverse set of stakeholders involved – can help design more effective industrial policies. This chapter distils the insights from three recent studies, offering practical examples of how to define the boundaries, stakeholders and challenges of the automotive, renewable energy and energy-intensive industrial ecosystems. It highlights the value of adopting an ecosystem perspective and the importance of relying on robust evidence coming from diverse data sources. The chapter provides insights on policies that foster growth and support thriving, resilient industrial ecosystems and economies.

Key messages

- Well-designed industrial policies – which include a variety of instruments such as research and development (R&D) grants, government venture capital, tax expenditures, loans and loan guarantees, etc. – can help address complex challenges like slowing productivity growth, the resilience of global value chains and the transition to a low-carbon economy.
- Sectoral policies that are often taken to implement industrial policies are not necessarily well suited to address these challenges as they do not account for key actors located outside sectoral boundaries or for the interdependencies linking them.
- More effective is an industrial ecosystem approach that identifies all relevant stakeholders associated with a given technology or product, including large and small firms, start-ups, technology providers, workers, trade partners, and investors.
- The industrial ecosystem perspective can help policymakers design better targeted and more effective policies that account for interdependencies between upstream, core and downstream stakeholders.
- Transitioning to an industrial ecosystem approach entails developing a robust data infrastructure that brings together granular data from multiple sources.
- Innovation and industrial policies for industrial ecosystems can help address major challenges such as access to critical inputs, the lack of skills, and barriers to technology development and diffusion.
- Ecosystem-based industrial policies represent an attractive middle ground between sectoral policies that are too narrow in scope and horizontal approaches that are not necessarily sufficient to address current challenges.

Introduction

OECD countries are facing an increasing number of challenges – including slowing productivity growth, the transition to a low-carbon economy and the uncertainty caused by a tense geopolitical landscape. There are also major opportunities, including the emergence of artificial intelligence. Major crises, like the COVID-19 pandemic and the Russian Federation's war of aggression against Ukraine, have exacerbated these mounting challenges and shown the fragility of global value chains, contributing to the renewed interest of many economies in industrial policy.

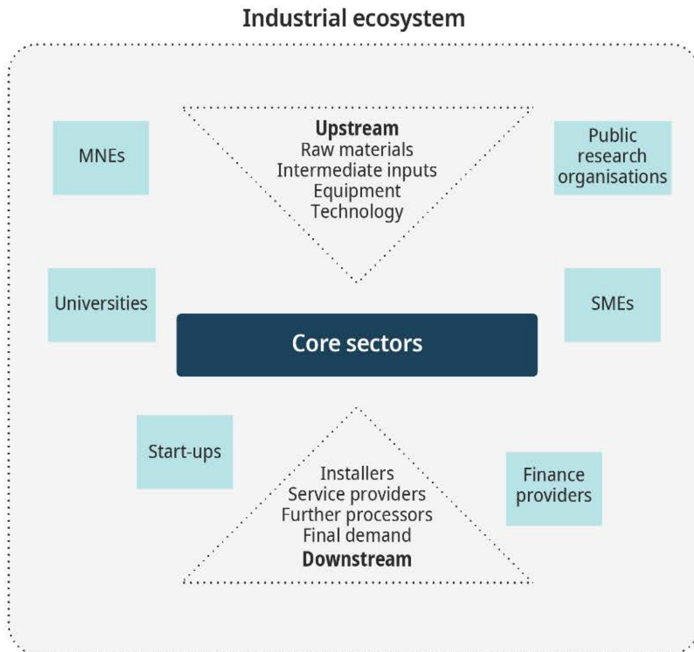
In this context, designing, implementing and evaluating industrial strategies aimed at enhancing productivity, fostering value chain resilience, and accelerating the development and diffusion of novel technologies has become a policy priority. A growing body of research has shown that purposeful industrial strategies can contribute to achieving these goals (Criscuolo et al., 2022[1]; Lane, 2020[2]; Criscuolo et al., 2019[3]; Dechezleprêtre et al., 2023[4]), especially when industries are characterised by spillover effects, benefit from economies of scale or are impeded by co-ordination failures.

The challenges facing OECD economies are unprecedented in both scope and complexity. The twin transition toward digital and sustainable technologies, for example, involves stakeholders not only from a variety of different institutions, including the private sector, government, academia and civil society, but also from very different sectors of economic activity. Designing policies capable of addressing the needs of stakeholders as different as multinational firms active in the energy sector, small start-ups designing specialised predictive maintenance software and local consumers associations represents a complex challenge, one that requires robust empirical evidence and strong, adaptable collaboration among all the parties involved.

Sectoral strategies, despite being a staple of industrial policy (Criscuolo et al., 2022[5]), are ill-suited for facing such an array of challenges. First, by focusing their interventions on firms belonging to a single sector, they can miss critical upstream suppliers of inputs, without whom downstream firms, even if adequately supported, may fail to thrive. Similarly, lack of support for downstream firms may stifle upstream firms unable to find adequate demand for their outputs. Upstream and downstream sectors are critical in a context where value chains are characterised by severe bottlenecks and are subject to natural and geopolitical threats. Beyond networks of production, sectoral strategies can fail to properly take into account providers of technologies that lie outside the boundaries of a given sector, as well as valuable human capital. These are essential to consider in a scenario of slow and dispersed productivity growth (Berlingieri, Blanchenay and Criscuolo, 2017[6]; Berlingieri et al., 2020[7]), where innovations appear to be increasingly difficult to find (Bloom et al., 2020[8]).

The industrial ecosystem approach aims to overcome these shortcomings by explicitly accounting for the wealth of actors and relationships that underpins modern industrial production. Figure 6.1 portrays a schematic, simplified representation of an industrial ecosystem, which "encompasses all players operating in a value chain, from the smallest start-ups to the largest companies, from academia to research, service providers to suppliers" (European Commission, 2020, p. 16[9]). The figure includes three main blocks of sectors – core, upstream and downstream – each composed of a variety of actors, including large, established firms that are commonly associated with a given industry; smaller firms and start-ups; and academic research centres and finance providers. Core sectors include the firms identifiable through (and typically targeted by) a sectoral approach: for example, firms belonging to the manufacture of motor vehicles are at the core of the automotive ecosystem. Upstream sectors supply inputs such as raw materials, intermediate goods, capital equipment and technologies. Downstream sectors use the outputs of core industries as inputs for further production, for further use by installers or other service providers, or for final demand. For instance, the steel industry (upstream) provides inputs to automotive manufacturers (core), while the car retailers (downstream) use outputs from car manufacturers. Note that the figure provides a simplified version of the many actors and relationships underpinning ecosystems: for example, it does not include the many feedback loops that link upstream, core and downstream sectors.

Figure 6.1. Schematic representation of an industrial ecosystem



Source: OECD.

The industrial ecosystem concept – rooted in an analogy between economic and biological ecosystems (Moore, 1993[10]) – draws heavily on similar paradigms, such as national innovation systems (Nelson, 1993[11]; Lundvall, 1992[12]; Freeman, 1995[13]), regional innovation systems (Cooke, 2004[14]), local clusters (Porter, 1998[15]), sectoral systems of innovation (Malerba, 2002[16]) and entrepreneurial ecosystems (Stam, 2015[17]; Stam and van de Ven, 2021[18]). Innovation ecosystems, in particular, share many characteristics with industrial ecosystems, both of which trace their origins to the concept of the National Innovation System – a framework to which the OECD contributed substantially (OECD, 1999[19]), especially thanks to the work of Freeman in the 1990s. As the field progressed, the OECD also contributed to the above-mentioned related fields, especially on sectoral innovation systems (OECD, 2006[20]).

Both these concepts emphasise that firms (or entrepreneurs) cannot be regarded as operating in a vacuum but are rather interwoven in a complex web of relationships that includes several different actors. As these actors depend on each other for their survival and growth, "ecosystems" represents not only a crucial unit of analysis for business leaders (Jacobides, Cennamo and Gawer, 2018[21]; Iansiti and Levien, 2004[22]) but also the most suitable unit of analysis for policymakers interested in strengthening their economy's resilience and promoting their growth (Box 6.1). However, key differences exist between the two types of ecosystems. Their objectives differ: innovation ecosystems focus on fostering collaboration in research, development and commercialisation of new technologies that address shared priorities whereas industrial ecosystems aim to increase the value added generated within a specific industry. Additionally, their boundaries are distinct. Innovation ecosystems are not constrained by industrial considerations and broadly encompass all actors contributing to innovation. In contrast, industrial ecosystems have a narrower sectoral scope but include actors who may not directly contribute to innovation yet play a crucial role in the ecosystem's overall success.

Box 6.1. The renewal of industrial policy and the role of industrial ecosystems

Industrial policy has been a crucial component of economic strategies at least since the Industrial Revolution (Juhász and Steinwender, 2023[23]). Nevertheless, the use of active industrial policies had fallen out-of-favour at the end of the 20th century (Warwick, 2013[24]) due to concerns regarding governments' ability to identify the most promising areas for investment, the risk of political capture of subsidies and budget constraints. Emerging trends and challenges like those described at the beginning of this chapter – productivity slowdown, the climate crisis, shocks to global supply chains and uncertainty caused by geopolitical tensions – have contributed to making industrial policies attractive again (Juhász, Lane and Rodrik, 2024[25]; Mazzucato, 2021[26]).

OECD countries have recently begun to design coherent industrial strategies again. For example, in 2025 the UK Government (2025[27]) recently published the UK's Modern Industrial Strategy, and Italy (Ministry of Enterprises and Made in Italy, 2024[28]) has published its industrial strategy delineating its industrial priorities and how the Italian government aims to support them. Similarly, numerous large-scale policy initiatives, such as the "European Green Deal" (2019), the "Next Generation EU" Fund (2020), the "Korean New Deal" (2020), the "Inflation Reduction Act" (2022), the "EU New Industrial Strategy" (2020, updated in 2021), the "US CHIPS and Science Act" (2022), and the "EU Green Deal Industrial Plan" (2023), have shown governments' commitment to a more active role in driving industrial development. The Draghi Report (Draghi, 2024[29]) also highlighted the growing importance of industrial policies, calling for better co-ordination across the European Union to ensure their effectiveness.

Ecosystems – industrial ones (Andreoni, 2018[30]), as in the focus of this chapter, but similarly innovation (Adner, 2006[31]) and entrepreneurial (Stam and van de Ven, 2021[18]) ones – represent natural targets for industrial policy interventions, as they avoid narrowness concerns that may otherwise hinder targeted industrial policies (Criscuolo et al., 2022[1]). As such, ecosystem thinking has already permeated policymaking initiatives. For example, the Dutch "Top Sector" approach has incorporated systemic considerations of upstream industries. Nevertheless, recent emergencies, such as the COVID-19 pandemic, have highlighted the need to further expand the scope of systemic analysis. For example, the European Commission adopted the industrial ecosystem concept in its 2020 industrial strategy, to subsequently bring it into even sharper focus in the 2021 amendment, where the Commission described industrial ecosystems as the lenses though which it analyses the EU Single Market Economy.

This chapter builds on the industrial ecosystem approach and draws on three sectoral case studies: the automotive, renewable energy and energy-intensive industries (EII) ecosystems. All three ecosystems are affected by (at least some) of the challenges delineated above: for example, the automotive ecosystem has experienced severe disruption in its value chain linked to chip shortages during the COVID-19 pandemic; furthermore, this ecosystem is characterised by increasing digitalisation and the need to reduce the carbon footprint of its end products. The renewable energy ecosystem is at the forefront of the transition toward a low-carbon economy, but at the same time is markedly dependent on several critical minerals that have the potential to turn into bottlenecks. EIIs are crucial upstream industries whose outputs are incorporated into a wide variety of downstream industries. They are, therefore, crucial for the competitiveness of multiple sectors but also face challenges related to their high and only slowly decreasing emissions intensity. Consequently, these three ecosystems constitute particularly insightful cases on the opportunities provided by the industrial ecosystem approach.

The remainder of this chapter focuses on showcasing how the industrial ecosystem approach, as operationalised by these three studies, can help policymakers address the challenges delineated at the beginning of the chapter. First, the industrial ecosystem approach can provide evidence on who the main actors in an ecosystem are, what role they play and their linkages. Second, the industrial ecosystem approach can shed light on the challenges, bottlenecks and dependencies that these actors face. Third, it can aid in designing more effective industrial strategies.

Delineating industrial ecosystems

The defining characteristic of an industrial ecosystem is that it extends beyond traditional sectoral boundaries to include both upstream and downstream activities, as well as a broader range of stakeholders than just private companies. This requires establishing criteria to define non-sectoral boundaries and identify key actors within the ecosystem. This section outlines the approach used in the three industrial ecosystem studies, with a particular focus on the diverse data sets used to define ecosystem boundaries, including input-output, trade, innovation, and workforce data. It also highlights the variety of stakeholders included in each industrial ecosystem. The section emphasises how relying exclusively on sectoral classifications would overlook critical inputs essential for thriving ecosystems (including raw materials and innovations) and would also provide a distorted view of the leading actors and the significance of a given ecosystem, for instance in terms of workforce.

Identifying relevant ecosystem stakeholders using multiple data sources

There are various approaches to identifying the boundaries of an ecosystem and, within it, the most important firms, sectors and economies. Despite the importance of moving beyond an exclusively sectoral approach, industrial classifications such as the International Standard Industrial Classification (ISIC), the Statistical Classification of Economic Activities in the European Community, and the North American Industry Classification System, remain important building blocks for defining an ecosystem.

Identifying the core sectors composing an ecosystem can be relatively straightforward or complex, depending on the specific type of ecosystem. Table 6.1 presents the sectors at the heart of the automotive, renewable energy and EII ecosystems. On one end of the spectrum, the “Manufacture of motor vehicles, trailers and semi-trailers” (ISIC rev. 4 Division 29) is a natural starting point for defining the core component of the automotive ecosystem. For the EII ecosystem, defining core sectors already requires additional assumptions, as there is currently no internationally agreed-upon definition of what an EII is. The approach adopted in Dechezleprêtre et al. (2025[32]) is to consider as core parts of the EII ecosystem all the 2-digit ISIC manufacturing sectors whose energy input cost share over total inputs costs is above the median. These sectors include: “Coke and petroleum” (ISIC rev. 4 19), “Non-metallic minerals” (ISIC rev. 4 23), “Chemicals” (ISIC rev. 4 20), “Basic metals” (ISIC rev. 4 24), “Paper” (ISIC rev. 4 17), “Rubber and plastics” (ISIC rev. 4 22), and “Wood” (ISIC rev. 4 16). Finally, at the other end of the spectrum, the renewable energy ecosystem core is particularly difficult to define based only on specific sectors. No sector at the 4-digit level of the ISIC classification corresponds to the production of electricity specifically from renewable sources, and a sector corresponding to the manufacture of solar cells, solar panels and photovoltaic inverters was only created as part of the ISIC Rev. 5. In addition, market leaders in electricity production often produce electricity from various sources, including fossil, nuclear and renewable ones, making clear-cut sectoral distinctions especially complex. Firms manufacturing other capital goods necessary for the production of renewable energy (e.g. hydraulic turbines and wind turbines) can be found in the “Manufacture of engines and turbines sector” (ISIC rev. 4 2811).

A lesson learnt across the three studies is that increasing the level of granularity of the analysis can help to better delineate ecosystems’ boundaries, as within broadly defined sectors firms are highly heterogeneous. For example, there is considerable heterogeneity in energy intensity among 4-digit sectors within the same 2-digit sector, and there is also vast heterogeneity among firms within 4-digit sectors (De Lyon and Dechezleprêtre, Forthcoming[33]). Therefore, a definition of the energy-intensive ecosystem based on energy input cost share over total input costs defined at the 2-digit, 3-digit, 4-digit or firm level would give very different results. Unfortunately, granular data are often difficult to obtain and unevenly available across industries and geographies. Furthermore, there is typically a trade-off between the granularity of the data and their sectoral coverage, which often makes it unfeasible to conduct analysis at a highly granular level, despite the value of such analysis for policymaking.

The identification of the core components of an ecosystem needs to be integrated with the identification of all its other non-core parts, which nevertheless play an important role in the ecosystem. Input-output relationships, trade relationships, technological and workforce relationships can all contribute to the definition of an ecosystem beyond its core components. The following sub-sections examine each of these linkages and explain how they are operationalised in the three studies on ecosystems.

Table 6.1. Core sectors across OECD industrial ecosystem studies

Automotive	Renewable energy	Energy-intensive industries
Manufacture of motor vehicles, trailers and semi-trailers (ISIC rev. 4 29)	Manufacture of engines and turbines (ISIC rev. 4 2811)	Coke and petroleum (ISIC rev. 4 19)
		Non-metallic mineral products (ISIC rev. 4 23)
		Chemicals (ISIC rev. 4 20)
		Basic metals (ISIC rev. 4 24)
	Manufacture of solar cells, solar panels and photovoltaic inverters (ISIC rev. 5 2611)	Paper (ISIC rev. 4 17)
		Rubber and plastic products (ISIC rev. 4 22)
		Wood products (ISIC rev. 4 16)

Notes: Only the hydraulic turbines and wind turbines subset of the “Manufacture of engines and turbines” is considered relevant. The “Manufacture of solar cells, solar panels and photovoltaic inverters” was only added to ISIC rev. 5.

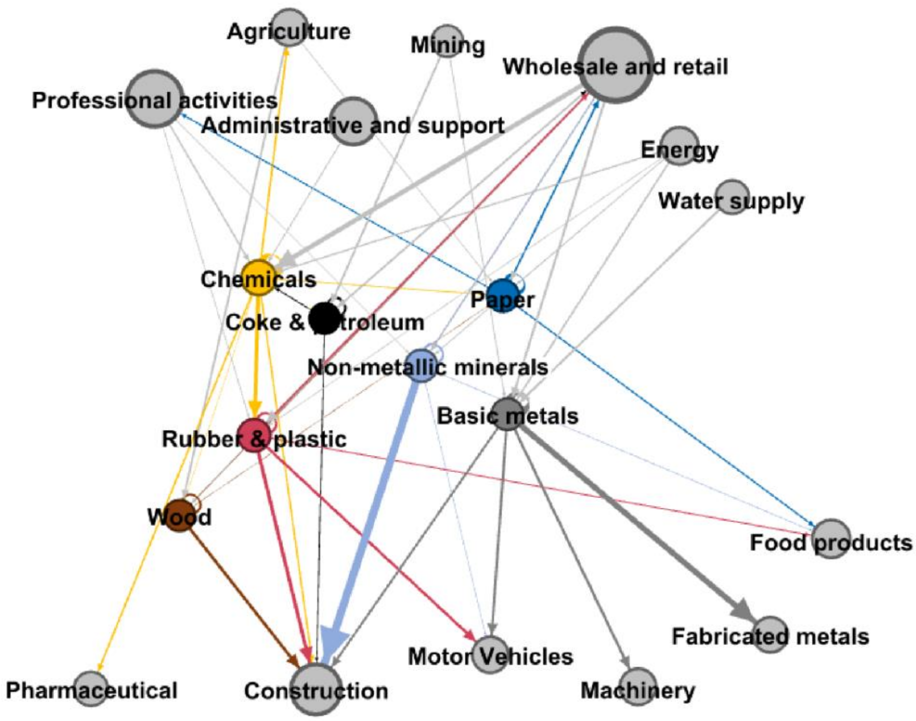
Input-output data

Upstream and downstream relationships are crucial for the delineation of an ecosystem. Taking them into account allows identifying critical inputs that core sectors include in their production, and vital markets that core sectors rely upon for selling their outputs.

Input-output tables make it possible to analyse both upstream and downstream linkages. For example, the significance of upstream sectors in the automotive ecosystem can be determined by assessing how much of the value added embedded in the final demand for automotive products originates from other sectors. Conversely, the importance of downstream linkages can be measured by examining the portion of value added in the final demand of other sectors that can be attributed to the automotive industry. In other words, upstream linkages are reflected in the portion of the value of motor vehicle production generated by sectors other than automotive manufacturing itself (e.g. the chips controlling airbags or the metal of the car frame), while downstream linkages are represented by the portion of value added generated by the motor vehicles sector embodied in the production of other sectors (e.g. the transportation sector uses outputs from the automotive ecosystem). OECD Trade in Value Added (TiVA) data[1] reveal that in the automotive sector, upstream linkages are especially important while downstream linkages are less so, i.e. value added produced in the motor vehicle sector does not contribute significantly to other final products. Notably, TiVA data have limitations: first, they provide only an aggregated view of value flows, which does not allow for granular product-level analysis; second, they do not encompass capital investment when it comes to intermediate transactions. Other data sources, like value-added tax data (Criscuolo et al., 2024[34]) can, therefore, be used to complement them.

Figure 6.2 shows the production network underpinning the EII ecosystem. It shows the breadth of both upstream and downstream linkages, highlighting how numerous sectors contribute to the value added by core EII industries, while many downstream sectors benefit from EII outputs. For example, the "Construction" sector is closely linked to "Non-metallic minerals", as well as "Rubber and plastics", "Wood", "Chemicals", and "Basic metals". Similarly, the "Motor vehicle" and "Electrical equipment" downstream industries depend on various EII core sectors, pointing to EIIs' overarching relevance as providers of critical inputs.

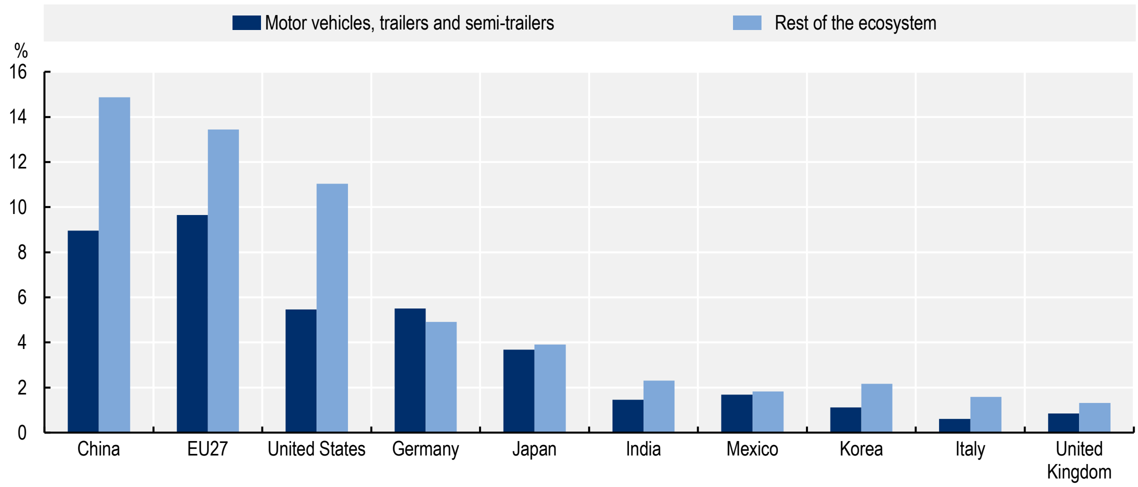
Figure 6.2. Production network of the energy-intensive ecosystem



Notes: The edges are weighted by the magnitude of the intermediate input flows while the nodes are weighted by the value added of each sector. The "Paper" sector is aggregated with "Printing and reproduction of recorded media" (ISIC 18 – rev. 4) in the underlying data. The figure only shows the seven main upstream and downstream sectors for the whole ecosystem. "Wholesale and retail" is both an upstream and a downstream sector but is located among the upstream sectors given that the value of its inputs supplied to energy-intensive industries are higher than for the inputs it sourced from them. Manufacturing n.e.c. is not included as a downstream sector given its general definition, instead the next downstream sector is reported ("Electrical equipment").
Sources: Dechezleprêtre et al. (2025, p. 23[32]), based on the OECD *Inter-Country Input-Output (ICIO) database*, 2023 edition.

