OECD Science, Technology and Innovation Outlook 2023

ENABLING TRANSITIONS IN TIMES OF DISRUPTION

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Foreword

The *OECD Science, Technology and Innovation Outlook 2023* is the latest in a series that reviews key trends in science, technology, and innovation (STI) policy in OECD countries and several major partner economies. This edition focuses on longstanding trends – including climate change and growing geopolitical tensions – and recent disruptions, notably the COVID-19 pandemic, that have highlighted risk, uncertainty and resilience as conditions and concerns for STI policy. Taken together, these have contributed to a growing “securitisation” of STI policy.

As the pandemic has shown, STI is essential to building capacity for resiliency and adaptation to shocks. However, it can only perform this role effectively if it is well-prepared to respond to known risks and unknown uncertainties. Good preparation requires long-term investments in research and development, skills and infrastructures, but this alone is insufficient. It also needs strong relationships in “normal times” among those who should mobilise rapidly to deal with crisis situations, as well as a strong “strategic intelligence” capacity to identify, monitor and evaluate emerging risks and responses.

Ambitions to mobilise research and innovation systems to absorb, respond to, and recover from crises and societal challenges as they emerge represents a distinct break from the status quo. Novel and experimental configurations of actors, institutions, and practices are needed to improve the resilience of STI systems and the relevance of outputs to emerging crises, challenges, and the everyday lives of citizens. This is particularly so for the climate emergency, which requires nothing short of a total transformation of sociotechnical systems in areas such as energy, agrifood and mobility. STI systems have essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies. They need to design policy portfolios that enable transformative innovation and new markets to emerge, challenge existing fossil-based systems, and create windows of opportunity for low-carbon technologies to break through. This calls for larger investments but also greater directionality in research and innovation, for example, through mission-oriented innovation policies, to help direct and compress the innovation cycle for low-carbon technologies.

International co-operation will also be essential, but rising geopolitical tensions, including strategic competition in key emerging technologies, could make this difficult. Growing policy efforts to reduce technology dependencies could disrupt integrated global value chains and the deep and extensive international science linkages that have built up over the last 30 years. Coupled with a growing emphasis on “shared values” in technology development and research, these developments could lead to a “decoupling” of STI activities at a time when global challenges, notably climate change, require global solutions underpinned by international STI co-operation. A major test for multilateralism will be to reconcile growing strategic competition with the need to address global challenges like climate change.

The six chapters in this edition of the STI Outlook explore these and other key trends and issues, including strategic competition and the governance of emerging technologies, mission-oriented innovation policies for net-zero, and lessons from the scientific response to the COVID-19 pandemic. Taken together, they highlight the need for greater urgency, ambition, and preparedness in STI policy to better equip governments with the tools and capacities to tackle global challenges and build resilience to future shocks.

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Chapter 1, “STI policy in times of global crises”, Chapter 2, “STI policy in times of strategic competition”, and Chapter 3, “STI policy for sustainability transitions”, were prepared by Michael Keenan (DSTI). They are based on work carried out in the context of the CSTP’s crosscutting project, *S&T Policy 2025: Enabling transitions through science, technology and innovation*. Chapter 4, “Mobilising science in times of crisis: Lessons learned from COVID-19”, was prepared by Carthage Smith and Jessica Ambler (DSTI). The chapter draws on recent work by the OECD Global Science Forum (GSF). Chapter 5, “Reaching Net zero: Do mission-oriented policies deliver on their many promises?”, was prepared by Philippe Larrue, with assistance from Bora Kim (DSTI). It draws on CSTP work on mission-oriented innovation policies for net-zero. Chapter 6, “Emerging technology governance: Towards an anticipatory framework”, was prepared by David Winickoff, Laura Kreiling and Douglas Robinson (DSTI). It is based on recent work carried out by the Working Party on Biotechnology, Nanotechnology and Converging Technologies (BNCT) on anticipatory technology governance.