Having identified both core and non-core components of an ecosystem, it is also possible to define which countries play the most relevant role within it. Figure 6.3 highlights the countries (and sectors) that contribute the highest share of value added embedded in the final demand for motor vehicles. The figure serves as a sharp reminder of the importance of accounting for the entire ecosystem, as the "Rest of the ecosystem" contributes substantially, and heterogeneously across countries, to the automotive value added. For example, although the European Union's (EU) motor vehicle sector remains the largest contributor among motor vehicle sectors, the People's Republic of China (hereafter "China"), when accounting for the entire ecosystem, has a higher share of value added. Similarly, the United States' automotive core sector's value added is lower than Germany's, but the rest of the US ecosystem generates considerably more value added than the German one.

Figure 6.3. Share of value added embodied in global final demand for motor vehicles, selected economies, 2018



Notes: The graph can be interpreted as follows: 23% of global value added embodied in final demand for motor vehicles comes from the European Union. Among these, 9.5 percentage points come from the automotive sector, while 13.5 percentage points come from the rest of the ecosystem.

Sources: Adapted from Dechezleprêtre et al. (2023, p. 22[35]), based on OECD, *Trade in Value-Added (TiVA) Database*, https://www.oecd.org/en/topics/sub-issues/trade-in-value-added.html (accessed in February 2022).

StatLink https://stat.link/fi7dkp

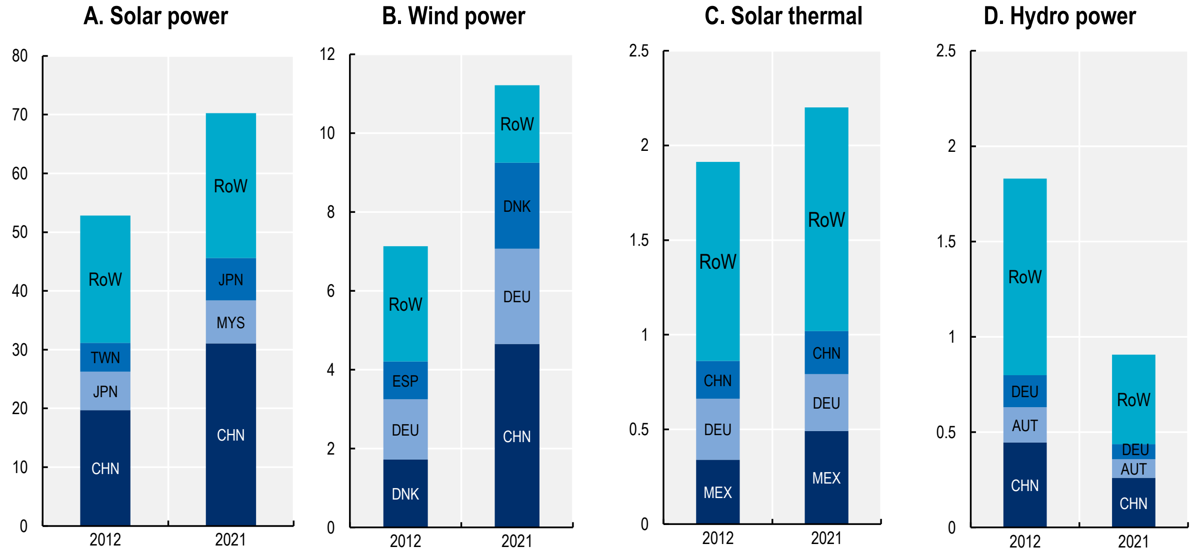
Trade data

Trade data can provide additional insights beyond value-added data, particularly in ecosystems where sectoral boundaries are less clear-cut. In such cases, granular information on specific products or technologies becomes especially relevant. The renewable energy ecosystem is a clear example of this, as it does not correspond to a single sector but rather comprises specific capital goods, products and raw materials. Due to their granularity, trade data are particularly well-suited to capturing the actors and relationships within such ecosystems. However, it is important to note that trade data fail to capture production that does not cross any border, pointing to the complementarity between trade and value-added data.

Figure 6.4 provides an example of the level of detail achievable when analysing trade data. It shows the main exporters of selected capital goods that are at the heart of four key renewable technologies: solar photovoltaic, wind power, solar thermal and hydropower. The analysis rests on the identification of a set of specific products, defined at the 6-digit level of the Harmonised System classification, for each of these technologies, rather than on a set of specific sectors. Therefore, while value-added data would not be able to identify key players active in the ecosystem, trade data can show export trends of capital goods across technologies. For example, China appears as a key player in the renewable energy ecosystem, being the most sizeable exporter in all technologies but solar thermal, where Mexico plays the leading role. Furthermore, trade data, similarly to value-added data, can be used to portray the flows of upstream goods. In the case of the renewable energy ecosystem, these correspond notably to critical raw materials, which will be a cornerstone of the trade dependency analysis presented in the next section.

Another advantage of trade data over value-added data is that they are more readily available and can therefore provide more up-to-date snapshots of the key countries active in an ecosystem than value-added data can. For a direct comparison, the EII ecosystem paper (Dechezleprêtre et al., 2025[32]) considers both value-added and trade measures, but the value-added measures are only available up to 2020 while the trade measures are available up to 2022.

Figure 6.4. Exports of capital goods used in renewable energy technologies, 2012 and 2021



Note: The figure shows the three largest exporters by technology. Data are reported in current USD billions. RoW = rest of the world.
Source: Dechezleprêtre et al. (2024, p. 15[36]), based on UN *Comtrade database*.

StatLink https://stat.link/42bmsu

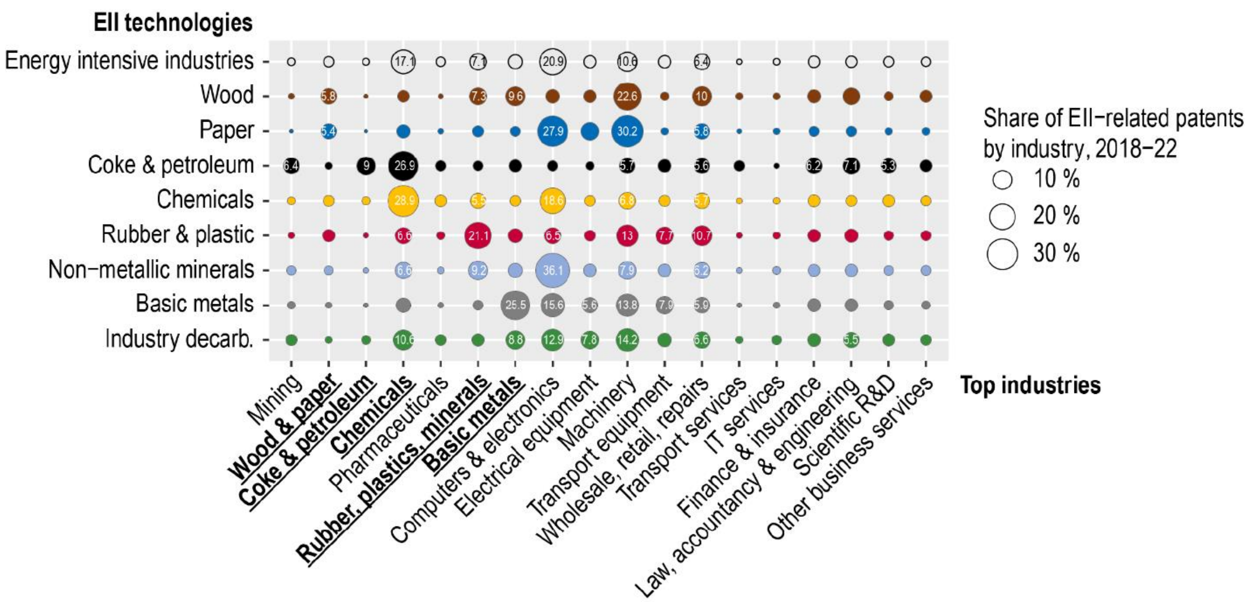
Innovation data

The importance of countries within an ecosystem is not limited to their contribution to value added and trade but also stems from their involvement in innovation activities. This is crucial to consider as innovation can provide a forward-looking perspective on the ecosystem: while value added and trade portray today's leading actors, innovation measures provide a glimpse on who is developing the capabilities that can help become tomorrow's leader.

There are several measures of innovative activities, including the number of active start-ups, investment in innovative firms, academic publications, among many others. Patents (OECD, 2009[37]), despite not being a perfect measure of innovation (Dziallas and Blind, 2019[38]; Acs and Audretsch, 1989[39]), include a wealth of information that can be especially helpful in describing innovation landscapes, and reveal information on the key actors of an industrial ecosystem (Supriya, 2023[40]).

The technological domain of patents can be identified based on patent classifications such as the Cooperative Patent Classification and the International Patent Classification. Dechezleprêtre et al. (2025[32]) use the correspondence table developed by Goldschlag, Lybbert and Zolas (2020[41]) to identify patents protecting technologies used in the EII ecosystem (such as innovations in steel, plastic or chemical products).[2] It is then possible to recover the sector of activity in which companies developing these patents operate. The data reveal that inventions relevant for the EII ecosystem are not only developed by firms operating in core EII sectors, companies from other industries may also develop innovations relevant to EIIs. For example, a company operating in the machinery sector might invent and patent a technology for a machine used in wood cutting. Figure 6.5 portrays patents filed in EII technologies (on the y-axis) and the sector of the firms filing them (on the x-axis). Core EII sectors, highlighted in bold, appear to be among the leading innovators in these technologies, as can be inferred by the size of the dots in the figure. However, only 30% of the patents filed in EII technologies in the period 2018-2022 were filed by firms in core EII sectors, indicating that most EII patents were developed outside the boundaries of the core sectors. Among these non-core sectors, "Computers and electronics" play an especially important role, as the sector filed about 21% of EII-related inventions worldwide, being the leading source of innovation for "Non-metallic minerals" technologies (with 36% of total patents). Firms belonging to the "Machinery" sector also contribute significantly to new EII technologies, especially in the fields of "Paper" (30% of patents related to "Paper" are from the "Machinery" sector) and "Wood" (23% are from the "Machinery" sector). Overall, this figure emphasises that limiting the analysis to EII core sectors would miss key innovation providers, supporting the importance of moving beyond a solely sectoral approach.

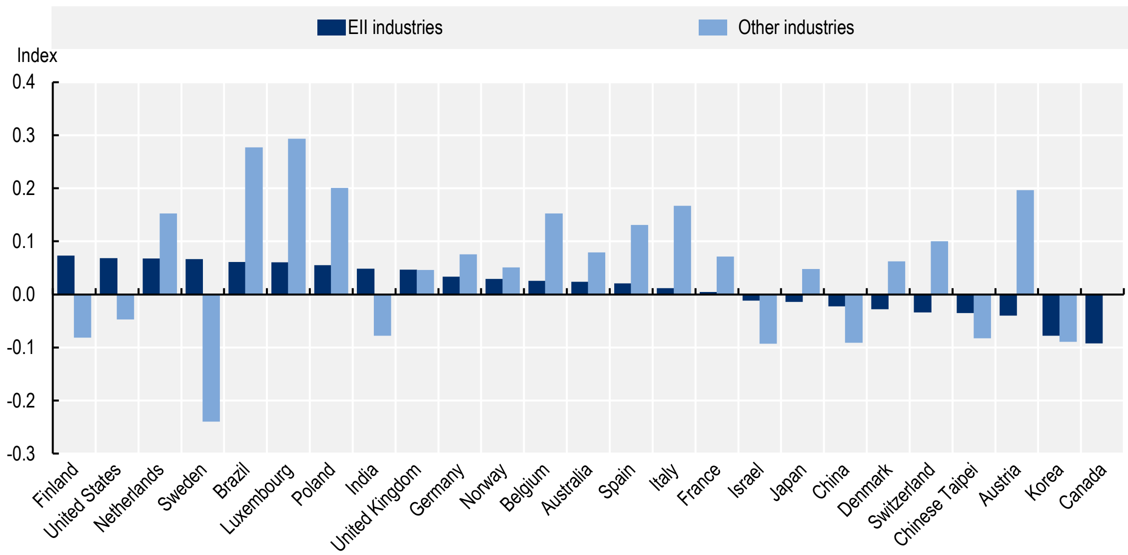
Figure 6.5. Industries patenting in energy-intensive industry technologies, 2018-2022



Notes: EII: energy-intensive industry. Data refer to IP5 patent families, by earliest filing date and applicant's location. See Annex B of Dechezleprêtre et al. (2025[32]) for further details on the patent data coverage and methodology.
Source: Dechezleprêtre et al. (2025, p. 43[32]), based on OECD, *STI Micro-data Lab: Intellectual Property Database*, http://oe.cd/ipstats, and ORBIS©, version 2022.1, Bureau van Dijk, October 2024.

This is further confirmed in Figure 6.6, which portrays countries' revealed technological advantage (RTA) for EII technologies, calculated as a country's share in EII patents compared to its share in total patents. As the range of possible values for the RTA goes from 0 to +∞, the RTA is shown in logs. In the figure, a log(RTA) greater than zero indicates that a country is specialised in a particular technology, compared to the world average. A log(RTA) below 0 indicates under-specialisation. The figure distinguishes between two different sources of innovation: core EII sectors (see previous sections for the complete list) and all other industries that generated patents in EII technologies. The figure clearly illustrates the importance of adopting an ecosystem approach, as the size of dark blue bars is often overshadowed by light blue ones, indicating that a country's specialisation in EII technologies stems primarily from sectors outside the core components of the EII ecosystem. Brazil, Luxembourg and Poland are clear – but not unique – cases of this tendency. The figure also shows how drastically the ranking of countries would change if only core sectors were considered. Finland, whose specialisation in EII technologies is entirely driven by core EII sectors, leads the ranking in Figure 6.6, but the scenario is markedly different when considering the rest of the ecosystem. For example, Brazil, which does not rank high in terms of value added or employment among the countries most involved in EIIs, shows very strong technical specialisation in EII technologies, driven by non-core EII sectors (especially mining and quarrying). A sectoral approach would likely overlook these peculiarities of the EII innovation landscape, underscoring the value of the ecosystem approach for policymakers.

Figure 6.6. Revealed technology advantage of economies in energy-intensive industry inventions, by industry, 2018-2022



Notes: EII: energy-intensive industry. Data refer to IP5 patent families, by earliest filing date and applicant's location. Only economies with a high matching rate to ORBIS© with more than 100 IP5 patent families in total for each set of industries are included. IP5 patent families are defined as sets of patent applications protecting the same invention filed in at least two intellectual property (IP) offices – with at least one application filed in one of the five largest IP offices worldwide (IP5): the European Patent Office, the Japan Patent Office, the Korean Intellectual Property Office, the State Intellectual Property Office of the People's Republic of China, and the United States Patent and Trademark Office. Patents for inventions related to EIIs are delineated using the concordance developed by Goldschlag, Lybbert and Zolas (2020[41]) that maps codes of the co-operative patent classification to the industry classification (ISIC, rev. 4), using a probabilistic approach. Only economies with more than 1 000 IP5 patent families in total for each period are included.
Sources: OECD calculations based on OECD, *STI Micro-data Lab: Intellectual Property Database*, http://oe.cd/ipstats, and ORBIS©, version 2022.1, Bureau van Dijk, March 2025.

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In the automotive area, adopting an ecosystem approach helps identify the fastest growing technologies, which in turn can enable the identification of economies that are building the capabilities that should be key for future growth in automotive. From this perspective, the surge in patents related to autonomous vehicles – which more than doubled between 2012-2015 and 2016-2019 – stands out as a key trend likely to shape the ecosystem's evolution in the coming years. Within the automotive ecosystem, countries differ in their technological specialisation. The United States, for instance, holds a strong RTA in the autonomous vehicle segment while other countries focus on mature, less innovation-intensive areas such as combustion technologies. This suggests a stronger potential for future leadership of the United States in the automotive ecosystem than would be suggested by considering their overall RTA across all automotive-related technologies.

Workforce data

Data on the workforce can also contribute to defining ecosystem boundaries, as a non-negligible portion of the occupations generated by a given industrial ecosystem lie outside the boundaries of its core sectors.

Figure 6.7 portrays this for the specific case of the renewable energy industrial ecosystem in the United States (but this holds true for the other countries considered in the analysis).[3] The figure shows that renewable energy vacancies are spread across various industries, regardless of the observed technology group. Most vacancies are concentrated in “Manufacturing” and “Electricity, gas, steam and air conditioning supply”, but employment is not limited to these core renewable sectors, including manufacturers of capital goods and adopters (such as firms in the electricity production sector). Many renewable energy vacancies are found in the “Professional, scientific and technical activities”, where renewable innovations are being developed, as well as in the “Construction”, “Finance and insurance”, and “Administrative and support service activities”. Overall, only approximately 39% of all vacancies are in what might be defined as core sectors, while approximately 61% are in other parts of the ecosystem.

This reinforces a key point from the previous section on innovation data, and a fundamental rationale behind the adoption of an ecosystem perspective: accounting only for the core sectors of an ecosystem overlooks a critical share of relevant stakeholders. This represents arguably the most crucial message for policymaking coming from the ecosystem perspective.

Figure 6.7. Sectoral distribution of renewable energy vacancies in the United States, 2022

Technologies \ Sectors	A - Agriculture	B - Mining & quarrying	C - Manufacturing	D - Electricity	E - Water supply & sewerage	F - Construction	G - Wholesale & retail trade	H - Transportation & Storage	I - Accomodation	J - ICT	K - Finance & insurance	L - Real estate	M - Prof. & scientific act.	N - Admin. & support act.	O - Public administration	P - Education	Q - Health & social care	R - Arts & entertainment	S - Other service act.	Total
Biomass	0.08	0.15	1.93	0.58	0.11	0.12	0.16	0.61	0.21	0.19	0.17	0.01	0.84	0.09	0.16	0.26	0.06	0.03	0.09	5.86
Generic	0.15	2.26	8.19	8.51	1.11	3.35	2.14	1.60	0.11	0.69	3.01	0.81	8.05	1.24	2.14	0.73	0.20	0.13	0.42	44.84
Geothermal	0.00	0.12	0.15	0.27	0.00	0.57	0.02	0.02	0.01	0.01	0.11	0.01	0.43	0.06	0.10	0.09	0.02	0.01	0.03	2.04
Hydrogen	0.00	0.01	0.12	0.02	0.00	0.03	0.04	0.01	0.00	0.00	0.01	0.00	0.17	0.01	0.02	0.03	0.00	0.00	0.00	0.48
Hydropower	0.03	0.09	1.14	0.20	0.06	0.60	0.08	0.05	0.00	0.03	0.11	0.01	1.37	0.04	0.22	0.03	0.02	0.00	0.03	4.10
Marine	0.00	0.01	0.09	0.01	0.00	0.01	0.01	0.15	0.00	0.01	0.04	0.06	0.10	0.05	0.02	0.02	0.00	0.00	0.00	0.57
Solar	0.04	0.44	3.89	4.99	0.18	3.36	0.68	0.30	0.08	0.15	2.30	0.21	2.41	2.17	0.51	0.19	0.17	0.16	0.20	22.42
Storage	0.01	0.38	3.60	1.84	0.00	0.63	0.28	0.26	0.01	0.17	0.44	0.20	2.80	0.21	0.39	0.15	0.06	0.15	0.10	11.69
Wind	0.03	0.43	2.58	0.95	0.00	0.38	0.73	0.15	0.05	0.19	0.22	0.05	1.23	0.43	0.29	0.11	0.06	0.02	0.11	8.01
Total	0.35	3.89	21.70	17.35	1.47	9.03	4.14	3.15	0.47	1.44	6.41	1.35	17.41	4.30	3.84	1.61	0.60	0.50	0.99	100.00

Note: The figure displays the distribution of renewable energy vacancies across sectors and technology groups in 2022 for the United States. Observations with missing sectors have been removed and not counted. The intensity of red colour corresponds to the share of vacancies, with all red-coloured cells collectively summing up to 100%. The intensity of blue corresponds to the sum of shares either across rows or across columns. Industry information is sourced through the North American Industry Classification System in the United States and aggregated into 1-digit sections for better comparability. Fractional counting is employed for cases involving multiple technologies. If a vacancy has been tagged through both a generic and a specific keyword, only the specific technology is considered. Technology groups are assigned to renewable energy vacancies based on the keywords used to identify them.
Source: Adapted from Dechezleprêtre et al. (2024, p. 44[36]), based on Lightcast data.

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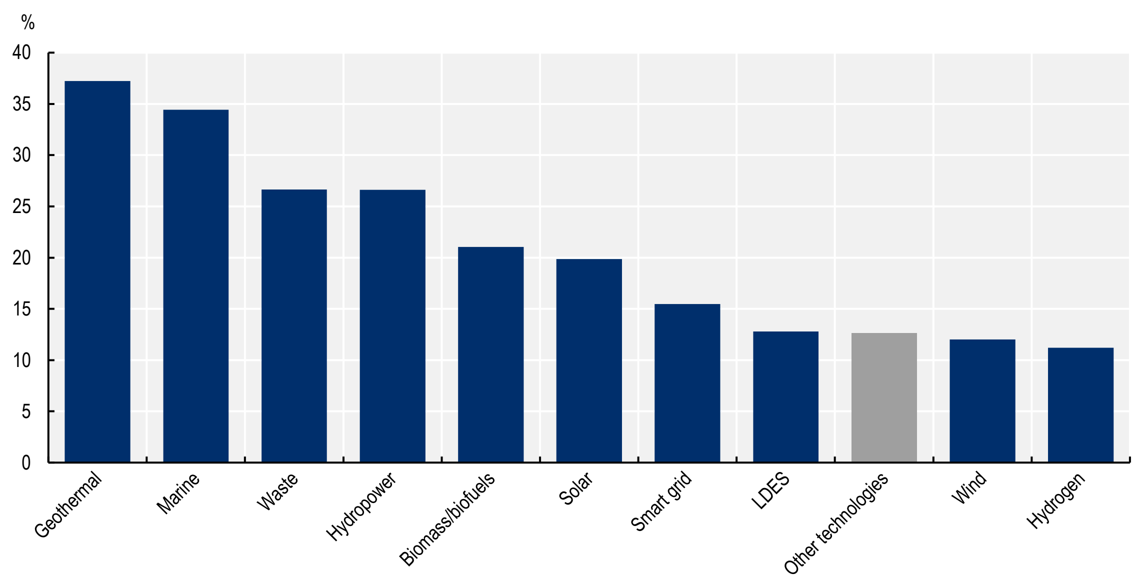
Accounting for the heterogeneity of industrial ecosystems stakeholders

It is also important to account for the heterogeneity of actors involved in industrial ecosystems. For instance, different types of firms – in terms of age, size or geographical location – have different roles in industrial ecosystems and tend to benefit from different sets of policies (Criscuolo et al., 2022[5]). Additionally, firms located upstream, at the core or downstream in a given ecosystem are also likely to play different roles, and the design of industrial strategies can benefit from taking these differences into consideration. Finally, ecosystems’ actors not only encompass firms but also public research organisations (PROs) and finance providers, among others, that need to collaborate to ensure the ecosystem’s success. This view is at the heart of mission-oriented policies: proponents of this approach acknowledge the need to consider and co-ordinate “systems” of stakeholders to address major challenges – like the transition toward a low-carbon economy (OECD, 2024[42]) – that are systemic in nature (Larrue, 2021[43]).

Start-ups are a category of firms commonly under policymakers' lenses, due to their contribution to net job creation (Criscuolo, Gal and Menon, 2014[44]) and the deployment of novel technologies (Audretsch et al., 2020[45]). Despite their crucial role in driving economic growth, start-ups often face greater challenges than established firms due to their lack of legitimacy (Lounsbury and Glynn, 2001[46]) and limited financial history (Da Rin, Hellmann and Puri, 2011[47]). As a result, they benefit more from certain policies, particularly those that ease capital constraints and facilitate market entry and exit (Criscuolo et al., 2022[1]). One example of start-ups' importance for innovation activities comes from the renewable energy ecosystem: in this ecosystem, incumbent firms (aged 20 years or more) file most inventions related to renewable energy. However, as Figure 6.8 indicates, younger firms (less than five years old) are not only filing a considerable share of patents in renewable energy technologies, but also a disproportionately high number relative to their contribution to overall patenting: when considering all other technologies (shown by the grey bar), young firms are responsible for around 12% of patents globally, but this share reaches 37% in geothermal technologies, 34% in marine energy, over 25% in waste and hydropower, and around 20% in biomass/biofuels and solar technologies.

Figure 6.8. Share of renewable energy technologies owned by young firms, 2017-202



Notes: LDES: long-duration energy storage. Data refer to IP5 patent families in renewable energy technologies, by earliest filing date. To be included in the sample, the patent family must be filed in at least two patent offices, one of which is among the IP5 offices (US Patent and Trademark Office, the European Patent Office, the Japan Patent Office, the Korean Intellectual Property Office, and the National Intellectual Property Administration in China) "Other technologies" refers to all technologies not related to renewable energy.

Sources: OECD calculations based on OECD, *STI Micro-data Lab: Intellectual Property Database*, *OECD Start-ups Database* and ORBIS©, version 2022.1, Bureau van Dijk, March 2025.

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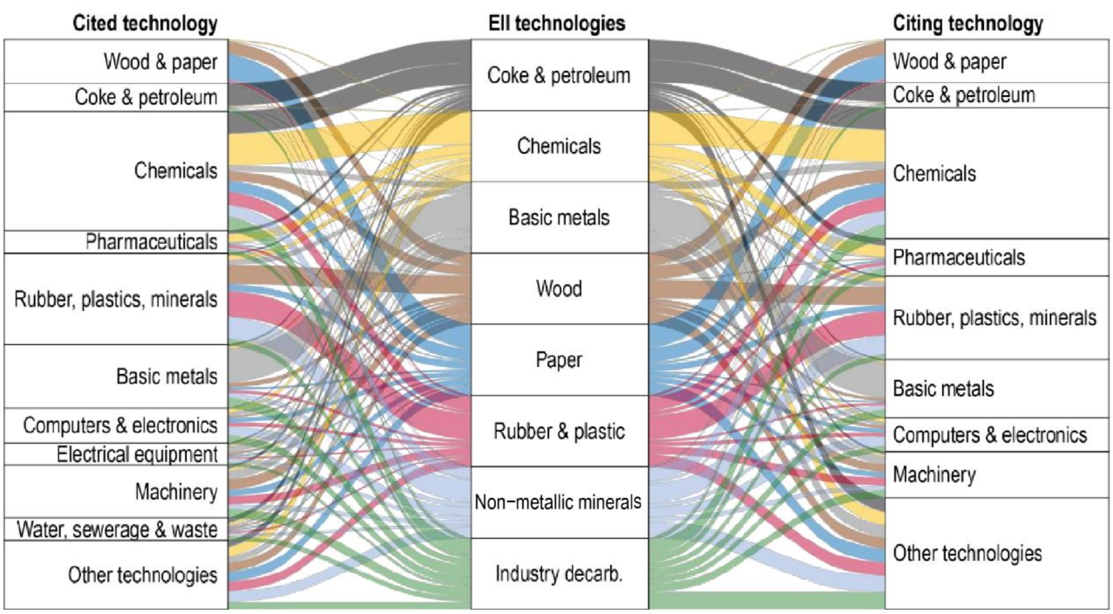
There are other important factors to consider when looking at the heterogeneity of firms involved in industrial ecosystems. One such element is their position – upstream, at the core or downstream – within the ecosystem. This is true not only in terms of inputs and outputs of production, but also in terms of innovative activities (Adner, 2006[31]). In this respect, the above-mentioned wealth of information included in patents can again play an important role, as patents include detailed data on both the prior-art cited by a patent (backward citations) and on other patents that would later mention the focal patent as part of their prior-art (forward citations).

Figure 6.9 portrays this analysis for the EII ecosystem. The central portion of the figure includes the different types of EII technologies while the left-hand side of the figure shows backward citations – from the EII ecosystem to its knowledge base – and the right-hand side shows forward citations – from other industries to the EII ecosystem. Focusing on the left-hand side, the figure shows that while some core components of the ecosystem, like "Chemicals", mainly rely on inventions from within the sector, others, like "Wood", do so to a much lesser extent. Furthermore, most EII inventions appear to benefit from patents filed in the "Chemicals" and "Rubber, plastics and minerals" sectors. Finally, there are sectors outside the core components of the ecosystem that play an important role as a knowledge base for the ecosystems: for example, "Machinery" and "Computers and electronics".

The right-hand side of the figure shows that the EII core-sectors have positive spillovers on other industries: for instance, 14% of forward citations of "Non-metallic minerals" inventions are made by patents in "Computer and electronics". Taking downstream adopters of innovation into account is essential for fostering industrial ecosystems, as research has shown that market demand serves as a "pull" for innovative activities (Mowery and Rosenberg, 1979[48]).

Figure 6.9. Top technologies in citations made by and received by energy-intensive industry-related patents



Notes: EII: energy-intensive industries. Data refer to patent applications filed under the Patent Cooperation Treaty, by earliest filing date and location of the applicants. Patents for inventions related to EIIs are delineated using the concordance developed by Goldschlag, Lybbert and Zolas (2020[41]) that maps codes of the co-operative patent classification (CPC) to the industry classification (ISIC, rev. 4), using a probabilistic approach. The technological scope is complemented with patents related to the decarbonisation of industries, including: selected climate change mitigation technologies in the production or processing of goods and patents for capture, storage, sequestration or disposal of greenhouse gases, identified using CPC codes. Cited technologies refer to the top 3 technologies listed in backward citations made in EII patents filed between 2018 and 2022. Citing technologies refer to the top 3 technologies listed in forward citations made to EII patents by patents filed between 2018 and 2022. Forward citation linkages exclude self-citations.

Sources: Dechezleprêtre et al. (2025, p. 39[32]), based on OECD, *STI Micro-data Lab: Intellectual Property Database*, http://oe.cd/ipstats (accessed in October 2024).

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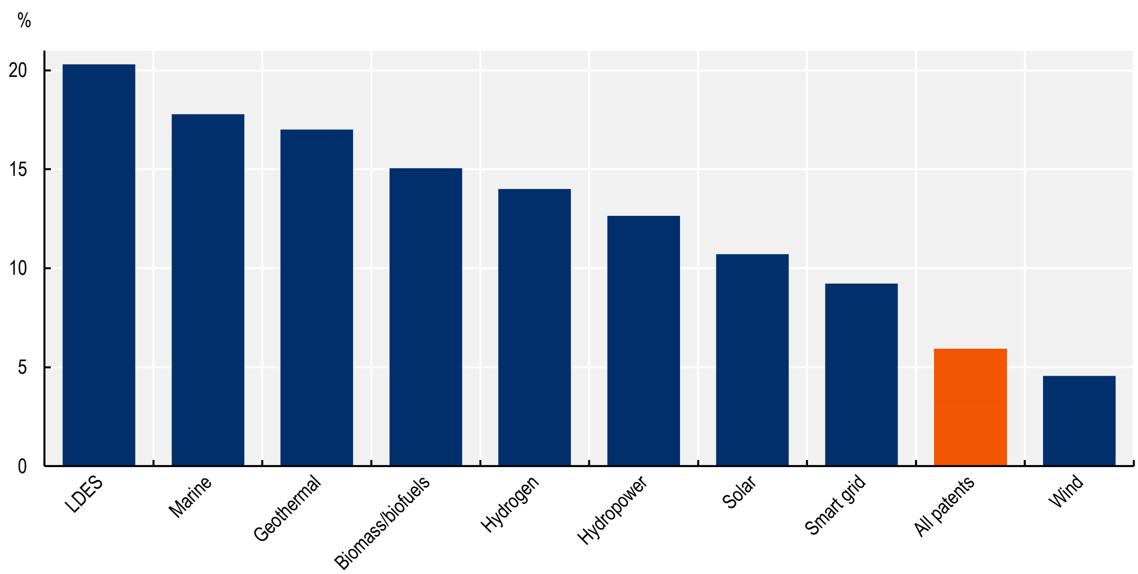
Finance providers, like banks, venture capital funds and angel investors, play a significant role, too, especially with respect to the above-mentioned funding challenges start-ups face. PROs – public research centres and other government institutions – and universities are other groups of stakeholders that should be considered when designing industrial policies targeting industrial ecosystems. Figure 6.10 focuses on their role within the renewable energy ecosystem. It shows that while innovations in this ecosystem mainly occur within private firms (with only 8% of patents originating from PROs and universities), the share of renewable energy patents owned by PROs and universities is relatively higher than that observed for all patents (6%). Additionally, there are specific technologies for which PROs and universities play a particularly important role, in particular long-duration energy storage (20%), marine energy (18%) and geothermal (17%). The technologies where PROs and universities tend to have a more relevant role are less mature technologies – like long-duration energy storage and marine – while in mature technologies like wind, industry takes a more outsized role in patenting activities, in line with existing evidence on academic innovation's closeness to the technological frontier (Roche, Conti and Rothaermel, 2020[49]).

Figure 6.10. Share of renewable energy patents developed by public research organisations and universities, worldwide, 2010-2021



Notes: LDES: long-duration energy storage. Data refer to IP5 patent families. Patents filed by public research organisations and universities only include patents for which the type of applicant is identified. To be included in the sample, the patent family must be filed in at least two patent offices, one of which is among the IP5 offices (US Patent and Trademark Office, the European Patent Office, the Japan Patent Office, the Korean Intellectual Property Office, and the National Intellectual Property Administration in China) "Other technologies" refers to all technologies not related to renewable energy.
Source: Dechezleprêtre et al. (2024, p. 31[36]), based on OECD, *STI Micro-data Lab: Intellectual Property Database*, http://oe.cd/ipstats (accessed in January 2024).

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Overall, the co-existence of these heterogenous stakeholders within the often-fuzzy boundaries of industrial ecosystems stresses the importance of designing policies capable not only of considering this multitude of actors, but also of fostering collaboration among them.

Identifying the main challenges faced by industrial ecosystems

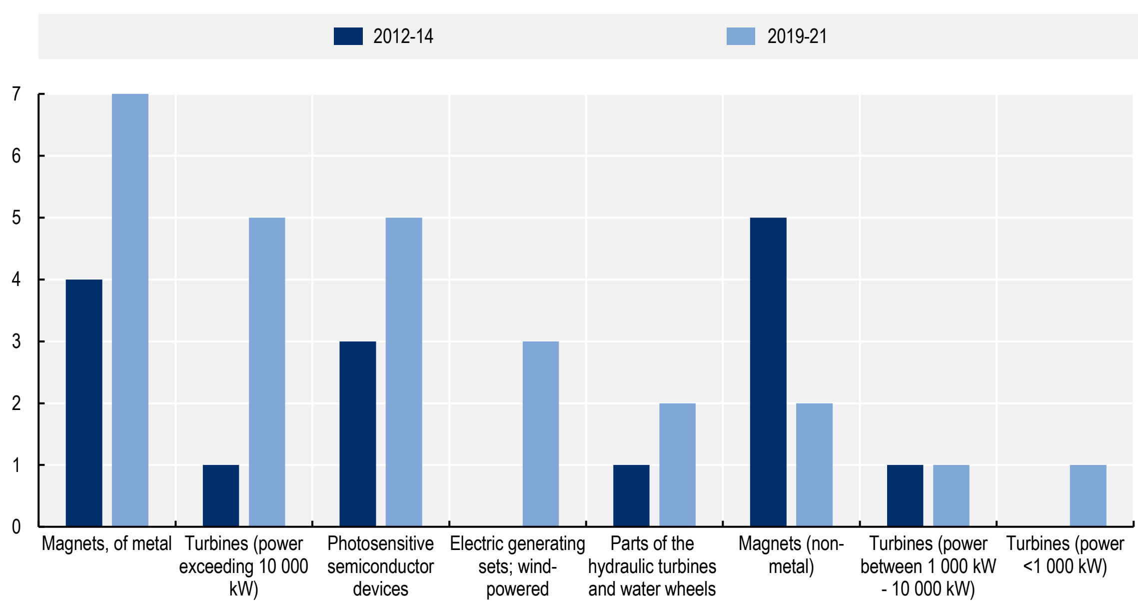
Delineating the boundaries of industrial ecosystems and identifying the ecosystems' stakeholders are essential building blocks to identify possible challenges, bottlenecks and dependencies within ecosystems. Indeed, these often stem from co-ordination frictions among ecosystems' actors (e.g. a lack of funding for start-ups), "choke points" around specific technologies or resources (e.g. niobium for wind technologies in the renewable energy ecosystem), or critical but ignored relationships with upstream or downstream firms. This section examines three types of challenges that affect ecosystems: trade, technology and skills.

Supply chain dependencies and bottlenecks

Supply chain bottlenecks can be particularly detrimental for industrial ecosystems due to the interdependency that characterises them, as the failure of a single link (e.g. sudden export restrictions on a critical mineral or the shutdown of a crucial factory) may cascade down to the rest of the ecosystem. For example, the automotive ecosystem's struggles during and following the COVID-19 pandemic can be linked to a failure of upstream suppliers to provide the chips needed for car manufacturing (Haramboure et al., 2023[50]). The resulting delays negatively affected not only core automotive sectors, but also other upstream sectors with high reliance on the automotive sector, as well as final customers. Monitoring and mitigating these supply chain risks is a key objective for policymakers interested in increasing the resilience of their economies (Bonnet and Ciani, 2023[51]).

The renewable energy ecosystem is also exposed to supply chain shocks. Figure 6.11 focuses on trade dependencies for capital goods employed in the production of renewable energy.

Figure 6.11. Number of trade dependencies for OECD Member countries, by renewable energy product, 2012-2014 and 2019-2021



Notes: Three conditions need to be met to consider that country *i* is dependent for its supply of good *k*. First, gross imports of good *k* by country *i* need to be overall highly concentrated (Herfindahl-Hirschman Index >0.410). Second, the largest non-OECD partner needs to account for a high share (>10%) of country *i*'s imports of good *k*. Finally, other OECD Member countries' import share for good *k* in country *i* needs to be less than 20%. Additionally, to avoid deeming as dependent a country with a high domestic production, two additional conditions were included. The ratio of exports to imports of the good *k* in country *i* must be lower than the 90th percentile of the distribution and the imports from country *i* of good *k* need to amount to USD 1 million or more. Conditions are verified over a three-year average, as shown in the figure specifically for the periods 2012-2014 and 2019-2021.
Source: Dechezleprêtre et al. (2024, p. 17[36]), based on UN *Comtrade database*.

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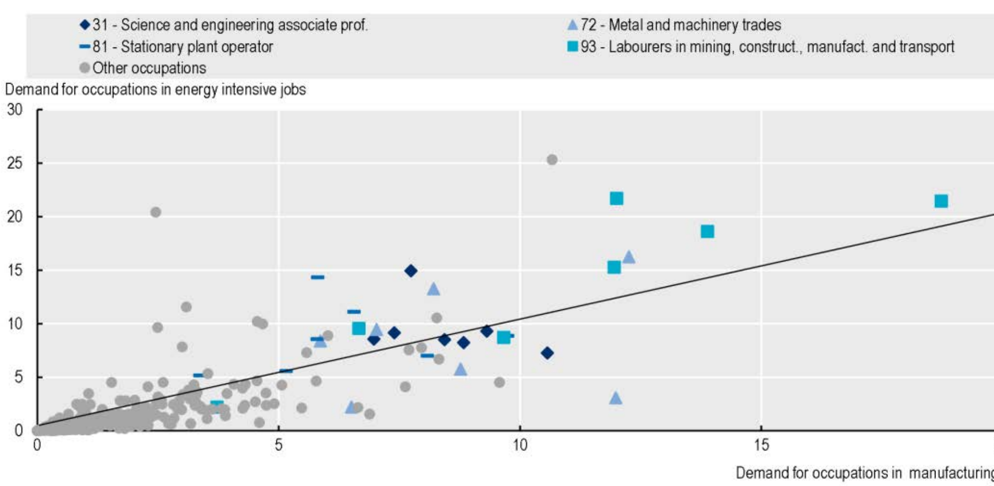
Figure 6.11 shows that, among all products, the imports of metallic magnets and of turbines of a power exceeding 10 000 kilowatts are particularly exposed to potential shocks, as several countries are dependent on a limited number of exporters for a large share of their imports (of the 26 identified dependencies, 23 are linked to trade flows with China). This implies that, should this limited number of exporters restrict exports of metallic magnets and turbines, countries relying on them would likely face supply chain disruptions. The figure also reveals that trade dependencies have increased for most products across the two periods considered.

Identifying skills' bottlenecks

The industrial ecosystem approach can also provide valuable insights into another critical challenge: skills bottlenecks. A shortage of relevant human capital, for instance, has been identified as a significant obstacle to the ambitious semiconductor-oriented initiatives recently launched by the European Union, Japan, Korea and the United States (see Box 6.2).

Online vacancy data can provide useful insights on the most required occupations within a given ecosystem. However, disentangling the occupations facing high demand but also high supply from those with demand-supply mismatches is not a trivial task. Figure 6.12 compares the occupational distribution of vacancies in EIIs (on the y-axis) and the distribution across all manufacturing vacancies (on the x-axis) for a sample of countries, with the denominator representing the number of online job postings in either manufacturing (x-axis) or energy-intensive industries (y-axis). While this does not allow the identification of precise mismatches, it pinpoints occupations that are especially salient to EIIs.

Figure 6.12. Demand for occupations in energy-intensive industries vs. manufacturing vacancies, 2022



Notes: The figure features a scatterplot illustrating distributions. Each point represents a specific occupation in one of seven European countries analysed in 2022, namely Austria, Czechia, France, Germany, Italy, Spain and Switzerland, while the black line is a 45° line. Dots above this line correspond to over-demanded occupations in a country. Between 0.04% (Switzerland) and 4.0% (Spain and Czechia) of vacancies in Lightcast do not have any occupational information, with the specific percentage varying by country. Vacancies in the manufacturing sector were identified at the 1- and 2-digit level, which may include some vacancies in energy-intensive industries (EIIs) for which sectoral information was only available at the 1-digit level. Coloured dots represent the most over-demanded occupations in the EII ecosystem.
Source: Dechezleprêtre et al. (2025, p. 50[32]), based on Lightcast data.

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Figure 6.12 shows that some occupations are considerably more requested in the EII ecosystem than manufacturing in general. While there are country-specific differences, over-demand is most evident for labourers in mining, construction, manufacturing and transport (3 percentage points higher on average than manufacturing), closely followed by stationary plant operators (2 percentage points), and science and engineering associate professionals (1 percentage point). The metal and machinery trades stand out as a notable exception, as they are in over-demand in Germany, France, Austria and Switzerland (in descending order) but under-demanded in Czechia, Italy and especially Spain.

Box 6.2. Semiconductor policies and lack of talent

The semiconductor ecosystem is incredibly complex due to the high degree of specialisation in the various stages – design; wafer production; fabrication; and assembly, testing and packaging (Haramboure et al., 2023[50]; OECD, 2024[52]) – of its value chain. Furthermore, the semiconductor ecosystem is characterised by the same challenges described in this chapter: significant bottlenecks at specific technology nodes (e.g. extreme ultraviolet lithography) and a strong dependency on critical raw materials.

Initiatives such as the CHIPS and Science Act (United States) and the EU Chips Act (European Union) have acknowledged not only the importance of the semiconductor industry as a provider of key inputs for downstream industries (Haramboure et al., 2023[50]) but also the challenges this industry has to face. Consequently, these policies have provided generous incentives to companies operating in the semiconductor ecosystem, especially for the construction of new fabrication plants. However, the success of these initiatives depends on firms' ability to access the necessary human capital, which can be in short supply, as suggested by anecdotal evidence on the construction of new manufacturing facilities (New York Times, 2024[53]) and empirical data on supply gaps (McKinsey & Company, 2024[54]; 2023[55]). This issue is not limited to the semiconductor ecosystem: the battery manufacturer Northvolt, a cornerstone of the European strategy for battery-making, experienced significant disruptions in its operations due to a lack of expertise with foreign equipment (Tagliapietra and Trasi, 2024[56]). Filling similar human capital gaps requires a co-ordinated effort from both private and public stakeholders: for example, recent OECD work (OECD, 2024[57]) on the Philippines semiconductor industry highlighted the potential for stronger co-ordination among education stakeholders to provide more targeted training.