All chapters of the 2023 STI Outlook were reviewed by Alessandra Colecchia, Hanna-Mari Kilpelainen, Jens Lundsgaard and Andrew Wyckoff of the DSTI. Chapter 2 was also reviewed by Kerri-Ann Jones, OECD Deputy Secretary General, Marion Jansen, Director of OECD Trade and Agriculture Directorate, Isabell Koske, Director of Country Studies Branch in the OECD Economics Department, and Tamas Hajba (OECD Global Relations and Co-operation Directorate). The team thanks them for their valuable comments and guidance. Thanks are likewise due to those CSTP delegates who provided comments on chapter drafts and to participants in a CSTP high-level debate on 25-26 November 2022 where the STI Outlook’s main findings were discussed. The overall publication owes much to Sylvain Fraccola who designed the infographics and oversaw all aspects of the publication process, and Blandine Serve for her statistical support. Thanks are also due to Silvia Appelt, Mario Cervantes, Agnès Cimper, Antoine Dechezlepretre, Hélène Dernis, Fernando Galindo Rueda, Antton Haramboure, Guillaume Kpodar, Guy Lalanne, Kuniko Matsumoto, Laurent Moussiegt, Alistair Nolan, Alan Paic, James Philp, Lea Samak, Brigitte Van Beuzekom, Fabien Verger and Norihiko Yamano (DSTI) and Suzy Leprince (IEA) for their helpful advice and statistical inputs. Andrés Barreneche and Laura Garcia (DSTI) also contributed with inputs from the EC-OECD STIP Compass. The authors are grateful to Beatrice Jeffries (DSTI) for her secretarial assistance and to Sebastian Ordelheide (DSTI) for his communications support. Special thanks are given to Romy de Courtay for her editorial contributions and bibliographic research.

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Abbreviations and acronyms

AI	Artificial intelligence
BERD	Business Enterprise R-D Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CERN	European Organization for Nuclear Research
COP	Conference of the Parties
CPC	Cooperative Patent Classification
DAC	Direct air capture
DARPA	Defense Advanced Research Projects Agency
EPO	European Patent Office
EU	European Union
EUIPO	European Union Intellectual Property Office
EV	Electric Vehicles
FAIR	Findable, Accessible, Interoperable and Re-useable
GDP	Gross domestic product
GERD	Gross Domestic Expenditure on Research and Development
GHG	Greenhouse gas
GOVERD	Government Intramural Expenditure on R&D
GTARD	Government Tax Relief for R&D Expenditures
HERD	Higher Education Expenditure on R&D
HPC	High-performance computing
IEA	International Energy Agency
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
JPO	Japan Patent Office
MOIP	Mission-Oriented Innovation Policies
MSTI	Main Science and Technology Indicators
MTIP	Mission-driven Top Sector and Innovation Policy
NDC	Nationally determined contributions
NGO	Non-governmental organisation

NZE	Net Zero Emissions
PET	Privacy-enhancing technologies
PHSM	Public health and social measure
PPP	Public-private partnerships
R&D	Research and development
RD&D	Research, development and demonstration
RI	Research infrastructures
STEM	Science, Technology, Engineering and Mathematics
SSH	Social sciences and humanities
STI	Science, Technology and Innovation
STIP	Science, Technology and Innovation Policy
TA	Technology assessment
TDR	Transdisciplinary research
TI	Technical infrastructures
UNFCCC	United Nations Framework Convention on Climate Change
USPTO	United States Patent and Trademark Office
WHO	World Health Organization
WTO	World Trade Organization

Executive summary

Enabling transitions in times of disruption

Longstanding trends and recent disruptions have created a new operating environment for STI policy. Climate change and its impacts are increasingly driving STI agendas, as is the fast pace of change implied by the digital transformation, in what is often termed the “twin transitions”. At the same time, the two most salient disruptions of the last couple of years – the COVID-19 pandemic and Russia’s war of aggression against Ukraine – have had far-reaching, cascading effects, including on STI.

Global crises are contributing to a growing “securitisation” of STI policy agendas

Climate change, growing geopolitical tensions and the COVID-19 pandemic have highlighted risk, uncertainty and resilience as conditions and concerns for STI policy. Taken together, these have contributed to a growing “securitisation” of STI policy. As the pandemic has shown, STI is essential to building capacity for resiliency and adaptation to shocks. However, it can only perform this role effectively if it is well-prepared to respond to known risks and unknown uncertainties. International scientific co-ordination and co-operation structures and mechanisms were severely tested by the pandemic and showed their limitations. Many countries and populations could not access the benefits of science and technology, such as vaccines and therapeutics. Good preparation requires long-term investments in research and development, skills and infrastructures, but this alone is insufficient. It also needs strong relationships in “normal times” among those who should mobilise rapidly to deal with crisis situations, as well as a strong “strategic intelligence” capacity to identify, monitor and evaluate emerging risks and responses. It is in the mutual interest of all countries to ensure these relationships and capacities are globally distributed to enable an inclusive scientific and technological response to future crises.