In addition to education, the availability of skills is also influenced by migration policies, including visa regulations and the phenomenon of brain drain. The Philippines serves again as an interesting case, as the country has experienced significant emigration, which may hinder its ambitions in the semiconductor ecosystem. To address this, the government launched the Balik Scientist Program to incentivise scientists to return to the Philippines and help strengthen the local semiconductor ecosystem (OECD, 2024[57]).

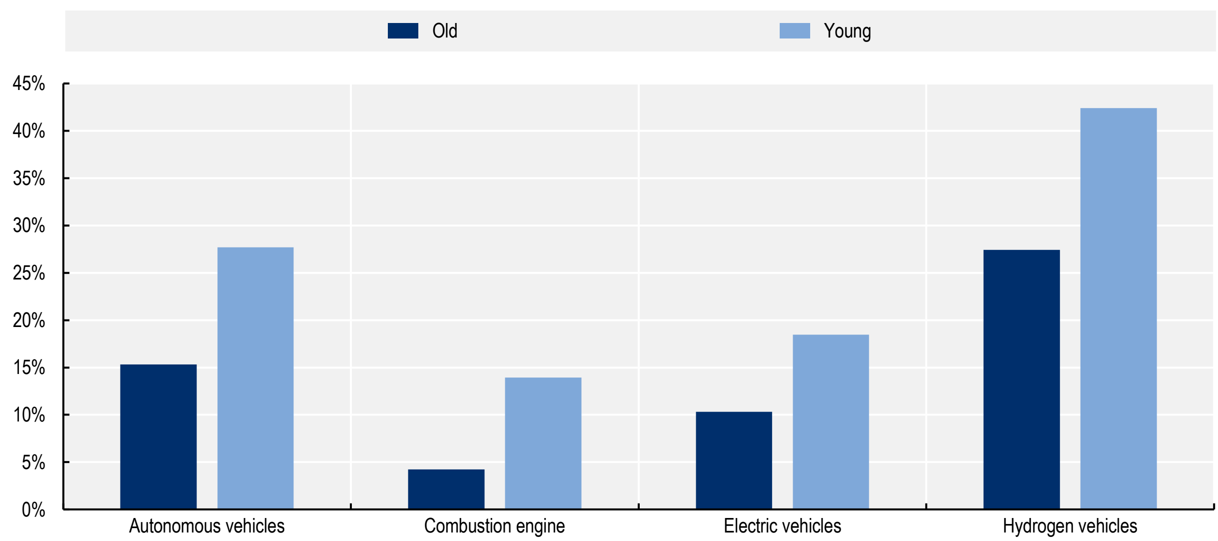
Sources: Haramboure et al. (2023[50]); New York Times (2024[53]); McKinsey & Company (2023[55]; 2024[54]); Tagliapietra and Trasi (2024[56]); OECD (2024[57]).

Technological interdependencies and adoption struggles

The industrial ecosystem approach, with its holistic perspective, is particularly well-suited to address the challenge of developing effective policies for fostering novel technologies, which rely on a complex web of collaboration between diverse actors. Start-ups are key engines of creative destruction and productivity-enhancing reallocation of market shares toward more innovative and productive firms (Decker et al., 2017[58]). Universities and PROs are also crucial in building a strong scientific knowledge base on which marketable innovations can be generated and can play a disproportionately significant role in the early stages of some emerging technologies.

Figure 6.13 highlights research links between start-ups and universities/PROs in the automotive ecosystem. It shows that, consistently across automotive-related technologies, young firms significantly cite more academic patents, a result which resonates with the literature emphasising the value of linkages between start-ups and academia (Thursby and Thursby, 2011[59]; Perkmann et al., 2013[60]), and hinting at the role of start-ups in further developing early-stage innovations originating in academia. This highlights the importance of creating opportunities for these two ecosystem actors to collaborate, for instance though technology transfer offices and university-affiliated incubators and accelerators.

Figure 6.13. Share of patents citing patents filed by academic institutions, automotive ecosystem, by firm age and technology, 2000-2019



Notes: Patent families are only assigned to one of the four technologies. If a patent family can be linked to multiple technologies, it is categorised based on the following order of priority: hydrogen, autonomous, electric and combustion. To be included in the sample, the patent family must be filed in at least two patent offices, one of which is among the IP5 offices (US Patent and Trademark Office, the European Patent Office, the Japan Patent Office, the Korean Intellectual Property Office, and the National Intellectual Property Administration in China). A patent is labelled as citing an academic patent if at least one application in the patent family cited a patent filed by an academic institution.
Source: Dechezleprêtre et al. (2023, p. 42[35]), based on data from OECD, *STI Micro-data Lab: Intellectual Property Database*, http://oe.cd/ipstats (accessed in June 2022) and ORBIS©.

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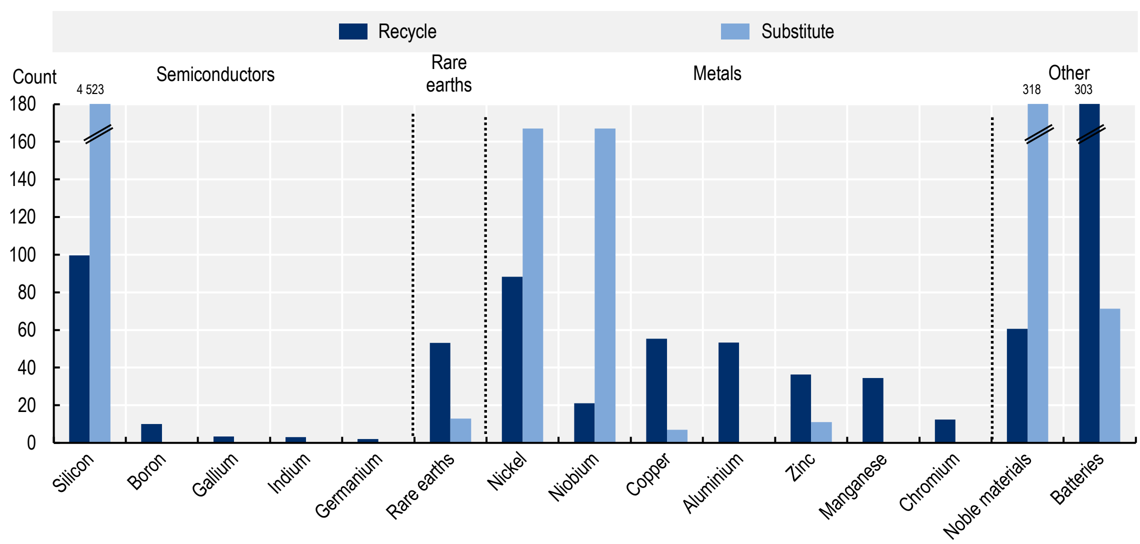
Taking an ecosystem perspective can also help better understand what parts of a given ecosystem have made the most progress in dealing with the key technologies of the twin transition. For example, given its relatively low energy efficiency, the energy-intensive ecosystem would particularly benefit from more rapid adoption of digital and low-carbon technologies. Indeed, digital technologies can have a positive effect on EIIs by providing efficient tools for monitoring, controlling and automating production and processes (Calvino, Dechezleprêtre and Haerle, 2025[61]). Between 2018 and 2022, the EII ecosystem developed digital technologies at a higher pace than other non-ICT manufacturing (7.4% of EII-related technologies on average also featured a digital component versus 6% in the rest of the manufacturing sector) but there is considerable heterogeneity across the sectors composing the ecosystem, for example between "Non-metallic minerals" technologies (16%) and "Coke and petroleum" (less than 1%), and countries (for instance, EU27 countries are lagging behind in this context).

The solutions to challenges faced by ecosystems are also interdependent

The various challenges discussed in this section are inherently linked and addressing one can have positive spillovers on the others. Figure 6.14 provides one example of this link. It shows patents filed to develop substitutes, and improve recycling, for raw materials employed in the renewable energy ecosystem. As such, these innovative efforts can play an important role in alleviating supply chain dependencies on specific products and improve supply chain resilience. The figure shows that most of these patents are focused on silicon, at least for the 2017-2021 period. Nickel and niobium are also targeted, but considerably less so than silicon. All three raw materials are characterised by low substitutability – hence the importance of finding alternatives to foster ecosystems' resilience – but nickel and niobium also face high export concentration, making them even more delicate for supply chain monitoring.

Figure 6.14. Patents in recycling or substitution of critical raw materials, 2017-2021

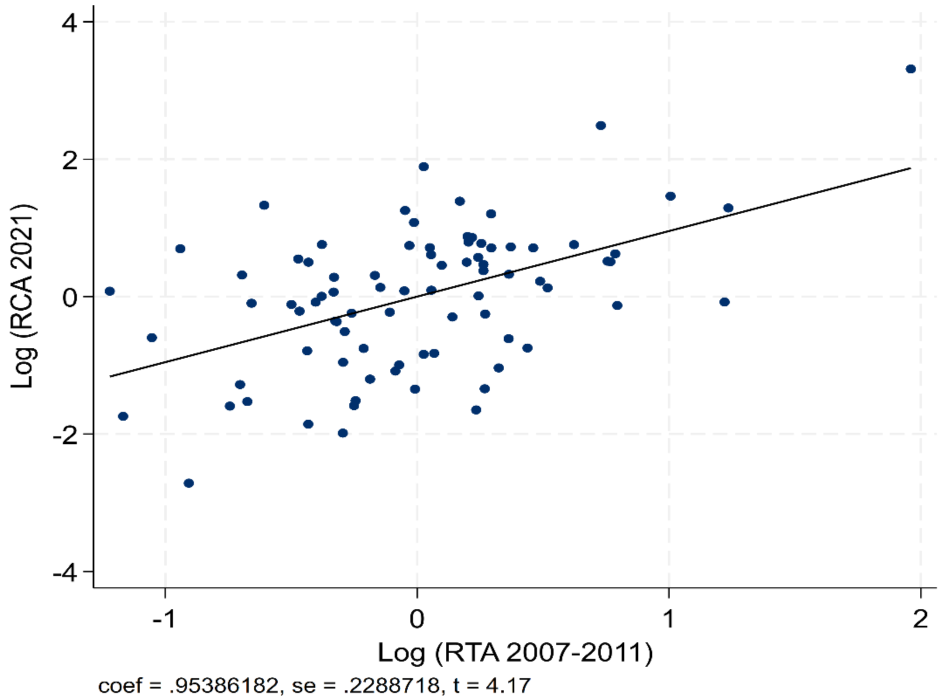


Notes: Data refer to IP5 patent families by filing dates. Patents for recycling or substitute for raw materials are identified using the search strategy described in Annex A B.2 and Table A B.3 in Dechezleprêtre et al. (2024[36]).
Sources: Dechezleprêtre et al. (2024, p. 36[36]), based on OECD, *STI Micro-data Lab: Intellectual Property Database*, http://oe.cd/ipstats (accessed in January 2024).

StatLink https://stat.link/evcstg

Figure 6.15 presents another example, portraying the relationship between technological specialisation and trade comparative advantage, focusing on a subset of renewable energy technologies, namely wind, hydro and solar power. The figure shows a positive relationship between countries' RTA, lagged by ten years, and relative comparative advantage, in particular in wind and hydro power, but also for solar power. This suggests that developing stronger innovation capabilities goes hand in hand with strengthening export performance, and while the directionality and causality of this relationship is not yet well-established in the literature, the fact that RTA values in Figure 6.15 precede relative comparative advantage values by ten years suggests that productivity gains associated to innovation (Cassiman, Golovko and Martínez-Ros, 2010[62]) and upgrading to higher value-added activities within technology-specific value chains (Caliari et al., 2023[63]) likely contribute to explaining this phenomenon.

Figure 6.15. Relationship between technological specialisation and trade comparative advantage



Notes: This regression is pooling all technologies together and controlling for technology and country fixed effects. Also, this regression controls for relative comparative advantage in the base year (2012). A placebo test was performed by regressing revealed technological advantage in 2017-2021 on relative comparative advantage in 2012. This correlation was still positive but with a much lower coefficient (0.09 vs 0.9) and t-values (1.79 vs 4.17) than in the original specification.
Source: Dechezleprêtre et al. (2024, p. 30[36]), based on OECD, *STI Micro-data Lab: Intellectual Property Database*, http://oe.cd/ipstats and UN *Comtrade database*.

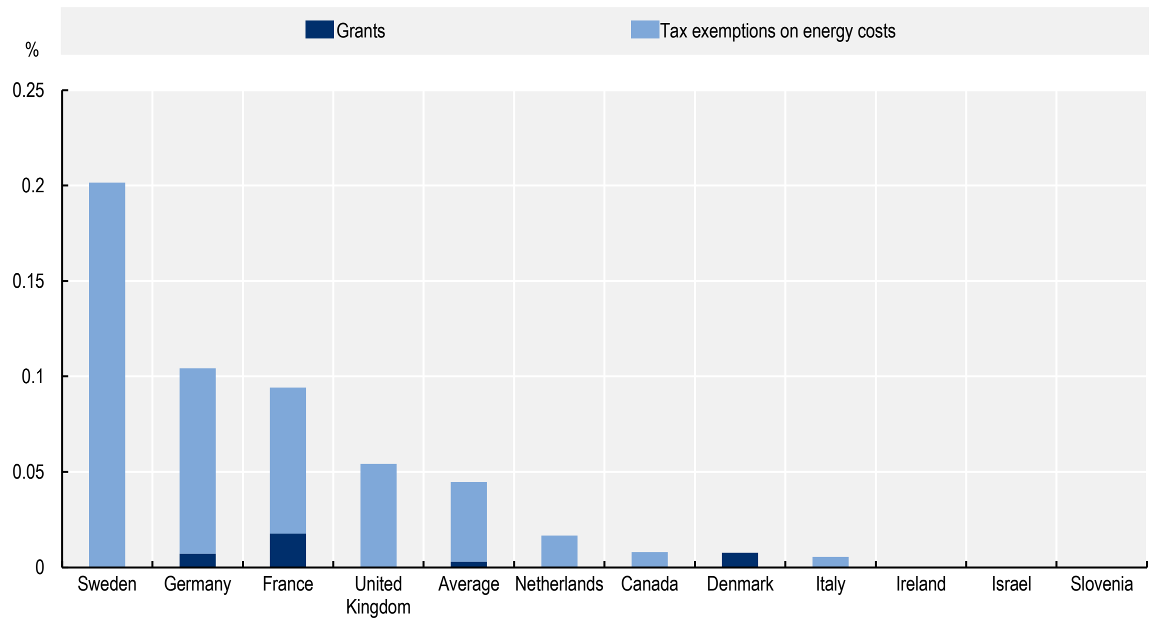
This section, focused on the policy implications of what has been described so far, shows there is room for improvement when it comes to adopting an ecosystem perspective in policymaking. While the chapter so far has highlighted the importance of non-core sectors, the interdependence among heterogenous actors and the multifaceted nature of industrial ecosystems, examples from the ecosystem studies show that existing policies typically overlook these elements.

Existing industrial policies are yet to consider ecosystem interdependencies

Despite significant conceptual advancements in industrial and innovation ecosystems and increasing awareness about their importance, the adoption of ecosystem thinking is still not the norm in industrial policymaking. One clear example comes from the energy-intensive sector, which is crucial for economies as its outputs are integrated in a variety of downstream industries. In addition, the EII ecosystem has relatively low R&D intensity and is only slowly increasing energy efficiency. Existing policies appear to provide only partial responses to these challenges: for example, policy support targeting the EII ecosystem, in the countries sampled in the QuIS project appear to be overwhelmingly focused on tax exemptions on energy costs (Figure 6.16).[4] As unbalanced as it may appear, the picture provided in Figure 6.16 is likely to be an underestimation of this type of support, as some economies have horizontal tax reductions on energy costs that are not covered in the QuIS project, since they alter the baseline taxation of the entire economy, including both households and businesses.

Figure 6.16. Direct business support explicitly targeted to the energy-intensive industry ecosystem by instrument type, average for 2019-2021

As a percentage of GDP



Notes: Data are available for 11 OECD countries. Instruments targeted to the ecosystem are defined as those that either target a specific sector of the ecosystem or specific objectives related to the ecosystem such as subsidising energy efficiency or energy input costs in manufacturing.
Source: Dechezleprêtre et al. (2025, p. 55[32]), based on the OECD *QuIS database*.

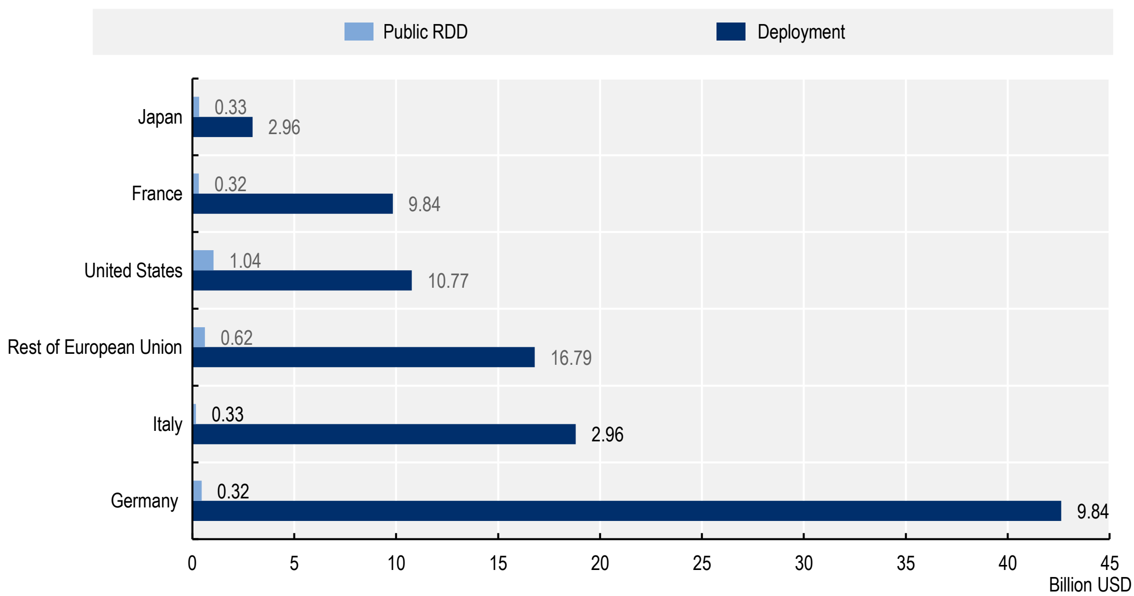
StatLink https://stat.link/ewgbhl

Tax exemptions on energy costs, coupled with the large extensions granted to EIIs under the EU Emissions Trading System and other carbon-pricing mechanisms – with a share of free allowances over total emissions of 82% (vs. 21% in the rest of manufacturing), on average, in the period 2005-2020 – respond to crucial concerns linked to promoting the competitiveness of sectors like EIIs, that are located upstream in many value chains and are also highly exposed to international trade. Nevertheless, a more balanced policy portfolio could be beneficial, as there is established evidence pointing to free allowances and energy tax exemptions both being contradictory to abatement incentives (Dechezleprêtre, Nachtigall and Venmans, 2018[64]; Flues and van Dender, 2017[65]). In other words, the incentives currently provided may not provide a strong incentive to innovate in green technologies, even if their logic answers to ecosystem concerns related to downstream industries. While this may simply call for a more balanced approach, it also points to the challenging trade-offs that policymakers need to face.

A second example of policies that appear not to consider the entire ecosystem comes from the renewable energy ecosystem. In this case, support for R&D is increasing across countries, especially for green hydrogen and smart grids, particularly in Germany and Japan. However, historically, most of the support in OECD Member countries targeting this ecosystem has focused on deployment policies rather than direct R&D funding (Figure 6.17). This imbalance seems particularly pronounced in European economies, suggesting a potential oversight in fostering innovation within an ecosystem that has experienced a decline in patents across key technologies since 2010. In an ecosystem heavily dependent on critical raw materials and with capital goods providers concentrated in a few countries, prioritising support for deployment over support for innovation may reinforce bottlenecks rather than resolve them. This is especially the case given that countries like China – the main player in terms of capital goods and raw materials for the ecosystem –

offer substantial direct subsidies to domestic companies (OECD, 2025[66]), thereby giving them an advantage over foreign competitors. Furthermore, Figure 6.7 already highlighted how the electricity sector, while being a relevant employer, accounts only for a limited share of renewable energy vacancies. More widely encompassing policies could benefit the numerous other sectors that account for renewable energy occupations.

Figure 6.17. Public Research Development and Demonstration versus deployment support in renewable energy, 2021



Notes:. The public RDD value for the United States is based on the 2023 edition of the IEA *Energy Technology RD&D Budgets database*, as more recent versions no longer include the previously reported estimates. Funding for European countries includes EU-wide public RDD packages funded by the European Commission. These funds are allocated to each country based on its share in EU GDP in 2021. Funding is expressed in nominal terms (2021 prices) for deployment, and in constant 2023 prices and exchange rates for public RDD.
Sources: Dechezleprêtre et al. (2024, p. 56[36]), based on IEA *Energy Technology RD&D Budgets database* (accessed in December 2025); IISD (2024[67]).

StatLink https://stat.link/3ev2ib

Policies designed to support the automotive ecosystem appear to have moved toward a stronger integration of ecosystem thinking, which is crucial in a sector strongly affected by the twin transition toward green and digital technologies. In this area, the inclusion of support for upstream segments, such as the semiconductor sector, appears crucial to increase resilience, as recent shocks linked to the COVID-19 pandemic have shown. Moving in the direction of “CASE” (Connected, Automated, Shared and Electric) vehicles requires policies that support providers of digital technologies – an area where ICT companies play a key role.

Another upstream sector that has received direct government support is the battery industry: the establishment of the European Battery Alliance and its related Important Projects of Common European Interest funding suggest that ecosystem thinking is becoming increasingly embedded in policymaking. Russia’s war of aggression against Ukraine has put pressure on energy prices, further highlighting the importance of energy independence based on domestic renewable electricity production. From this perspective, policy initiatives like the Inflation Reduction Act, which include tax credits linked to manufacturing and investment to support electric vehicle and renewable electricity producers, can contribute to the shift toward electric transportation.

How can the industrial ecosystem approach support the identification of relevant policies?

The key policy lesson offered by the three ecosystem studies is that policies aiming to foster a given ecosystem should not target its core individual components but rather the variety of actors that compose them and the relationships characterising them. In addition, such policies should consider whether support needs to be tailored to different actors, including academia, investors, and small and medium-sized enterprises and start-ups, so that all stakeholders – regardless of size – can contribute to and benefit from the growth of the ecosystem. Policies that focus solely on core components can be short-sighted, as they may overlook factors such as upstream-driven innovation, demand in downstream markets, supply chain bottlenecks and other critical ecosystem dynamics. Similarly, "mission-oriented" policies emphasise the need for co-ordination across different policies (and across the actors overseeing them) to address overarching "grand" challenges like those posed, for example, by climate change (Mazzucato, 2018[68]; Larrue, 2021[43]; OECD, 2023[69]). This is a challenging task that requires capable public agencies, effective data infrastructure, alignment with national priorities and broad public consensus. Innovation, skills and competition-oriented policies should all be considered, as they all contribute towards creating more vibrant, resilient ecosystems.

Policies promoting innovation are crucial across the studied ecosystems as they contribute to building the capabilities needed for future success. There are various instruments available to policymakers seeking to support innovation, including R&D tax credits, grants for R&D expenditures, support to university-based research, etc. The literature (Bloom, Van Reenen and Williams, 2019[70]) so far has highlighted that these instruments, particularly tax credits and to a less clear extent R&D subsidies (Criscuolo et al., 2022[1]), are effective at increasing R&D spending and generating innovations (Appelt et al., 2016[71]; Dechezleprêtre et al., 2023[4]; OECD, 2023[72]; 2023[73]). Grounding the design of these policies in an industrial ecosystem approach can be beneficial; for example, the patent analysis discussed in this chapter identifies sectors and technologies upon which core parts of an ecosystem are dependent, and where support to investment in R&D might be necessary. For example, R&D support to automotive firms might be less effective if crucial innovations are happening outside the core portion of the ecosystem, in sectors like computers and electronics. Policymakers can rebalance R&D incentives to also target specific upstream sectors and technologies (in this example, digital ones) and exploit complementary instruments to facilitate the market-entry of start-ups active in these technologies. Figure 6.5 provided strong evidence on this point, as it clearly showed that a considerable portion of innovations related to EII technologies does not originate from the core components of the ecosystem. Another area where an ecosystem approach can benefit policymakers is in addressing supply chain bottlenecks: the identification of hard-to-substitute raw materials (as discussed above for the renewable energy ecosystem) is a precondition to design specific R&D incentives targeting substitute materials or recycling techniques.

Notably, strong complementarities exist across policies. For example, providing tax credits to R&D may not lead to innovative outcomes when required skills are lacking, as their absence tends to hinder the adoption of innovative technologies (Calvino, Criscuolo and Verlhac, 2020[74]). On the contrary, it may lead to inflationary pressures on R&D salaries (Criscuolo et al., 2022[1]) with negative consequences on other business functions. However, support to human capital is one of the most challenging areas for policymakers, as it can take years to bear fruit and typically relies on the collaboration between academia, technical and vocational education and training providers, and private firms. Adopting an industrial ecosystem approach can be beneficial for policymakers also in this context: in this respect, Figure 6.7 showed how job vacancies related to renewable energy technologies originate from a variety of disparate sectors, including but not limited to manufacturing and electricity, but also professional and scientific activities and construction, finance and insurance. A solely sectoral approach would, therefore, miss a critical mass of jobs related to the renewable energy ecosystem. Furthermore, it can highlight occupations that are demanded in both the core and non-core sectors of an ecosystem, rather than just in specific segments. This is helpful in mitigating potential "poaching" concerns which may arise if a policy lowers labour costs in one segment, leading to shortages elsewhere in the ecosystem, resulting in no net benefit overall. For example, in the EII ecosystem, digital skills are currently highly required across industries: investing in training for these skills specifically could lead to double dividends. To avoid talent bottlenecks, industrial ecosystem strategies should incorporate upskilling, reskilling and talent retention initiatives, ensuring that human capital development keeps pace with technological and sustainability ambitions.

Other areas for complementarity regard venture funding and competition policies. The previous sections have highlighted that start-ups are crucial economic engines, generating and diffusing innovations (especially for emerging technologies), with a positive effect on employment and on productivity via reallocation effects (Decker et al., 2017[58]; Calvino, Criscuolo and Menon, 2018[75]). Start-ups face tougher conditions than more established firms due to their lack of resources and financial track-record in the market. Obtaining access to venture funding is then crucial for them (Hall and Lerner, 2010[76]). However, scholarly reviews of public interventions in this area have found mixed results, with some studies pointing to crowding out issues and underperformance of government-backed venture capital versus private ones (Howell, 2024[77]), other studies finding comparable performance between the two (Berger, Dechezleprêtre and Fadic, 2024[78]) and yet others finding that a mix of private and government venture capital outperforms other modalities (Brander, Du and Hellmann, 2015[79]).

Similarly, competition policy has an important role to play in ensuring that established incumbents do not stifle innovation via aggressive acquisition strategies (Cunningham, Ederer and Ma, 2018[80]), especially in an economic context characterised by declining business dynamism (Calvino, Criscuolo and Verlhac, 2020[74]) in light of new evidence regarding the declining innovation rates of acquired companies (Berger et al., 2025[81]). Notably, competition is commonly regarded as having an inverted-U shape effect on innovation (Aghion et al., 2005[82]): positive up to a certain threshold (Levine et al., 2020[83]), negative afterwards (Kang, 2019[84]), as excessive competition may decrease firms' resources available for investment. Grasping the role that various actors play in an ecosystem can help highlight where interventions might be needed: for example, the decreasing contribution to innovation by small and medium-sized enterprises in the renewable energy ecosystem might be linked to the increasing M&A activity experienced in this sector.

Overall, the complexity and interdependencies that exist among these policies – and potentially many others in areas such as public procurement, programmes for entrepreneurship, labour market policies, etc. – point to the need for co-ordination among policymakers in charge of different policies, which, even when centrally designed, are often administered and monitored by different ministries and agencies (OECD, 2024[42]) – as well as ecosystem stakeholders, grounded in robust empirical evidence.

Conclusions

Industrial ecosystems can be a crucial unit of analysis for policymakers seeking to design industrial policies fostering the growth and resilience of their economies. The three case studies used in this chapter (automotive, renewable energy and energy-intensive industries) have described concrete approaches to delineating industrial ecosystems (both their boundaries and stakeholders) and highlighted some of the key challenges affecting them.

Key messages include: first, sectoral definitions are relevant, but increasing the granularity of the analysis allows accounting for key components (e.g. upstream suppliers and downstream customers) and relationships (e.g. innovation linkages) that would be omitted in a standard sectoral approach. Second, ecosystems include a variety of heterogenous actors: their mapping, and the identification of the specific roles they play, and their respective importance, rests upon the use of a wide array of data (e.g. value added, trade, patent, online vacancies, etc.). Third, many of the challenges described, be it in the trade, human capital or innovation, originate in a well-defined part of the ecosystem but tend to spillover to other areas. Fourth, acting upon one challenge can be beneficial for others, too. For example, innovations generated upstream in the value chain will cascade to downstream sectors, with productivity gains going beyond sectoral boundaries, and positively affecting production and trade as well.

The ecosystem approach has room for improvement. For example, many analyses still rely on value-added data that are currently only available at the 2-digit sectorial level. Analysing ecosystems based on more granular data could provide deeper insights for policymaking. Second, the network of customers and suppliers could be extended to more distant relationships to identify hidden bottlenecks and strengthen an ecosystem's resilience. Third, the analyses presented in this chapter focus on firms, industrial sectors and countries. However, the literature in the ecosystem field has highlighted the role of geographically bounded clusters and districts, which is not accounted for in this work.

A promising area for further ecosystem research is the exploitation of firm-level value-added tax data (Criscuolo et al., 2024[34]) to describe firm-to-firm interactions. More granular ecosystems can also be analysed. One example is the ongoing work on the semiconductor ecosystem, based on a taxonomy distinguishing different types of chips and production facilities (OECD, 2024[52]). As these approaches become more widespread, and the level of precision and granularity increases, policymakers will be increasingly able to make targeted interventions based on clear-cut evidence and capable of not only targeting specific pain-points, but also confidently addressing the interdependency existing within ecosystems.

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Notes

[1] TiVA data describe the value added generated by each sector-country in the production of goods and services that are consumed worldwide.

[2] More specifically, patents protecting technologies related to EIIs are identified through the concordance between technology classes assigned to patent documents, specifically the Cooperative Patent Classification (CPC) codes, and industries, as developed by Goldschlag, Lybbert and Zolas (2020[41]). The technological scope includes also patents related to the decarbonisation of industries, identified using CPC codes. See Annex B of Dechezleprêtre et al. (2025[32]) for further details on the coverage and methodologies used to build patent-based indicators.

[3] The insights presented here are based on data from Lightcast, an employment analytics and labour market information firm that collects data from firms' websites and online job boards.

[4] Data from QuIS include 11 countries as to the 2022 vintage: Canada, Denmark, France, Germany, Ireland, Israel, Italy, the Netherlands, Slovenia, Sweden and the United Kingdom.

7 Tools for agility: Actionable strategic intelligence and policy experimentation

Rapid technological advancements, growing global uncertainties, increasing competition, and the need to address global and societal challenges are increasing demands for science, technology and innovation policy. To respond to these challenges, policy needs to be agile: proactive, timely and responsive. Strategic intelligence and policy experimentation enable policymakers to “tool up” for agility. Strategic intelligence can provide timely insights through anticipatory and real-time evidence production, while policy experimentation enables testing new ideas and critically evaluating policy impacts. Together these approaches support evidence based policymaking.

Key messages

- In times of turbulence, or in situations of great strategic need, science, technology and innovation (STI) policymaking must be rapid in highly uncertain situations. The COVID-19 pandemic revealed challenges in the rapid response to create STI solutions. STI solutions may also be entangled in regulatory reconfigurations, particularly for new and emerging technologies, where the pace of regulatory change may slow down the emergence, development and deployment of novel technology solutions. In such situations, agile policies are needed that are informed (by appropriate strategic intelligence), that can be adaptive (through integrating learning by doing) and innovative (through experimentation of new policy approaches).
- Agility in STI policymaking means anticipating and quickly adapting to new trends, challenges and circumstances by focusing efforts where they are needed the most. Agile policies are proactive, timely and responsive, allowing decision-making bodies to swiftly implement policies, adjust to unexpected situations, halt ineffective ones and redefine strategies as necessary.
- Strategic intelligence and policy experimentation constitute core reinforcing priorities to boost policy agility. Despite their recognised potential, there are several barriers to implementing agile, adaptive and responsive STI policies, including institutional rigidity and risk aversion within public administrations, insufficient capacities and skills for their implementation, and challenges in scaling successful initiatives.
- Fostering the use of strategic intelligence and policy experimentation among policymakers requires institutionalising experimentation by embedding it into national programmes and frameworks; increasing flexibility and adaptability within bureaucratic structures (through better co-ordination mechanisms and simplified processes); and investing in training programmes for public sector officials for them to embrace experimental approaches.
- What happens after experimentation ultimately determines its policy impact. Ensuring there is a clear pathway for scaling up interventions that prove successful or phasing down those that fail is key. Those decisions, in turn, rely on rigorous evaluation processes as the basis on which to learn about the performance of a policy initiative.
- Ensuring that structures put in place for policy experimentation remain reversible and adap JenErgieRea is key to facilitating scaling up or discontinuing initiatives without major disruption. Another key element is that responses to the outcomes of evaluations are not held back by vested interests.

Introduction

Growing global uncertainties, increasing competition and the urgent need to address societal challenges are increasing demands on STI policies. Traditional policy approaches have proven inadequate to deal with the much larger transformation challenges. To remain effective, policies must be agile: adaptive, forward-looking, and capable of responding to complex and evolving challenges.

Strategic intelligence, in the public and private sectors, and policy experimentation constitute core reinforcing priorities to boost agility. Strategic intelligence – usable knowledge that helps policymakers understand the impacts of STI and anticipate future developments (Robinson et al., 2021[1]) – enables governments to harness the benefits of emerging technologies while mitigating risks. It also serves as a foresight tool, helping policymakers prepare for and respond to new challenges (Robinson, Winickoff and Kreiling, 2023[2]).

Policy experimentation in its various forms is another component of agility for STI policy and refers to the deliberate implementation of small-scale and/or temporary policy interventions designed to test the outcomes of new approaches. This chapter focuses on building small-scale environments for policy experimentation in the form of innovation policy labs and regulatory sandboxes; and using assessment methods for policy experimentation, as exemplified by randomised control trials (RCTs). Other dimensions of policy experimentation, notably in relation to stakeholder engagement, are left out in view of the space constraints and complexity of also covering those topics as part of the analysis.

This chapter examines how strategic intelligence and policy experimentation can enhance agile and informed decision making in a rapidly changing world. It includes country examples and highlights key challenges and policy lessons learnt regarding how to overcome those challenges and introduce agility.

This chapter is structured as follows. It begins with explaining why there is a current need for agility and introduces the concepts of strategic intelligence and policy experimentation. It then outlines key requirements for their implementation. The chapter then moves to a discussion of strategic intelligence and policy experimentation in practice, providing specific country examples. The chapter then examines key challenges limiting broader adoption of agility and policy responses. The final section concludes and sets the agenda ahead.

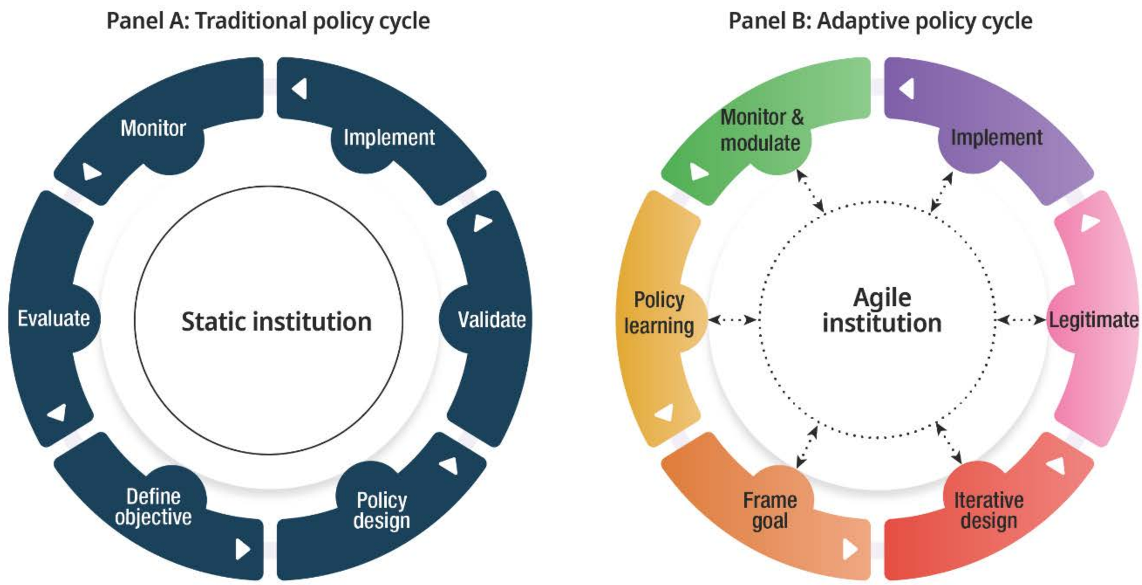
Why agile policymaking is needed

What is policy agility?

Agility entails proactive, timely and responsive policymaking, being able to anticipate and adapt fast to new circumstances, trends and challenges by focusing efforts where they are needed the most (OECD, 2024[3]; Arnold et al., 2023[4]). It ensures decision-making bodies remain flexible, able to adjust to unexpected situations, halt ineffective policies and redefine strategies as needed. Clear responsibilities and feedback mechanisms are essential to support this process (Weber et al., 2021[5]).

Agility marks the change from policymaking based on traditional "tried and tested" routines along the policy cycle to more adaptive cycles (Cairney, 2012[6]; Haddad et al., 2022[7]). Unlike traditional policy cycles that place an emphaisis on incremental policy learning over long time frames in relatively static (slowly evolving) institutions, agile processes prioritise real-time policy learning, allowing for faster, more responsive decision making (Figure 7.1). Agile policies work best when the policymaking institutions themselves can learn from policy experimentation and can adapt and become agile institutions (as opposed to the rather static institutions prevalent in traditional policymaking). Each approach has its strengths. Traditional policy cycles follow tried and tested routines, are relatively predictable, and can draw on cumulative learnings – this is particularly useful in highly predictable situations. Traditional policy cycles allow other stakeholders to adapt their plans, which is particularly useful for long-term strategy making. Agile policy cycles are suitable during times of turbulence and low predictability; this allows for learning while doing and is particularly useful in times of crises or of new opportunity but high uncertainty.

Figure 7.1. Incremental and dynamic policy cycles for stable and agile institutions



In agile policy processes, the policy cycle is highly iterative due to factors like uncertainty and evolving technologies. The initial phase recognises the challenge of defining policy goals in this dynamic environment. Next, policy approaches co-evolve with broad objectives through iterative design, leading to potential strategies for testing. This phase also considers alternative policy pathways for future use while building both internal and external legitimacy through stakeholder engagement. Implementation involves tailoring and testing policies via tools like regulatory sandboxes, with continuous monitoring that integrates "learning-by-doing" for real-time adaptation.

What is driving demand for STI policy agility?

OECD countries widely recognise the need for agile STI policies (OECD, 2024[8]) due to:

- **The pace of transformative technological change:** Many technologies are advancing at an unprecedented pace. Artificial intelligence (AI) tools like ChatGPT, for example, gained millions of users within weeks after its launch, demonstrating how quickly innovations can change the way people work, communicate and access information. Such technologies are transforming industries by automating tasks, enhancing customer service and optimising decision-making processes. The convergence of synthetic biology with AI and automation is likely to accelerate transformative innovations in a range of sectors (see Chapter 5). These technologies require policies that can keep pace with the changes to support further business innovations and ensure that adaptive regulations protect consumers from risks such as misinformation, privacy breaches and unfair market practices.
- **The need for preparedness to operate in a context of uncertainty:** The future is marked by uncertainty and vulnerabilities, but also emerging opportunities, requiring policies that can adapt to rapidly changing circumstances. Global crises, like the COVID-19 pandemic, have revealed gaps in resilience, showing how existing systems can be overwhelmed by unexpected shocks. These events highlight the importance of policies that can respond quickly to safeguard public health and

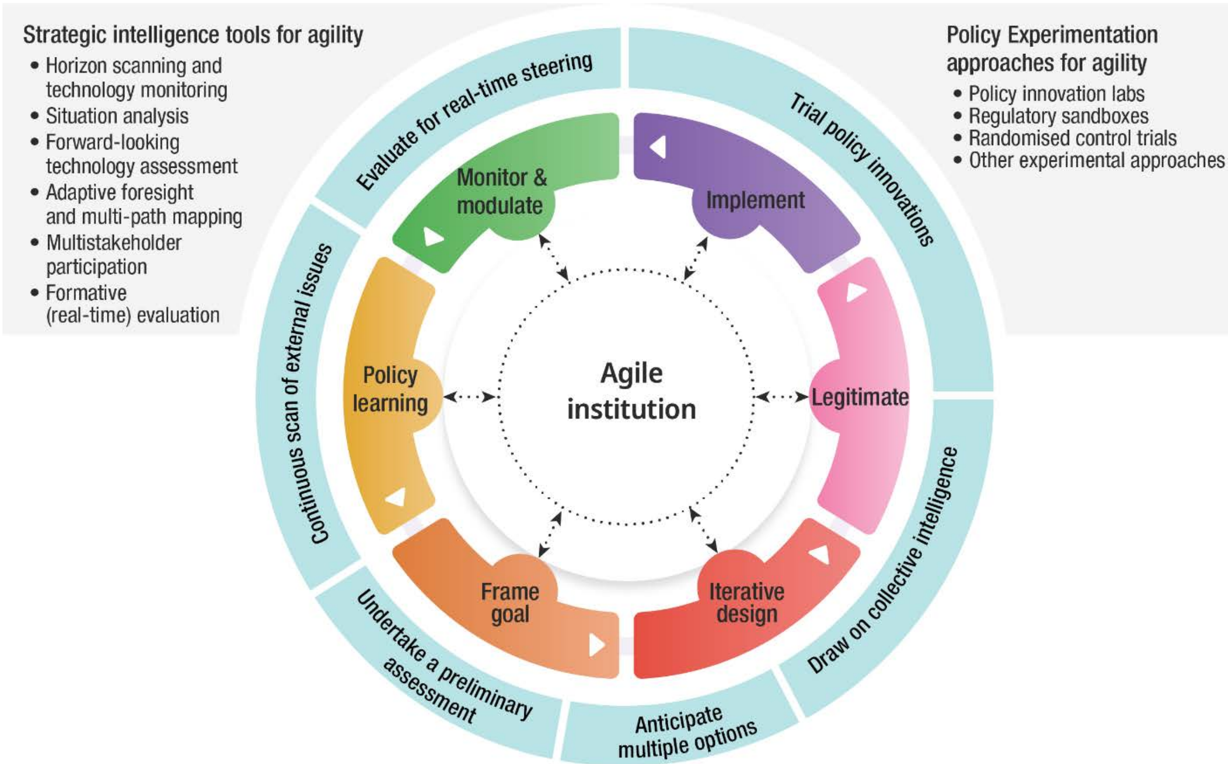
ensure economic stability while managing other crises. Similarly, geopolitical tensions underscore the need for policies that can address the broader consequences of conflicts, like disrupted supply chains and migration flows. Without agile policy responses, societies risk greater instability, economic disruption and long-term social challenges. Policy agility is also essential to seize new opportunities for more sustainable and inclusive development.

- **The need to strengthen national competitiveness in key strategic areas:** In an era of intensified technology-based international competition, the concepts of "technology sovereignty" and "strategic autonomy" – which refer to a polity's capacity to act strategically and autonomously in an era of intensifying global technology-based competition – have gained ground in national policymaking (see Chapter 2). Traditional policy approaches may struggle to keep pace with technological change and the opportunities and challenges it brings for markets and society. Agile policymaking enables governments to be more responsive and to target support where it is needed the most.
- **The need to address global and societal challenges:** Addressing global challenges such as those related to food security, extreme weather events, and poverty and resource depletion requires significant innovation. The International Energy Agency states that most CO_2 emissions reductions through 2030 will come from technologies already available. However, by 2050, 35% of these reductions require technologies that have not yet been developed. To meet these goals, major innovation efforts are needed this decade to bring these technologies to market (IEA, 2023[9]). To drive this change, policies must be agile and experimental, allowing public resources to be used more effectively in supporting green technologies, such as renewable energy, carbon capture and electric vehicle infrastructure. Agile policies can break down barriers to scaling these technologies, helping them reach broader adoption more quickly.

Agile policy requirements: Six support actions

The need for agile policies requires actions that can be served through tools and approaches that support and inform agile policy processes. Agility can be promoted in different ways. Figure 7.2 presents the agile policy cycle encircled by six "support actions" that are particularly helpful for catalysing and informing agile policies.