Geopolitical tensions are contributing to strategic competition in emerging technologies

The growing ascendancy of China in frontier technologies raises various concerns for liberal market economies, including rising competition in critical technologies that are expected to underpin future economic competitiveness and national security; and growing vulnerability from technology supply-chain interdependencies, for example, in semiconductors and critical minerals. These concerns translate into a growing convergence between economic and security policy agendas and intensifying global technology-based competition. Governments are putting in place measures to (i) reduce STI interdependency risks and restrict international technology flows; (ii) enhance industrial performance through STI investments; and (iii) strengthen international STI alliances among like-minded economies. These measures could disrupt integrated global value chains and the deep and extensive international science linkages that have built up over the last 30 years. Coupled with a growing emphasis on “shared values” in technology development and research, they could lead to a “decoupling” of STI activities at a time when global challenges require global solutions underpinned by international STI co-operation. A major test for multilateralism will be to reconcile growing strategic competition with the need to address global challenges like climate change.

STI systems are crucial for enabling sustainability transitions

The climate emergency requires nothing short of a total transformation of sociotechnical systems in areas such as energy, agrifood and mobility. STI systems have essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies to support them. They need to design policy portfolios that enable transformative innovation and new markets to emerge, challenge existing fossil-based systems, and create windows of opportunity for low-carbon technologies to break through. Larger investments and greater directionality in research and innovation activities are needed, for example, by using mission-oriented innovation policies, to help direct and compress the innovation cycle for low-carbon technologies. These should coincide with a reappraisal of STI systems and their supporting STI policies to ensure they are "fit-for-purpose" to contribute to sustainability transitions. Systems thinking can help identify and understand critical linkages, synergies and trade-offs and empower policy makers to better recognise policy constraints and identify leverage points where they could act to unblock transition barriers.

The global STI response to COVID-19 provides important lessons for sustainability transitions

Science played an essential role in generating the knowledge and technologies needed to respond to the COVID-19 crisis. The pandemic offers lessons that can position science to respond more effectively to future crises. For instance, much can be learned from successful co-operation between various actors during the pandemic, but reinforcing these relationships over the longer term may require significant change to academic culture, structures, incentives and rewards. Many of the required changes – including in research performance assessment, public engagement, and transdisciplinary research – are already underway but have not yet been adopted at the necessary scale and speed because of embedded inertia in science systems. More radical change is necessary to spur science to engage with other societal stakeholders to produce the broader range of outputs and solutions that are urgently required to deal with complex global challenges and crises.

Mission-oriented innovation policies could help achieve net-zero targets

Mission-oriented innovation policies are increasingly popular as a policy response to meeting net-zero targets. They have clear objectives and measurable targets, promote broader co-ordination of policy plans across administrative silos, and better integrate various support instruments across the different stages of the innovation chain. These policies remain unproven, however, and early indications suggest they lack sufficient scale and reach to non-STI policy domains to have wide-ranging impact. The challenge remains to move these initiatives from effective coordination platforms to integrated policy frameworks that mobilise and align a wide range of actors. Overcoming many of the barriers – including administrative and legal rules, accounting structures and governance models – requires changes that are far beyond the reach of STI authorities alone and will need significant political support.

Good technology governance can encourage the best from technology

Emerging technologies can be pivotal for much needed transformations and responses to crises, but rapid technological change can carry negative consequences and risks for individuals, societies and the environment including social disruption, inequality, and dangers to security and human rights. The democratic community is increasingly asserting that "shared values" of democracy, human rights, sustainability, openness, responsibility, security and resilience should be embedded in technology, but questions remain on how this should be accomplished, especially when technology trajectories are set by developments in firms and public labs that are widely distributed across the globe in a variety of governance contexts. Using "upstream" design principles and tools can help balance the need to drive the development of technologies and to scale them up while helping to realise just transitions and values-based technology.

1 Science, technology and innovation policy in times of global crises

Longstanding trends and recent disruptions have created a new operating environment for STI policy. Climate change, growing geopolitical tensions and the COVID-19 pandemic have highlighted risk, uncertainty and resilience as conditions and concerns for STI policy. As the pandemic has shown, STI is essential to building capacity for resiliency and adaptation to shocks. However, it can only perform this role effectively if it is well-prepared to respond to known risks and unknown uncertainties. Good preparation requires long-term investments in research and development, skills and infrastructures, but this alone is insufficient. It also needs strong relationships in "normal times" among those who should mobilise rapidly to deal with crisis situations, as well as a strong "strategic intelligence" capacity to identify, monitor and evaluate emerging risks and responses. It is in the mutual interest of all countries to ensure these relationships and capacities are globally distributed to enable an inclusive scientific and technological response to future crises.