Figure 7.2. Six support actions to catalyse and inform agile policymaking



The six support actions for agile policy are:

1. **Undertake a preliminary assessment:** For situations of high complexity, uncertainty or urgency, it is not always evident whether policy action is necessary or how it should be targeted. Thus, a preliminary diagnosis of the situation is required. For example, the OECD Framework for Anticipatory Governance of Emerging Technologies (OECD, 2024[10]) argues that an appropriate preliminary diagnosis process can, with limited resources, help scope the potential policy issue and focus further intervention. This provides an opportunity for sense-making, learning and targeted action (including the decision not to take any policy action).
2. **Anticipate multiple options:** Rapid and agile policies can benefit from identifying multiple policy pathways that can potentially be followed. Tools like adaptive foresight can help identify multiple potential modes of action while also providing some insights to their potential impact. While an eventual choice will be made to pursue a particular policy pathway, the alternative potential options can be used as a benchmark for comparison during the agile policy cycle.
3. **Draw on collective intelligence**: To support a robust design of policies and facilitate legitimacy of the novel policy measure with those that the policy measure will impact, it is advantageous to engage with, and harvest intelligence from, a wide range of stakeholders. Incorporating collective intelligence into research and innovation policymaking ensures that policies are robust and aligned with societal and environmental needs. Engaging a wide array of stakeholders, including researchers, industry leaders and the public, provides diverse perspectives and enhances the design and legitimacy of a new policy measure. Tools that can assist in this support action include, but are not exclusive to, participatory technology assessment and multistakeholder dialogues.
4. **Trial policy innovations:** Agile policy is characterised by the need to develop and apply policies to rapidly changing contexts, often requiring new policy approaches. This can be catalysed by

supporting the testing and assessment of new approaches during the policy cycle. Policy experimentation in its many varieties can provide support for this (see Figure 7.2).

5. **Evaluate for real-time steering**: While ex post evaluation is useful for stable and predictable contexts, where policy learning can take time, when circumstances are changing, such learnings may come too late. There is thus a need to shift from evaluation for ex post assessment of a policy's success towards evaluation as a means for real-time learning. Here, formative evaluation tools and approaches, which place an emphasis on learning and adapting policies during their implementation, are a key support action.
6. **Continuous scan of external issues:** This entails staying abreast of the changing context outside of the organisation, be it indications of evolving policy drivers or weak signals of rapidly emerging technologies that may become a concern. Such context scanning is useful to trigger new agile policy cycles and/or to place current policy cycles in the changing and evolving context.

While the support actions are more suited to certain stages in the policy cycle than others, they are not exclusive to a particular stage. The six support actions act as requirements for evidence that can be provided by various strategic intelligence tools and approaches and a variety of forms of policy experimentation. They are presented in Table 7.1 and are unpacked in detail later in this chapter.

Table 7.1. Matching strategic intelligence and policy experimentation to agile support actions

Agile support action	Strategic intelligence	Policy experimentation
Continuous scan of external issues	Horizon scanning and technology monitoring	
Undertaking a preliminary assessment	Situation analysis Forward-looking technology assessment	
Anticipating multiple options	Adaptive foresight	
Drawing on collective intelligence	Multistakeholder participation (including participatory technology assessment)	Policy innovation labs Regulatory sandboxes Randomised control trials
Trialling policy innovations		Policy innovation labs Regulatory sandboxes Randomised control trials
Evaluating for real-time steering	Formative (real-time) evaluation	Regulatory sandboxes

Strategic intelligence for agile and adaptive policy

Strategic intelligence will have a key role to play in building policies for new science and technologies whose importance is clear but the precise implications and pathways are still uncertain. For example, emerging quantum technologies (such as quantum computers, sensors and communications), promise to transform multiple industries, bolster advances in traditional computation and help tackle complex societal challenges through the harnessing of quantum mechanics.

Strategic intelligence refers to knowledge and evidence on current and future developments of new STI and their potential impacts on the economy and society. A broad range of methods can provide strategic intelligence, such as statistical benchmarking, forecasting and modelling, foresight, technology assessment, systems and pathway mapping, and technology monitoring and evaluation. Strategic intelligence providers include agencies carrying out technology foresight and assessment, national academies of science and technology, statistical offices and agencies, ad hoc national commissions, regulatory bodies, and standard-setting bodies.

In the context of STI, strategic intelligence relates to usable knowledge that helps policymakers understand the impacts of STI and anticipate future developments (Robinson et al., 2021[1]). Particularly for rapidly emerging and evolving technology areas, where few systematic data are available to provide trend analysis or direct evidence, strategic intelligence tools and approaches are mobilised to fill the gap.

Strategic foresight and technology assessment have a long history (Robinson and Doherty, 2025[11]), but are now challenged to evolve to suit current STI policy needs, with new approaches to meet these new demands – many of which relate to the need for speed and agility (Robinson, Winickoff and Kreiling, 2023[2]).

Detecting early signals of technological and socio-economic change: Continuous horizon scanning

Horizon scanning functions as a systematic exploratory method designed to detect early indicators of potentially significant technological and socio-economic developments. Horizon scanning identifies "weak signals", which are early-stage trends or emerging issues that may evolve into transformative and disruptive changes. These signals undergo structured analysis to assess their relevance, trajectory and potential implications for policy and decision making. This process enables policymakers to anticipate emerging challenges and opportunities, particularly in rapidly evolving domains such as synthetic biology, metamaterials, or quantum science and technology.

Continuous or regular horizon scanning provides decision makers with insights into the drivers of change, supporting the formulation of proactive policies that align with evolving technological and societal landscapes (Box 7.1). The process primarily relies on desk-based research, drawing upon existing literature, reports and data sets. To enhance the robustness of findings, horizon scanning is supplemented with expert consultations, participatory workshops and structured foresight exercises to refine, prioritise and contextualise identified signals. Consequently, the effectiveness of horizon scanning is contingent upon the diversity of the consulted experts, the breadth and reliability of data sources, and the methodological rigour applied in synthesising insights.

Unlike conventional trend analysis, which are based on past (including even recent past) data, which extrapolates trends (from what is known), horizon scanning explores areas of potential importance that have not yet fully materialised (exploring the unknown). Horizon scanning, therefore, deals inherently with high levels of uncertainty. Many weak signals may fail to materialise, evolve in unexpected directions, or challenge prevailing assumptions within a given technological or policy domain. As such, horizon scanning serves as an adaptive intelligence tool, equipping policymakers with early warning capabilities to navigate complexity and uncertainty in the innovation landscape. Advancements in automated data analytics have introduced new methodologies in horizon scanning, including web scraping, large language models and machine learning-driven data mining to detect emerging trends at an earlier stage. These computational approaches enhance the ability to capture weak signals in real time, complementing traditional expert-driven scanning processes. This automation in gathering and analysing disparate data sources is a new turn in strategic intelligence – more complex and heterogeneous data can be mobilised in near-real time – opening the possibility for more complex, more agile and more timely horizon scanning.

Box 7.1. Examples of horizon scanning for agile policy

In Germany, the Federal Ministry of Research, Technology and Space developed two data-driven analysis tools for internal use in the federal government. The tools were developed as part of its foresight process. The *Technology Monitoring Dashboard* provides an overview of the international competitive landscape, displaying key innovation indicators (publications, patents, start-ups, venture capital funding) for 16 technology areas and over 90 individual technologies. The second tool, the

Emerging Technologies Radar, which is still under development, uses an experimental approach to identify and evaluate emerging technologies using several artificial intelligence methods.

Another illustrative example is how the UK Government Office of Science conducts continuous technology horizon scanning on a weekly basis to systematically identify emerging trends and weak signals within the science and technology landscape. This process begins by gathering inputs, primarily through desk-based research, which incorporates diverse sources such as high-impact scientific publications (for example, general science journals like *Science* and *Nature*), third-sector reports, white papers and select social media channels. Where feasible, additional insights are incorporated through participation in specialist conferences, expert consultations and industry events to ensure a comprehensive and dynamic assessment of technological developments. Each week, the collected intelligence is synthesised to identify patterns, emerging themes and novel advancements. A shortlisting process is then undertaken to determine which signals hold the most potential impact and policy relevance. These shortlisted items are subsequently reviewed within a broader analytical group, where key findings may be escalated for inclusion in an early warning brief to inform senior policymakers and stakeholders. As part of this, so-called “rapid technology assessments” are developed to provide the basic information on the emerging technology of interest stemming from the horizon scanning activity.

The example is interesting, and not only for continuous and regular scanning. The UK Government Office for Science is developing a structured list of weak signals. The aim in the future is to prioritise this list based on the likelihood of the signal to “surprise” or be disruptive in the context of the UK government. Early identification of emerging technologies that may “surprise” is essential for enabling more proactive assessments and policymaking. The UK Government Office for Science is currently working on developing metrics based on understanding of technology progression, to determine a weak signal’s likelihood for disruption. These metrics are to be reviewed regularly to ensure that prioritisation of signals remains responsive to dynamic shifts in the technological landscape.

In Japan, the National Institute of Science and Technology Policy (NISTEP) has regularly conducted horizon scanning to feed into broader foresight processes that inform policy, beginning with the 11th NISTEP Science and Technology Foresight Survey (NISTEP, 2019[12]). This survey incorporated horizon scanning as the first phase of a foresight study to identify emerging trends; potential future developments; and early signs of change in the relationship between society, science and technology. To capture the societal data, the activity extracted trends from existing materials (including press releases and policy documents) and incorporated insights from regional workshops that explored desired futures from across different regions of Japan. This was complemented by gathering expert opinions through international workshops. To capture scientific and technological insights, data was extracted from materials such as meeting minutes of the National Diet, policy reports and text mining of databases (e.g. the *Database of Grants-in-Aid for Scientific Research*). This was also complemented by gathering science and technology expert opinions and scanning research and development-related press releases. The outputs of these activities have been referenced in the context of science, technology and innovation policy formulation, including those for the Sixth Science, Technology and Innovation Basic Plan. More recent examples of horizon scanning include online questionnaires on emerging and weak signals with the NISTEP science and technology expert network made up of approximately 1 700 experts.

Getting to grips with the context: Situation analysis

Agile policy approaches are considered worthwhile when circumstances are rapidly changing, there is high uncertainty, or an event or opportunity means that policy action is urgent. Situation analysis, therefore, is an essential step when agile policies are being considered – if circumstances suggest agile policies as a solution, it is highly likely that the "situation" is volatile and requires a preliminary diagnosis.

For controversial or potentially game-changing technologies, situation analysis can take the form of identifying the key issues at play and/or the stakeholders that may be affected by a new technological innovation. For agile policies seeking to harness a new or emerging technology, mapping the key actors in the innovation ecosystem can be beneficial to target further intelligence gathering and help identify policy inroads. For agile policies targeted at driving transformational change at the sector or system level, mapping the key actors and infrastructures in a particular system will help set a baseline for a portfolio of policy interventions. Box 7.2 gives a few examples.

Box 7.2. Examples of situation analysis that can be used for agile policy

In 2021, the European Parliament's Science and Technology Options Assessment Unit conducted an online stakeholder engagement exercise elucidating the societal concerns surrounding a highly topical and controversial issue – genome editing in crops – to support decision making by the members of the European Parliament who were considering whether regulatory change would be necessary for this rapidly emerging and historically controversial technology field. The situation analysis at the beginning of the process aimed to identify the main hopes and concerns as well as the key stakeholders that are, or could be, implicated in the development and deployment of new genomic technologies applied to crops. The Science and Technology Options Assessment Unit uses the STEEPED approach to support this activity – a systematic way of conducting an initial overview of existing and emerging opinions (hopes and fears) concerning the topic that is being explored. STEEPED as an acronym represents an exploration across seven perspectives: societal, technological, economic, environmental, political/legal, ethical and demographic. The STEEPED approach was also used to identify representatives of the various stakeholder groups that would, or could be, concerned by the new genomic technologies for crops and to ensure a broad spectrum of opinions. In this way, situation analysis combined identifying the hopes and concerns around a technology field and the potentially concerned stakeholder groups (Robinson, Winickoff and Kreiling, 2023[2]).

Situation analysis can also be at the level of understanding the innovation capacity of a region, country or sector. In recognition of the strategic importance for its manufacturing sector of supporting innovation in advanced materials, the province of Quebec, Canada, created PRIMA Québec to identify and bolster the province's competitiveness. It undertook an initial mapping of the key actors in the industrial advanced materials ecosystem, revealing a critical mass of ~340 firms in 2018 and 570 in 2024 that mobilise advanced materials research and development to create products and services. Intended to be a baseline study with further iterations, the industrial ecosystem mapping was an essential tool for identifying and improving the sector's market position and facilitating the implementation of public policies to better support advanced materials in the province. Repeating this situation analysis through regular mapping activities allowed PRIMA Québec to better target science, technology and innovation policies to support the growing ecosystem and leverage this fast-moving and strategic area of critical technologies (PRIMA Québec, 2024[13]).

Sources: Robinson, Winickoff and Kreiling (2023[2]); PRIMA Québec (2024[13]).

An important approach to situation analysis includes systems mapping with associated indicators and statistics. Changes in the fundamental properties of a system and the way it behaves have important implications for analysis and the estimation or forecasting of future outcomes. Simple extrapolation from past experience will fail to foresee the way that a system may behave after it has been transformed or once the process of change has begun. Many of these aspects are not well-served by existing metrics, and the current knowledge and evidence base of indicators and statistics that supports policy decisions can further evolve to meet the complexity and uncertainty of STI-enabled transformative change.

Understanding the implications of emerging technologies: Forward-looking technology assessment

Technology assessment (TA) plays a key role in providing strategic intelligence on new and emerging technologies. As an evidence-based and interactive process, TA systematically examines the societal, economic, environmental and legal dimensions of technological innovation. It serves to inform public debate, shape research and development agendas, and support the formulation of policies that enable and regulate technological progress.

Box 7.3. Examples of forward-looking technology assessment

With regards to technology assessment (TA) for the legislative branch, in the United States, the Science, Technology Assessment, and Analytics group within the Government Accountability Office exemplifies expert-driven TA. It delivers high-quality analyses to Congress, identifying technical challenges and outlining policy options with associated risks, opportunities and implementation considerations. The rapid technology assessments offer concise and timely evaluations of specific technologies for agile policymaking.

For the executive branch, another example from the United States is the Novel and Exceptional Technology and Research Advisory Committee at the National Institutes of Health (NIH), which was set up to provide recommendations directly to the NIH Director and facilitates public dialogue on the ethical, legal and social implications of novel biotechnologies. For example, one of the committee's past activities was setting up the Gene Drives in Biomedical Research Working Group, which considered whether existing biosafety guidance is adequate for contained laboratory research using gene drive technology and conditions (if any) under which the NIH could consider supporting field release of gene drive-modified organisms.

The OECD is developing an experimental approach referred to as forward-looking technology assessment (FTA). While most TAs look at an existing technology area and explore the potential societal, economic and environmental impacts, FTAs also look forward at future developments in the technology area itself. In this way, the FTA can get ahead of technology developments and support agile policies, including anticipatory governance of emerging technologies. Two FTA activities are currently being conducted. The first looks forward at the future convergence of synthetic biology, artificial intelligence and robotics to explore a range of policy issues such as skills and workforce, research security, the clash of governance cultures, etc. Backcasting from this, forward-looking intelligence can aid in making a preliminary diagnosis of what policy actions should be addressed in the near term and which do not require immediate action. A second FTA focuses on the future embedding of quantum technologies in a variety of sectors, such as health and the space sector. This activity assesses the innovation ecosystem factors that could catalyse and nurture the translation of quantum technologies into various sectors and also anticipates the potential impacts of the integration of quantum into a variety of sectors.

Sources: Robinson and Doherty (2025[11]).

A core function of TA is to enhance understanding of the current state and potential implications of emerging technologies. This is particularly vital in the context of complex and uncertain technological developments such as synthetic biology, neurotechnologies, and quantum science and technology. TA contributes by structuring fragmented or ambiguous information and transforming it into actionable insights to guide policy decisions. Institutionalised TA efforts provide targeted analyses to legislative and executive bodies (Examples are provided in Box 7.3).

Exploring the future with alternative scenarios: Adaptive foresight

Strategic foresight encompasses a suite of methodologies designed to enable policymakers to systematically explore plausible future developments, particularly under conditions of uncertainty and complexity. Rather than aiming to predict a singular or most likely future development, foresight processes map a range of alternative futures and identify the opportunities, risks and interdependencies that could shape policy effectiveness across diverse contexts. This approach helps expand the scope of policy deliberation by challenging conventional assumptions and surfacing latent connections across policy domains.

In the context of technology policy, strategic foresight plays a critical role in assessing how emerging technologies may interact with evolving societal, economic and institutional environments. Typically, this is achieved through the construction of scenarios that explore how external drivers – often beyond the control of individual organisations – may influence the conditions into which technologies are introduced. These scenario exercises serve both an analytical and introspective function: they inform strategic choices within current policy remits while also prompting reconsideration of broader systemic assumptions that underpin those choices.

Importantly, strategic foresight supports long-term, holistic thinking and enhances policy systems' capacity to act with agility and coherence. By fostering shared reflection among stakeholders, foresight processes help align technology governance with societal values, reinforce interdepartmental co-ordination, and contribute to the development of robust and resilient policy strategies. Ultimately, the value of strategic foresight lies not in foreseeing the future but in enabling preparedness for a range of plausible futures. In doing so, it strengthens the adaptive capacity of technology policy in a rapidly changing world.

As a tailored tool for agile policymaking, adaptive foresight represents a strategic evolution of forward-looking policy practices, blending elements of foresight, adaptive planning and contemporary innovation theory. It seeks to inform policy decisions under conditions where precise prediction is neither possible nor sufficient. At its core, adaptive foresight is both a method and a mindset that supports strategic intelligence for navigating disruptive change. It is grounded in three pillars: 1) participatory foresight practices; 2) adaptive strategic planning that incorporates real options thinking; and 3) an evolutionary understanding of innovation as complex and co-evolutionary. This approach acknowledges the Collingridge Dilemma: in early innovation stages, there is too little information to steer developments effectively; later, entrenched trajectories are difficult to influence. Rather than defining fixed endpoints, adaptive foresight facilitates sense-making and option-building under shifting contexts. Adaptive foresight thus promotes flexibility, anticipatory learning and iterative policy framing.

The adaptive foresight process typically involves elements of futures analysis (for example, scenario development to explore divergent futures), engagement with experts and stakeholders to ensure relevance and legitimacy, real-time learning loops that enable policy feedback and recalibration, and the integration of strategic options to preserve flexibility in the face of uncertainty (Examples are provided in Box 7.4).

Box 7.4. Examples of adaptive foresight

The European Commission's techno-economic foresight on creative content industries, the European Perspectives on the Information Society project (Abadie, Friedewald and Weber, 2010[14]), is one example of adaptive foresight. This project used an adaptive approach to account for rapid digital transformations in the creative industries. By embedding scenario techniques within a flexible, stage-gated process, the project produced nuanced policy-relevant insights while maintaining the ability to adjust methods and focus based on emergent knowledge.

Another example of adaptive foresight is the "Foresight on Demand" initiative which supported the European Commission's 2nd Strategic Plan for Horizon Europe (2025-2027) through a broad, multi-actor process (European Commission, 2023[15]). It combined context scenario-building, expert workshops and public consultations to explore disruptive areas such as climate engineering, artificial intelligence, global governance and health futures. The results not only informed priority-setting but also identified governance and resilience strategies, underlining the role of foresight in adaptive programming.

Sources: Abadie, Friedewald and Weber (2010[14]); European Commission (2023[15]).

By structuring uncertainty rather than removing it, adaptive foresight enhances strategic agility by enabling decision makers to anticipate and prepare for a range of plausible futures. Adaptive foresight can help frame the policy goal and provide input into the iterative design of the agile policy, which is key for the agycycle.

Integrating multistakeholder insights in policy processes: Participatory methods

Engaging diverse stakeholders in the development of STI policies has become an increasingly recognised practice, fostering more inclusive, anticipatory and socially responsive policy frameworks. Stakeholders – including scientists, engineers, affected communities, investors, companies and citizens – offer unique perspectives that contribute essential (and often missing) knowledge and broaden the framing of policy development and implementation with contextual knowledge. Such a deliberative process strengthens the science-society relationship, enhances public trust and facilitates more effective communication about the emerging policy's objectives (Paunov and Planes-Satorra, 2023[16]). However, engagement efforts that are pre-ordained with predetermined outcomes risk undermining these objectives, reducing trust and legitimacy (OECD, 2024[17]). A range of participatory methods exists to ensure that multistakeholder insights are integrated into policy and governance discussions (Box 7.5). Consensus conferences, citizen assemblies and citizen juries exemplify such participatory TA mechanisms, directly involving diverse societal actors in evaluating and shaping STI policy development and implementation.

Box 7.5. Examples of participatory methods for agile policymaking

Between November 2021 and March 2022, approximately 50 citizens from different backgrounds met at the German Federal Ministry of Education and Research (BMBF; since May 2025: the Federal Ministry of Research, Technology and Space) Citizens' Assembly for Research. The citizens contributed ideas, received advice from experts, and engaged in intensive discussions on how to further strengthen participation in research and research policy. The report of the Citizens' Assembly for Research, with its 25 recommendations for action and 5 overarching guiding principles, was incorporated in the White Paper process for the development of the ministry's Strategy for Participation in Research launched in 2023. In this way, Germany is taking concrete measures to ensure that multi-stakeholder insights are integrated into science, technology and innovation policy discussions.

Another case is the participatory development of Brazilian Artificial Intelligence Strategy (MCTI, 2021[18]). The objective was to crowdsource recommendations and commentaries to create a collective vision for "What AI do we want for Brazil?" and to ensure that the eventual strategy addressed societal needs and concerns. Collective intelligence was mobilised to support the design of the strategy, through stakeholder consultation over iterative drafts. This not only allowed tailoring the policy, it also meant that by the time the strategy was developed, a range of stakeholders were already aware of it and, in a way, co-owned it. This supported the legitimacy of the policy.

Another example was the Citizen and Multi-Actor Consultation on Horizon 2020 project, implemented from 2015 to 2018 under the European Union's Horizon 2020 framework, which focused on integrating public engagement into research and innovation agenda-setting. Co-ordinated by the Danish Board of Technology, the project involved a consortium of 29 partners spanning 30 European countries. The project's methodology drew upon various theoretical frameworks, including Responsible Research and Innovation, Participatory Technology Assessment, and Foresight. The project's primary objective was to enhance the relevance and responsiveness of the European research and innovation agenda by engaging over 1 000 citizens across 30 countries to articulate desirable sustainable futures. A notable outcome was the formulation of 23 research topics, which were presented as suggestions for the Horizon 2020 work programmes. To validate and enrich these proposals, an extensive online consultation engaged over 3 400 participants, encompassing a broad spectrum of societal perspectives.