Key messages

- Multiple crises are triggering turbulence, instability and insecurity in contemporary societies, with impacts on economies, the environment, politics, and global affairs. The two most salient disruptions of the last couple of years – the COVID-19 pandemic and Russia's war of aggression against Ukraine – have had far-reaching and cascading effects, including on science, technology and innovation (STI).
- Assessment of the pandemic response provides key and actionable insights into what will likely be required of STI systems to respond more effectively to future crises. Looking back on how the pandemic has unfolded provides an opportunity to identify and resolve structural challenges to the effective operation of STI systems and support them in fostering the resilience needed to prepare for, respond and recover from, future crises and complex societal challenges.
- Research and innovation capabilities make economies and societies more resilient, but they require long-term investments in R&D, skills and infrastructures. Strong relationships in "normal times" between those who should mobilise rapidly to deal with crisis situations should be nurtured. Several OECD countries have announced substantial STI investments to improve pandemic prevention, preparedness and response. But these should be complemented by greater investment in research infrastructure as well as production capacities in low- and middle-income countries to enhance global preparedness and response.
- Geopolitical tensions led to vaccine competition between countries, creating a patchwork of vaccine approvals around the world. The global architecture to provide equitable access to vaccines has not met expectations, owing (among other factors) to insufficient funding, wealthier-country hoarding and logistical challenges. Vaccine "nationalism" and "diplomacy" raise concerns about strategic competition in other technology areas, as well as the prospects of future STI co-operation on global challenges such as climate change.
- More broadly, the pandemic and war in Ukraine have brought risk, uncertainty and resilience to the fore as conditions and concerns for STI policy. They have contributed to a growing "securitisation" of STI policies, whose definition is broadly defined to cover a range of issues beyond traditional defence concerns. These include biosecurity, for example, where promising research in fields like synthetic biology carry inherent risks.
- The concept of research security has also strongly emerged in recent years, to counter unauthorised information transfer and foreign interference in public research. OECD governments have put in place measures to improve research security, emphasising the values, norms and principles that constitute good scientific practice.
- Russia's war of aggression against Ukraine has had few direct impacts on STI activities in OECD countries. Nevertheless, OECD countries have levied unprecedented science "sanctions" on Russia and continue to support Ukrainian scientists through a range of policy measures. Ukraine has longstanding "brain drain" challenges, which the war could exacerbate. OECD countries should aim to promote genuine brain circulation and the establishment of sustainable and productive long-term partnerships with Ukrainian scientific institutions.
- The pandemic demonstrates the implausibility of anticipating and addressing all the cascading implications of ongoing and future crises as they emerge and hence the importance of focusing on improving systemic resilience. To manage crises and contribute to society's resiliency, policy needs to be more anticipatory, systemic, inclusive and innovative. Good preparation also calls for a strong "strategic intelligence" capacity to identify, monitor and evaluate emerging risks and responses. Such policy qualities also depend on government capacities that will take time and investment to develop.

Introduction

Longstanding trends and recent disruptions have created a new operating environment for STI policy. Climate change and its impacts, along with the fast pace of change implied by the digital transformation, are driving STI agendas in what is often termed the “twin transition”. At the same time, the two most salient disruptions of the last couple of years – the COVID-19 pandemic and Russia’s war of aggression against Ukraine – have had far-reaching, cascading effects, including on STI. During the pandemic, STI played prominent roles in understanding the virus and its transmission and designing appropriate countermeasures, notably by developing highly effective vaccines over a very short period. The pandemic has also impacted STI, for example, by introducing greater flexibility in R&D funding and boosting open science. Beyond the impacts of advanced weaponry, the role of STI in the war in Ukraine is less prominent or clear-cut. However, the war and ensuing energy crisis have highlighted the need to accelerate the transition from fossil fuels to clean energy sources. Achieving this objective will depend on the rapid deployment of existing or close-to-market green innovation solutions to improve energy security in the short term, as well as boosting investments in R&D to underpin longer-term transitions to net-zero (see Chapter 3).

The significant uncertainty arising from the war in Ukraine adds to the challenges already facing policy makers owing to unexpectedly strong inflationary pressures and imbalances related to the pandemic. In many economies, inflation in 2022 has been at its highest since the 1980s, while rising debt service burdens are also likely to compound challenges for public finances. With recent indicators taking a turn for the worse, the global economic outlook has darkened, with global growth projected to slow even further in 2023 (OECD, 2022[1]).