On a smaller scale, the Canadian Institutes of Health Research convened citizen panels to set priorities in areas like precision medicine and health data sharing (CIHR, 2021[19]). In 2021, one of these panels focused on unpacking issues and opportunities in the use of artificial intelligence (AI) in healthcare diagnostics. The outcomes of the panel informed federal guidelines on AI ethics in health. Although punctual, rather than iterative, this initiative reveals that participatory policy approaches like citizens' panels can be applied to emerging technology policies that are informed by societal hopes and concerns (and thus are responsive) and include a wide range of stakeholders to build legitimacy and trust in a policy that is related to a potentially controversial area.

Sources: MCTI (2021[18]); CIHR (2021[19]).

These methods are particularly valuable for controversial and ethically complex technologies, as they facilitate multi-perspective dialogue, stimulate public and political debate, and contribute to more socially attuned technology governance. Moreover, participatory TA plays a convening role, fostering mutual understanding among stakeholder groups and enhancing public confidence in policy decisions through inclusive engagement.

Continuous feedback and learning: Formative (real-time) evaluation

Formative real-time evaluation has emerged as a distinct approach that diverges from traditional result-oriented evaluation methodologies by prioritising learning and adaptive capacity in the context of STI policies. Unlike conventional results-oriented evaluation frameworks, which primarily focus on accountability, performance measurement and adherence to predefined objectives, reflexive monitoring and evaluation facilitates critical reflection on existing assumptions (based on learning during the implementation of a policy), changing institutional positions (the overall mission of a policy organisation may have changed) and evolving external contextual factors. By fostering a continuous process of feedback, dialogue and critical inquiry, reflexive monitoring and evaluation enables policymakers and practitioners to identify, question and potentially reconfigure entrenched norms, governance models and institutional settings that may hinder agile policies for uncertain and complex policy areas such as rapidly emerging technologies or transformative innovation policies.

This reflexive approach acknowledges the dynamic and uncertain nature of innovation systems, recognising that initially defined goals may need to be adapted in response to emergent challenges and opportunities. As such, it serves as a mechanism for institutional learning in the policy-formulating organisation, ensuring that evaluation is not merely a retrospective exercise in compliance and impact assessment but a proactive tool for shaping adaptive and agile policy processes (Examples are provided in Box 7.6).

Box 7.6. Example of formative evaluation for agile mission-oriented research policy

In 2019, the French government launched the programme Cultiver et Protéger Autrement (Growing and Protecting Crops Differently), a priority research programme aimed at accelerating the transition toward zero-pesticide agriculture. Initiated by the Ministry of Higher Education, Research and Innovation and the General Secretariat for Investment, this initiative embodies a mission-oriented research programme. Recognising the long lead times required for research to influence practice (typically 10-20 years), the programme strategically directs fundamental research toward enabling pesticide-free agricultural systems by 2030-2040.

The funding programme supported ten transdisciplinary, trans-sectoral and multi-actor research projects, each funded with approximately EUR 2 million, with the aim of producing radical, potentially breakthrough innovations. These projects operate within controlled experimental environments to mitigate risk and inform broader application. However, the dual nature of the research – both open-ended and mission-driven – necessitates navigating high levels of uncertainty regarding research outcomes and their practical impact.

To manage this complexity, the programme embedded a governance structure centred on strategic intelligence, designed to support the orientation, programming and execution of the ten mission-oriented research projects. This structure enables adaptive steering through real-time learning and co-ordination. Specifically, four core functions guided this process: 1) monitoring and learning from the project activities; 2) anticipating contextual developments; 3) assessing the performance of ongoing experiments; and 4) fostering synergies within the project portfolio and with external programmes (elsewhere in France and in Europe).

A central mechanism for strategic steering was the use of impact pathways, or projections of how the project's research activities link to the broader mission goal. Each of the ten projects, as well as the funding programme as a whole, was tasked with constructing and iteratively refining these impact pathways. Initially, ex ante impact pathways provided the foundation for back-casting exercises to align research design with the envisioned transformation (allowing a further articulation of the mission goal). Subsequently, real-time monitoring transformed these pathways into "evolving benchmarks" for assessing progress, facilitating timely adjustments.

These impact pathways were co-developed through participatory workshops involving diverse stakeholders, ensuring the mobilisation of distributed intelligence and the integration of multiple perspectives. Crucially, the nested architecture of ten project impact pathways, the funding programme-level pathways and the overall policy aim enabled the programme manager to monitor progress, identify and exploit synergies, co-ordinate with complementary initiatives, and engage with key stakeholders to maximise collective impact.

Sources: https://www.cultiver-proteger-autrement.fr/eng.

Formative evaluation plays a crucial role in governance experimentation, supporting the real-time adaptation of policy instruments and intervention strategies. Through "reflexive monitoring", policymakers can assess the effectiveness of different governance instrument mixes and make necessary adjustments in near real time, ensuring greater responsiveness to technological advancements and market dynamics. This capability is particularly valuable in mission-oriented innovation policies, where policy agility and iterative learning are essential for achieving long-term strategic objectives.

Policy experimentation in practice

Policy experimentation involves the deliberate implementation of small-scale and/or temporary policy interventions designed to test the outcomes of new approaches (OECD, 2024[20]). The goal is to assess whether these interventions should be scaled up if successful or phased out if they do not achieve the desired results. Experimentation is essential for developing agile STI policies because it enables policymakers to test and refine approaches in real time, respond to unforeseen challenges, adapt to evolving conditions, and take data-driven decisions that are aligned with the needs of society and the economy.

This section discusses the following two types of policy experimentation and focuses on specific examples therein to be able to cover more ground:

1. **Environments for policy experimentation**, where new ideas and technology solutions can be tested at a small scale, based on which they can be later scaled up or phased out. Examples include policy innovation labs and regulatory sandboxes.
2. **Methods for policy experimentation**, aimed at monitoring and evaluating the impacts of diverse policy approaches and programmes. Examples include RCTs and in-field experiments.

STI policy experimentation goes beyond these two types (Arnold et al., 2023[4]; Bravo-Biosca, 2019[21]). It can also take the form of experimentation with governance models, such as initiatives to enhance cross-governmental collaborations or effectively involve citizens and businesses in policymaking processes (Paunov and Planes-Satorra, 2023[22]).

Experimental environments: Policy innovation labs and regulatory sandboxes

Policy innovation labs (PILs) are organisations or initiatives that apply experimental, scientific lab-like methods to generate and test innovative, evidence-based policy solutions on a small scale before wider implementation. They support agile policymaking by equipping the public sector with practical experience in experimentation and by actively promoting the use of innovative approaches. PILs often act as collaborative hubs, bringing together diverse stakeholders (including citizens, businesses, experts and policymakers) to analyse policy challenges and develop user-centred solutions (Bellefontaine, 2012[23]). These labs can be embedded within government or operate as external entities. In both cases, they act as instigators of change, challenging conventional processes and catalysing new ways of working across the policy system. They provide a space for knowledge mobilisation and policy innovation. Four types of PILs can be distinguished (Wellstead, 2020[24]) (see examples in Table 7.3):

1. **Design-led labs**: Concerned with the application of "design" thinking to policy and focused on "user-centred" methods such as visualisation techniques, and collaboration with citizens and other stakeholders to clarify problem definitions and co-create solutions.
2. **Open government/data labs:** Employ innovative approaches in data analytics such as applying new digital and web-based tools to open up and interrogate public data, therefore drawing on expertise from diverse participants to run and apply data analytics.
3. **Evidence-based labs:** Focused on the application of rigorous evaluation techniques, principally RCTs.

4. **Mixed labs:** Employ any one of these three approaches.

Table 7.2 outlines the key benefits and potential risks associated with PILs while Table 7.3 provides selected examples.

Table 7.2. Benefits and risks of policy innovation labs in science, technology and innovation policy

Benefits	Limitations and risks
Agility: Policy innovation labs (PILs) benefit from their small size, which allows them to act as agile change agents. With fewer oversight and accountability requirements than public sector organisations, they can take more risks, experiment with new ideas and adapt quickly.	**Difficulties in scaling up:** PILs can lack a clear focus on how to scale up their ideas and experiments into real-world policies and systems. Policy proposals generated within the labs are often set within a "close" environment, therefore there is an imperative to provide a reasonable "way forward" if they are to be advanced.
Collaboration: PILs promote a more participatory and design-focused approach to innovative policymaking. They foster collaboration by engaging stakeholders, encouraging participation and supporting co-creation. Unlike centralised government structures that operate in isolation, these labs adopt networked approaches, working closely with both internal and external stakeholders, including civil society organisations, the private sector, universities and research centres.	**Lack of genuine engagement:** PILs operate within broad networks involving multiple stakeholders with diverse perspectives and interests. Ensuring meaningful participation is essential for their effectiveness. However, in some cases, stakeholder involvement may be limited to consultation rather than active engagement, reducing the impact of their input on decision making.
Capacity building: PILs help public servants and managers develop practical skills, confidence and empathy in using innovative approaches, methods and tools. By fostering hands-on learning, they support cultural shifts in public administration, enhancing both skills and mindsets. These labs serve as learning spaces that complement traditional training methods and encourage a more adaptive and forward-thinking public sector.	**Funding constraints:** Organisational risk aversion and limited commitment from senior decision makers (both internal and external) can create funding challenges, restricting the resources available for innovation. **Insufficient skills and expertise:** PILs may face a shortage of in-house expertise in experimental approaches and encounter difficulties in attracting and retaining highly skilled staff.

Sources: Monteiro and Kumpf (2023[25]); Lewis (2020[26]); Damgaard and Lewis (2014[27]).

Table 7.3. Selected examples of policy innovation labs for science, technology and innovation policy

Country	Type	Description
Chile	Design-led lab	The Laboratorio de Gobierno is a Chilean state agency under the Ministry of Finance that aims to accelerate public service transformation through collaborative design and a people-centred approach. Established in 2015, the lab has a team of approximately 25 employees and provides services such as consulting support for public initiatives to adopt experimental trial and error-based innovation methods. The lab has also built a network of public innovators and a platform where public sector officials can share experiences and learn from one another. The lab's flagship initiative is the Public Innovation Index, which, developed in collaboration with the Inter-American Development Bank, assesses the innovation capacity of public institutions. Based on a survey of 161 public organisations, the index evaluates institutional resources, practices and processes, and collaboration and openness.
Colombia	Design-led lab	Bogota's Public Innovation Lab was established in 2021 through the District Development Plan to foster public sector innovation. With a team of approximately 16 employees, the lab facilitates virtual exchanges with experts through seminars and discussions on topics like funding, procurement and skills development for public sector officials, alongside providing open-access guides to help navigate the various stages of implementing innovative initiatives (including stakeholder mapping and roadmap development). As part of its activities, the lab offers an online database with information on available public innovation training programmes for government officials in Bogotá.
Global	Evidence-based lab	The Innovation Growth Lab (IGL), established in 2014, is a policy lab hosted by Nesta (United Kingdom) and the Barcelona School of Economics (Spain). It has a team that provides direct support to public agencies in designing, implementing and scaling experimental approaches, including the use of randomised control trials. Since its creation, IGL has supported over 70 policy experiments across 28 countries (as of July 2025) and has contributed to the establishment of experimentation funds in the United Kingdom and the European Commission. The lab also provides capacity-building services to help public bodies embed experimentation into their institutional frameworks and policymaking cycles.

Sources: Information on the Laboratorio de Gobierno (Chile) was extracted from Arnold et al. (2023[4]) and Government of Chile (2025[28]); information on the Public Innovation Lab (Colombia) was extracted from OPSI (2018[29]) and Alcaldía Mayor de Bogotá D.C. (2025[30]); information on IGL was extracted from IGL (2025[31]).

Regulatory sandboxes are controlled environments where businesses can test new products, services or business models under relaxed regulations and under the supervision of public authorities (Attrey, Lesher and Lomax, 2020[32]). Their main characteristics are that they are: temporary; use a trial-and-error approach; and involve collaboration and iteration between stakeholders. They originated in the financial services sector, but their use has expanded rapidly to new areas, particularly in highly regulated industries such as transport, energy and health (OECD, 2023[33]). In the context of STI policy, notable examples include AI regulatory sandboxes that enable firms to test machine learning tools under regulatory supervision, and urban mobility sandboxes that support the testing of autonomous or low-emission transport solutions.

Regulatory sandboxes allow policymakers to embed flexibility into policy design by collecting real-world data, identifying potential risks of emerging technologies early on, and adjusting regulations to prevent them (Almeida Shimizu, 2020[34]; Ranchordás, 2021[35]). Additionally, by promoting continuous stakeholder engagement, they enable closer collaboration between regulators and businesses and facilitate quicker responses to market changes. Their popularity results from the recognition that the technologies required to build more sustainable socio-economic systems and embrace digital futures may be hampered by existing regulatory frameworks. Table 7.4 outlines the key benefits and potential risks associated with the use of regulatory sandboxes and Table 7.5 presents a set of specific examples.

Table 7.4. Benefits and risks of regulatory sandboxes

Benefits	Limitations and risks
Early regulation learning: Regulatory sandboxes offer a safe space to experiment with innovative ideas without the full burden of existing regulations. They help identify opportunities and risks associated with new innovations at an early stage. Insights gained can inform legal adjustments, allowing regulators to approve specific innovations based on real-world results.	**Limited duration and scale:** Sandboxes often operate on a small scale with a typically limited duration, meaning that they may not be able to test the full potential of certain innovations. Some technologies, especially those in areas like artificial intelligence, blockchain or sustainable energy, need longer time frames and larger user bases to assess their real-world impact, risks and scalability.
Faster innovation deployment: By bridging the gap between experimentation and real-world application, sandboxes speed up the transition of innovations from concept to market. They provide a structured yet flexible environment where businesses, researchers and policymakers can test novel ideas under regulatory oversight but with temporary exemptions or tailored rules. This reduces uncertainty and administrative delays, allowing innovators to refine their solutions based on real-world data before full-scale implementation.	**Competitive imbalances:** If sandbox participation does not result in clear regulatory approval or market access, some participants may struggle to move beyond the testing phase. Start-ups, for example, often lack the resources to scale quickly once the sandbox period ends and depend on regulatory certainty to attract investors and customers. This creates an uneven playing field, where larger companies with more resources have a competitive advantage, ultimately reducing the sandbox's overall effectiveness in driving inclusive growth.
Enhanced public participation and acceptance: By involving stakeholders in the innovation process, sandboxes create space for dialogue and collaboration, helping to build societal trust in new developments.	

Sources: German Federal Ministry for Economic Affairs and Energy (2025[36]); Didenko (2019[37]).

Table 7.5. Selected examples of regulatory sandboxes for science, technology and innovation policy

Country	Description
Denmark	GreenLab is a green industrial park and research and development (R&D) facility established by the Danish government. It focuses on accelerating innovation in green energy generation, storage and sharing, and facilitating the commercialisation of new green energy solutions. Products of the GreenLab include systems for thermal storage in rocks to share surplus energy between companies in the industrial park; and hydrogen, ammonia, methanol, proteins and methane for use in transport, agriculture, materials, food and energy industries (De Silva et al., 2023[38]). GreenLab has been designated as an official regulatory energy test zone, exempting it from existing electricity regulations to test new solutions for integrating unprecedented amounts of renewable energy into the energy system (GreenLab, 2021[39]). One of GreenLab's current projects is GreenHyScale, which is exploring the use of pressurised alkaline electrolysis for large-scale onshore and offshore green hydrogen production (IRENA, 2022[40]).

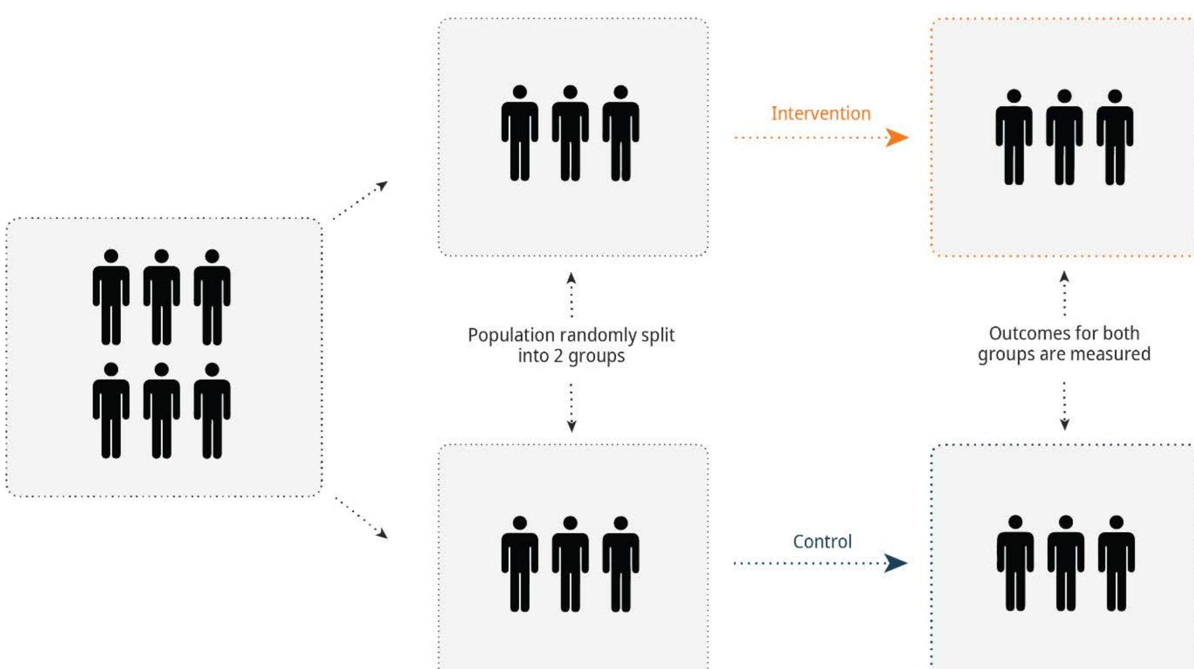
Germany	Launched in 2021, the Digital Test Field on the Federal Waterway Schlei is a regulatory sandbox in Schleswig-Holstein, Germany, co-ordinated by the start-up Unleash Future Boats GmbH. Built as a European test and validation centre for autonomous maritime systems, it operates along a 42-kilometre stretch of the Schlei waterway and serves as a real-world environment to trial zero-emission vessels, digital navigation and connectivity solutions.The company's ZeroOne boat, the world's first autonomous and zero-emission boat powered by fuel-cell technology, which is internationally registered and globally insured, is used for testing. Funded under the Federal Ministry for Digital Affairs and Transport, the project won the Federal Ministry for Economic Affairs and Energy's 2022 Regulatory Sandbox Prize. Beyond testing new technology solutions, the sandbox provides insights regarding system limitations and safety regulations, which can contribute to informing the development of international standards for autonomous and clean inland waterway transport. Other examples of regulatory sandbox initiatives in Germany can be found on the Federal Ministry for Economic Affairs and Energy's Regulatory Sandbox Innovation Portal (in German).
Malaysia	The National Technology and Innovation Sandbox was announced in June 2020 under the Short-Term Economic Recovery Plan (PENJANA) and launched in August 2020. With a USD 22 573 400 (MYR 100 million) allocation, it supports researchers, innovators and entrepreneurs in testing their products and services in real-world conditions while accessing grants to accelerate commercialisation. By relaxing certain regulatory requirements, the sandbox fast-tracks innovation from R&D to market readiness. Notable pilots include "HelloWorld Robotics", which developed an autonomous delivery system for transporting goods from merchants to end-users, and "Akar Indah Engineering", which created a smart waste management system integrating Internet of Things, sensor technology and cloud computing for local fresh markets.
Portugal	Established in 2021, the technological free zones are regulatory sandboxes that provide real or quasi-real environments for testing innovative technologies, products and services. Two such zones are currently operational: Infante D. Henrique, which focuses on testing vehicles or technologies that can operate either with human control (manned) or autonomously/remotely (unmanned), primarily for security and defense applications; and Matosinhos, which aims to position Portugal as a leader in developing and testing innovative mobility solutions for urban carbon neutrality.

Sources: Information on GreenLab (Denmark) was extracted from De Silva et al. (2023[38]); GreenLab (2021[39]); IRENA (2022[40]); EC-OECD (2025[41]). Information on the Digital Test Field on the Federal Waterway Schlei (Germany) was extracted from German Federal Ministry for Economic Affairs and Energy (2025[36]). Information on NTIS (Malaysia) was extracted from Malaysian Ministry of Science, Technology and Innovation (2024[42]). Information for the technological free zones (Portugal) was taken from Portugal's National Innovation Agency (2025[43]).

Assessment methods: Randomised control trials

Randomised control trials are a type of impact evaluation method in which participants (individuals, households, firms, etc.) are randomly assigned to two or more groups (Figure 7.3).

Figure 7.3. Randomised control trials



These typically include one or more treatment groups that receive different versions of an intervention, and a control group, which may receive no intervention or the current standard policy or practice (against which the new intervention is benchmarked). Researchers then compare outcomes between these groups. Because the assignment is random, the treatment and control groups should be similar in all respects except for the intervention received. This allows researchers to attribute any differences in outcomes to the intervention itself, rather than to confounding factors or selection bias (J-PAL, 2023[44]).

RCTs ensure strong monitoring and evaluation by allowing researchers and policymakers to design studies that answer specific questions about a programme's effectiveness and its underlying economic theory. Beyond determining whether a policy or programme works, RCTs can also identify which components drive success, which version of an intervention is most effective, whether results can be replicated in different contexts and how impact is achieved (or not achieved) (Edovald and Firpo, 2016[45]). In today's rapidly evolving landscape, where significant investments are being made in green and digital transitions, RCTs can help test new approaches and ensure public resources are allocated efficiently.

RCTs have long been used in clinical research, but have recently gained more widespread application in public policy. Notably, the number of RCTs in innovation, entrepreneurship and business growth has been growing in recent years (Firpo and Phipps, 2019[46]). The *IGL Trials Database*, which aims to compile all RCTs conducted in this field, included 226 such experiments as of 2022 (Serin et al., 2022[47]). Table 7.7 provides some illustrative examples of how RCTs have been applied in the field of STI policy. Despite their potential, the applicability of these methods in the field of STI policy also faces several limitations, as outlined in Table 7.6.

Table 7.6. Benefits and risks from randomised control trials

Benefits	Limitations and risks
Establishing causal effects: Randomised control trials (RCTs) help determine the effectiveness of a policy or intervention. Since participants are randomly assigned to different groups, the only systematic difference between them is the intervention itself, creating a credible counterfactual for comparison. This eliminates biases, including selection bias, where certain groups (e.g. more innovative firms) are more likely to benefit from a policy.	**Limited generalisability and transferability of the results:** One of the most frequent criticisms of RCTs is around their low generalisability, meaning that it can often be difficult to transport learnings from an RCT to different contexts. Although trials present the best evidence on the outcomes of an intervention, that evidence is specific to the context in which the intervention was set, and it is not always possible to infer that similar interventions would have the same effect in other environments, or even with a bigger population.
Practical insights for policymakers: RCTs can provide policymakers and innovation programme managers with valuable insights to refine policies or programme design after the trials. By analysing the experiment's results, they can assess how an intervention was implemented, identify constraints and make necessary adjustments to improve policy effectiveness.	**Limited insights into causal mechanisms:** While RCTs help identify whether an intervention works and to what extent, they often provide limited understanding of why it works or not. This is typically left to researchers' interpretation. However, understanding these mechanisms is critical for policymakers and practitioners to decide whether to adopt, scale or replicate the intervention being tested.
Efficient public spending and government accountability: By establishing causal effects, RCTs provide reliable evidence on whether a programme works, helping to prevent wasteful spending and ensuring public funds are directed toward effective policies. They also enhance government accountability by offering transparent, data-driven justifications for funding decisions.	**Cost and time requirements:** Because of operational requirements inherent to their design, notably the random allocation of the policy intervention under investigation, RCTs can be expensive and time-consuming to implement, particularly when dealing with large sample sizes and long-term outcomes.
	Fairness and ethical concerns: RCTs can sometimes face ethical constraints, such as the impossibility of denying an intervention to a subset of participants. These relate to deeply rooted moral and legal traditions around the equal treatment standards that are challenged by random selection criteria.

Source: Based on Edovald and Firpo (2016[45]).

Table 7.7. Selected examples of randomised control trials for science, technology and innovation policy from Horizon 2020

Country	Description
Italy (co-ordinated by Hub Innovazione Trentino)	The 200SMEchallenge project, funded through Horizon 2020 with a budget of EUR 499 737, was implemented between 2020 and 2022 to assess whether innovation contests using user-centred design methods could increase small and medium-sized enterprises' (SMEs) readiness to adopt digital design practices. The project involved running a UX Challenge, a one-week structured design sprint carried out by multidisciplinary teams of students and supported by experts, to help SMEs improve the user experience of their digital products. A randomised control trial (RCT) was conducted with nearly 200 SMEs from 7 European countries. Sixty SMEs were randomly selected to participate in the UX Challenge; the remainder formed the control group. Three weeks after the intervention, treated firms reported significantly higher knowledge of Design Sprint methods (a 19% increase) and practical understanding of user-centred design (a 12% increase). However, no statistically significant differences were found in firms' short-term intentions to invest in digital design. This suggests that while user-centred design challenges can raise awareness and technical knowledge, their impact on behaviour change may require complementary support to overcome internal organisational and financial barriers.
Lithuania (led by the Lithuanian Innovation Centre)	The InReady Project, funded through Horizon 2020 with a budget of USD 64 889 (EUR 60 000), was implemented between 2019 and 2021 to support start-ups in enhancing their investment pitches through a structured digital tool (InReady).The tool was tested through an RCT involving 27 start-ups, divided into a control group (which pitched without support) and a treatment group (which used the InReady tool). The evaluation showed that the treatment group significantly improved in areas such as business strategy, market positioning and financial projections, while the control group faced challenges in structuring their pitches and defining their value proposition.
Netherlands (led by the Netherlands Enterprise Agency and Statistics Netherlands)	The Dutch innovation voucher scheme, implemented in 2004-2005, aimed to stimulate collaboration between SMEs and public knowledge institutes. Vouchers were allocated by lottery, enabling an RCT with over 1 000 firms. By linking the trial to administrative data over a 12-year period, researchers found that treated firms had higher survival rates (4%), greater use of research and development (R&D) tax credits (5%), more R&D activity (12% increase in hours) and a higher employment rate. While productivity gains were not statistically significant across the entire sample, firms that sustained R&D after receiving the voucher did show improvements. This study provides robust evidence that even small-scale interventions can have lasting effects on innovation behaviour, especially when they help firms take their first steps into R&D collaboration.
Spain (led by the Instituto para la Competitividad Empresarial de Castilla y Leon)	The DIHnamic Project, funded through Horizon 2020 with a budget of USD 536 185 (EUR 496 250), was implemented between 2019 and 2022 and aimed to determine the optimal level of support in digital innovation hubs for SMEs to accelerate their digitalisation processes. To assess the impact of additional support, the project conducted an RCT involving 47 SMEs across 6 digital innovation hubs. SMEs were randomly assigned to 2 groups: a control group (23 SMEs) receiving Service A, which included 20 hours of specialised advice on digitalisation strategies, and a treatment group (24 SMEs) receiving Service B, which included 80 hours of consultancy and hands-on experimentation with digital solutions. The evaluation aimed to determine whether the extra support in Service B led to a significant increase in digital investment and maturity. However, results showed no statistically significant difference between the two groups in the analysed dimensions, suggesting that additional support did not accelerate digitalisation beyond the standard advisory service.

Sources: Examples were taken from the Innovation Growth Lab trials dataset (IGL, 2024[48]). Information on InReady (Lithuania) was also extracted from European Commission (2024[49]) and for DIHnamic (Spain) information was taken from European Commission (2024[50]).

Challenges and policy responses to support wider policy agility

Despite their benefits, the use of policy intelligence and policy experimentation face several challenges, which helps explain why they are not more widely used. This section discusses these challenges.

Challenges and opportunities for embedding strategic intelligence and policy experimentation

While policy experimentation and various tools for strategic intelligence can provide important returns on investment, with respect to the resources spent on such activities, several challenges have to be addressed for successful implementation, including:

- **Building public sector capacities and skills:** Policy experimentation for STI can be challenging for the public sector, and officials may need new training and capacities to play a role as an incubator and accelerator of new experimental approaches to policy. The ability to design and deliver public services in new ways, combined with a user-centric focus on how industry and consumers benefit from them, are important skills for innovation and experimentation in STI policy development. Recruiting staff with diverse skills and profiles into the public sector contributes to this, including staff with scientific and entrepreneurial backgrounds. With regards to strategic intelligence, a key challenge is the uptake of the results of strategic intelligence activities into STI decision making. This may require fit-for-purpose institutional capacities and structures as well as the skills needed to interpret such results. This is discussed in more detail below.

- **Overcoming power dynamics and structural barriers limiting the integration of evidence in policymaking:** Intelligence has no practical meaning unless it can be actioned and used. Likewise, learnings from policy experimentation must also be recognised as legitimate and integrated into policymaking processes to inform policy. This poses a major challenge. For example, as earlier OECD work has shown (Robinson, Winickoff and Kreiling, 2023[2]), strategic intelligence is often developed by a neutral "honest broker" at a distance from the decision-making process – therefore, independent and trustworthy. Similarly, those engaged in policy experimentation are often engaged in advisory or analytic roles but remain peripheral to the core decision-making space. However, for agile policy cycles and the greatest impact, such intelligence would benefit from being conducted as part of the policymaking process and with the involvement of decision makers. Bridging this disconnect requires deliberate integration of strategic intelligence and experimentation functions into the political and strategic centres of decision making. One approach to resolve this is to build best practices in agile intelligence production close to, or conducted by, policymaking institutions.

  Vested interests and established networks of incumbent actors can pose a further barrier to evidence uptake. Even well-substantiated recommendations may be ignored if they threaten existing systems. These dynamics may significantly limit the potential for strategic intelligence and experimentation to influence decision-making processes.

- **Enhancing the legitimacy of strategic intelligence and policy experimentation:** Mainstreaming experimentation in STI policy requires governments to create an environment where testing new approaches is not only accepted but actively encouraged. Providing clear mandates, adequate funding and institutional backing ensures that actors have the means and authority to drive experimentation forward. This means ensuring that policymakers and institutions have the support and resources to experiment.

  Political legitimacy plays a key role in building trust among stakeholders by showing that experimentation is deliberate and transparent, and that strategic intelligence provides for an evidence-based process aimed at improving policies. Clear and proactive communication about the goals, processes and outcomes of these efforts helps reinforce that legitimacy. Establishing rigorous yet adaptive evaluation frameworks – and openly learning from both successes and failures – further strengthens accountability and public trust in innovative approaches.

- **Embedding agility while ensuring robust monitoring and evaluation:** Incorporating iterative learning and regular assessment into STI policy implementation helps determine whether initiatives are effectively achieving their goals. This enables timely identification of what works, what does not, and when to scale up or discontinue initiatives. To support this, experimental structures should remain reversible – so that they can be discontinued without major disruption if they prove unsuccessful – and adaptable to lessons learnt during implementation. However, over time, vested interests can form around certain initiatives, making it harder to make changes. Experimentation as part of a broader portfolio of support actions can enhance flexibility (BMWK, 2025[51]).

Constraints on risk-taking required for experimentation in public policy

Several factors constrain risk-taking required for experimentation in public policy. These include limitations on the use of public funding for experimental approaches in policy. For example, there might be constraints on the random disbursement of public funding – as required for RCTs – or rigid criteria and long processes to apply for new funding instruments – as would be required for more agile approaches to policymaking, such as piloting at a small scale and deciding on that basis whether to expand or downscale those initiatives.

Spending taxpayer money on initiatives with uncertain outcomes and no guaranteed results is a valid concern. Accountability and checks on spending are similarly important as are other oversight mechanisms to prevent the misuse of public resources.

At the same time, it is important to avoid "false efficiency" – a system that appears to be cost-effective in the short term but ultimately stifles innovation by rejecting the "good waste" that comes with testing and learning (Potts, 2009[52]). Potential benefits of experimentation are often abstract, uncertain and shared across multiple stakeholders. In contrast, risks of failed experimentation are often specific, measurable and directly linked to individual decisions (Torugsa and Arundel, 2017[53]; Ritchie, 2014[54]). This creates a bias where failures stand out more than successes, making public servants more risk-averse and less likely to adopt innovative approaches.

Enabling policy experimentation will require addressing those constraints, including by ensuring the transparency, accountability and pay-offs of these experimental policy initiatives; adopting portfolio assessments of policy packages; engaging in efforts to ease bureaucratic hurdles; and adopting regulatory adjustments. Importantly, being transparent as to policy experiments, including by submitting them to rigorous assessments, contributes to reducing the risk of spending public resources poorly. This is where policy experimentation in evaluation and monitoring itself can help.

More complicated is the notion of dealing with new policy initiatives that may or may not succeed, such as policy tools for breakthrough innovations that have higher risks of failure. What is essential is to identify ways to evaluate a policy portfolio's overall success – rather than looking for every single one to succeed.

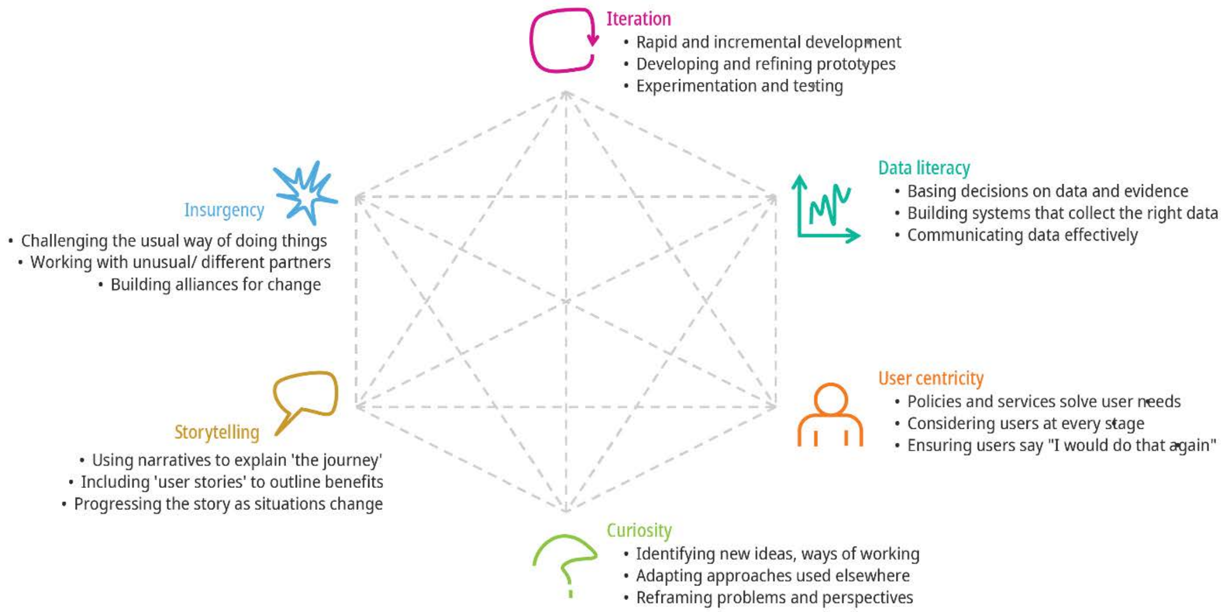
Bureaucratic and regulatory procedures should be another continued target for assessments. While they play a vital role in safeguarding key principles such as accountability, compliance, transparency, stability and risk minimisation, they can also challenge the flexibility needed for implementing agile policy approaches. This includes laws and regulations that limit or prohibit policy experimentation, as well as lengthy approval cycles and rigid budgeting mechanisms.

Finally, experimentation might also lead to saving funds. Rigorously evaluating policies with experimental methods, such as RCTs, provides evidence on what works and what doesn't, helping governments spend limited public funds more effectively. Raising greater awareness of the benefits of such methods as part of monitoring and evaluation processes supports responsible public spending. The higher costs of setting up new more rigorous assessments may well be justified and also decrease over time with more experience in conducting and applying them.

Incentive structures and capacities

Building capacities to support public sector officials in implementing innovative policy approaches is another key factor holding back further progress (OECD, 2024[20]). This includes ensuring that a range of disciplinary backgrounds and forms of expertise are represented within public administrations, including expertise from industry and diverse scientific fields, ranging from social sciences and legal backgrounds to engineering and natural sciences. Moreover, offering specific training on policy experimentation and evaluation methods to public administrators and civil servants can help by illustrating how they work and clearing up misconceptions about their use. Other core skills for public sector innovation include data literacy for evidence-informed decision making and storytelling to effectively communicate ideas (Figure 7.4).

Figure 7.4. Core skills for public sector innovation



Source: OECD (2017[55]).

Moreover, the adoption of more user-centric approaches can help improve how policies respond to the evolving needs of the users of these services (see Figure 7.4). This involves systematically assessing whether proposed projects, policies or services meet users' needs as part of the policy approval process. Adequate resources and time must be allocated to understanding and analysing these needs, as well as conducting regular research and testing to ensure policies remain relevant (OECD, 2017[55]). This is particularly important for policy experimentation, where iterative testing and feedback loops are crucial to refining and improving initiatives. Without meaningful engagement, experimental policies risk being misaligned with real-world needs and may fail to gain public trust and adoption. To build trust and ensure impactful participation, it is preferable for policymakers to prioritise a few well-designed engagement processes with higher policy impacts rather than spreading efforts across numerous low-impact processes organised as "tick-the-box" formalities (OECD, 2024[56]; Paunov and Planes-Satorra, 2023[16]). Poorly executed engagement risks disappointing participants and eroding trust in government.

Beyond capacities, there is the key imperative of creating a culture for innovation, where incentives are provided for engaging in experimental policy approaches, with an experimentation-prone system that encourages public servants to embrace agile policy approaches and use new digital tools for data collection and analysis (Arnold et al., 2023[4]). This requires exploring public officials' incentives as regards policy experimentation, which largely depend on the performance assessment and employment promotion dynamics in place and the internal hierarchies and the opportunities these provide for bottom-up initiatives. Champions within the public sector – whether senior leaders, analysts or programme managers – can be instrumental in shaping this culture by creating protected spaces for learning, even in systems with limited formal incentives.

Top-level endorsement of policy experimentation – as illustrated for Canada in Box 7.7 – is also of paramount importance in building and institutionalising a culture of experimentation. Canada's "Experimentation Direction for Deputy Heads" gives government departments a mandate to allocate a portion of programme funds for experimentation and create clear processes for evaluating and integrating lessons from experiments into new programmes. Finland established the Experimental Finland initiative

(OECD, 2017[57]), which encourages and supports line ministries to undertake policy experiments by means of explicit top-level endorsement.

Establishing cross-sectoral governance mechanisms to jointly learn about policy experimentation, such as by using centralised databases, can also be used to track experiments, share results and minimise duplication of efforts. Improving co-ordination helps reduce the risk of "projectification", which occurs when too much focus is placed on small-scale pilots, leading to fragmented efforts and making it harder to scale successful initiatives due to limited resources and capacity (OECD, 2024[20]).

Box 7.7. Canada's approach to supporting policy experimentation

Since 2015, Canada has adopted a new governance approach that promotes public sector innovation, with a strong focus on encouraging federal departments to experiment with new methods to enhance policymaking. To support this, the government has launched several programmes to overcome barriers to policy experimentation and expand its use. A subset of these initiatives is outlined below.

Institutionalising policy experimentation

The Impact Canada initiative, launched in 2017, seeks to promote the adoption of innovative approaches by supporting government departments in designing and evaluating projects using prizes, challenges, micro-funding and other outcome-based approaches.

A key achievement of this initiative has been improving access to information for policymakers and other stakeholders through clear, accessible materials on policy experimentation. As part of this effort, the Canadian government developed the Measuring Impact by Design: A Guide to Methods for Impact Measurement, which seeks to promote the use of experimental and quasi-experimental approaches across the country. The guide demonstrates that, with proper planning, most programmes can integrate experimental impact evaluation methods with minimal or no disruption to their normal operations.

The Experimentation Direction for Deputy Heads is another important framework introduced under Impact Canada. This document reinforces the government's commitment to allocating a fixed percentage of programme funds for testing new approaches and provides guidance for deputy heads on implementing this commitment.

To address these challenges, Canada launched the Experimentation Works initiative in 2018 to train public servants in experimental methods. The initiative used a hands-on, "learning-by-doing" approach, offering accessible learning modules, supportive tools and an "experimenting in the open" model that encouraged transparency and collaboration. A key feature of the initiative was the support provided to five small-scale, department-led experiments, designed and implemented by public servants (see detailed descriptions here). By guiding these experiments from start to finish, Experimentation Works strengthened practical understanding of experimentation, demonstrating its value and generating concrete examples of federal experiments.

Sources: Government of Canada (2024[58]); OPSI (2018[29]).

Institutionalising experimentation and strategic intelligence

Institutionalising experimentation and strategic intelligence production and use can support broader uptake by embedding it into national programmes and frameworks. It requires that governments create an environment where testing new approaches is not only accepted but actively encouraged. This involves:

- **Facilitating access to information:** Providing policymakers with clear, accessible materials on policy experimentation and strategic intelligence approaches. These resources could explain different types of experimentation (e.g. sandboxes and RCTs) and strategic intelligence methods, their distinct roles, and how they contribute. This includes developing guidelines and frameworks that clarify their impact and ensuring their integration into national strategies.

- **Building a well-defined roadmap:** Outlining clear objectives, identifying key areas for experimentation and establishing mechanisms for scaling successful initiatives. This would include defining success criteria, setting benchmarks for progress and ensuring continuous evaluation (OECD, 2024[20]).
- **Securing long-term political and financial support:** Embedding policy experimentation and strategic intelligence into national budgets and legislative frameworks. This involves creating dedicated funding streams, addressing administrative hurdles, fostering cross-sector collaboration and ensuring high-level political commitment to sustain experimentation beyond political cycles.

Learning from combinatorial approaches

In some cases, strategic intelligence and policy experimentation approaches are used in combination. For example, in July 2024, the UK Regulatory Innovation Office was set up as a pro-innovation governance unit to facilitate rapid deployment of innovation underpinned by responsible innovation. It is built around three main pillars: 1) a knowledge pillar mobilises strategic intelligence to better understand the evolving nature of technology areas and appropriate metrics to support strategic decision making over time; 2) a strategic pillar establishes priorities, particularly industrial priorities, by developing an agile and responsive system that can develop and deliver the governance required for these new technologies; and 3) a capability pillar enables institutional reform and builds the regulatory skills required to identify and respond to the significant economic and societal changes that emerging technologies may bring. This and other examples reveal the added value of combining these different approaches into a coherent programme of activities to support STI policy.

Conclusions

Incremental policy cycles as shown in Figure 7.1 provide stability for the public, strategic orientation for industrial stakeholders to align with, and for patient and long-term investment. However, as outlined in this chapter, there are circumstances where agile policy making holds promise – in times of urgency, whether planned (driving forward technological innovation to improve competitiveness or solve societal challenges) or unplanned (reacting to crises, for example pandemics or the ramifications of war and other conflicts).

Building capacity for informed and agile policymaking requires experimentation and strategic intelligence. Anticipating, testing and modulating policies in real-world conditions helps identify what works, what doesn't and where improvements are needed. Integrating various strategic intelligence tools to feed into the support actions for agility can help create a culture of anticipation and of learning while doing while increasing flexibility and adaptability within bureaucratic structures (through better co-ordination mechanisms and simplified processes). This flexibility and adaptability can reduce the cost and complexity of launching experiments.

Multiple actions can foster and accelerate an agile and adaptive culture among policymakers. These include institutionalising policy experimentation by embedding it into national programmes and frameworks to help overcome fear of failure or political consequences that often make public administrations hesitant to innovate. Additionally, training programmes help build capacities in the public sector to leverage strategic intelligence and use policy experimentation.

Overcoming these challenges requires substantive rethinking of incentive schemes. In the case of policy experimentation, for instance, moving from successful small experiments to phasing out failures or expanding successes is not a given. Acknowledging failure is often discouraged due to misaligned incentives, while scaling success can be hindered by limited financial resources and legal or regulatory complexities that emerge when moving toward wider implementation (OECD, 2024[20]).

As regards strategic intelligence, the application of these tools needs to be cognisant of the absence of hard evidence, particularly in the context of high uncertainty and complexity in the field of rapidly emerging and evolving technologies. Understanding these limitations and focusing on learning matter for a more robust use of these tools to the benefit of agile STI policy.

This chapter has presented experiments in agile strategic intelligence and policy experimentation. Together the insights presented build an ideal picture of an agile and intelligence driven policymaking process. However, the realities of the daily work of those in public administrations, their practices and institutional constraints must not be ignored. While there are promising approaches to strategic intelligence production and policy experimentation, a large array of challenges remain. The opportunity remains to explore further these challenges and gather additional insights from policy experimentation and the use of strategic intelligence.

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