The chapter begins by discussing two recent disruptions – COVID-19 and Russia’s war against Ukraine – and their impacts on STI. Both the pandemic and Russia’s aggression have required large-scale government interventions to stave off economic crises. The pandemic resulted in the first recession where R&D expenditures have not fallen, largely because of their significant roles in tackling the crisis. It is too early to tell what impact Russia’s aggression will have on R&D expenditures, but there is the possibility their growth will falter in the event of a deep or protracted economic slowdown. The chapter then describes how these disruptions, together with the climate crisis and anxieties related to technological change, have brought risk, uncertainty and resilience to the fore as conditions and concerns for STI policy. They have contributed to a growing “securitisation”[1] of STI policies, where economic competitiveness rationales for policy intervention are now combined with rationales emphasising national security, sustainability transitions and (to a much lesser extent) inclusion. The final section draws some lessons and presents a brief outlook for STI policy in times of global crisis.

STI and the COVID-19 crisis

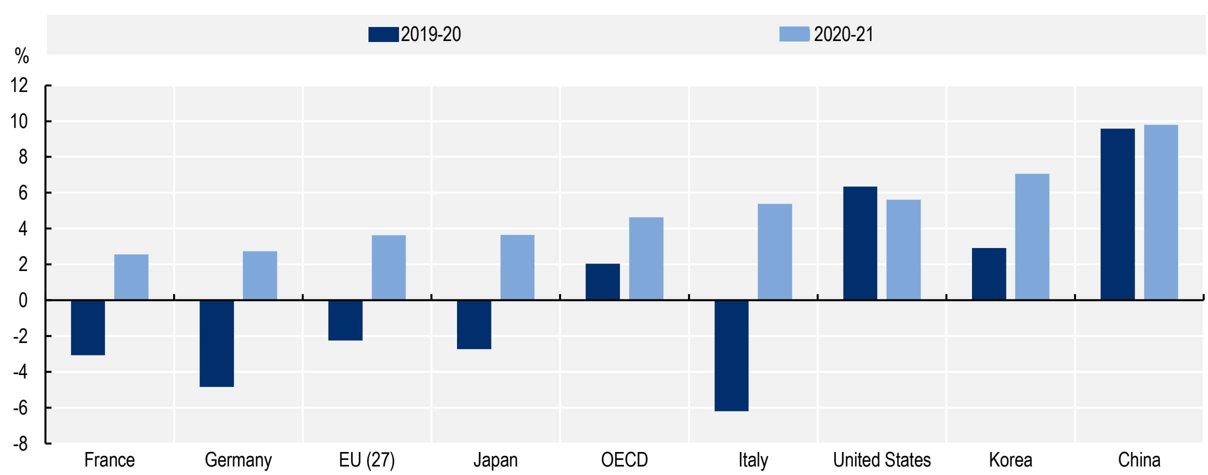
At the time of publication of the last edition of the STI Outlook (OECD, 2021[2]), the COVID-19 pandemic was less than a year old, but the science and innovation community had already responded decisively and at pace. Through multibillion-dollar public and private investments, the first vaccines had already been approved and tens of thousands of scientific articles had been openly published, many reporting on research performed by international teams. At the same time, COVID-19 restrictions were still largely in force, with more to follow during 2021-22. These were having a range of negative impacts, both directly on STI activities and indirectly through their wider social and economic effects, although these were difficult to measure at the time. Two years on, it is possible to get a better sense of the pandemic’s effects on STI activities and how STI responded. Chapter 4 provides an overview of how science was mobilised to respond to the pandemic. This chapter focuses on selected key indicators of R&D expenditures and vaccine developments.

Impact of COVID-19 on R&D expenditures

OECD gross domestic expenditure on R&D (GERD) grew 2.1% between 2019-20 (Figure 1.1). While this was a sharp slowdown compared to previous years (when it was growing at around 5% annually), it was nevertheless exceptional, marking the first time a global recession has not translated into falls in R&D expenditures. This reflects how investments in R&D were an integral part of the response to the pandemic (OECD, 2022[3]). Growth in R&D in the OECD area in 2020 was primarily driven by the United States (+6.4%), in contrast to declining R&D expenditures in Germany (-4.9%)[2] and Japan (-2.7%). Provisional data for 2021 show that OECD growth rates bounced back to pre-pandemic levels, with OECD GERD growing 4.5% between 2020-21. This reflects a recovery in R&D expenditures in many countries that had experienced a decline in the previous year.

Figure 1.1. Growth in gross domestic expenditure on R&D, between 2019-20 and 2020-21

Percentage growth rate in constant price

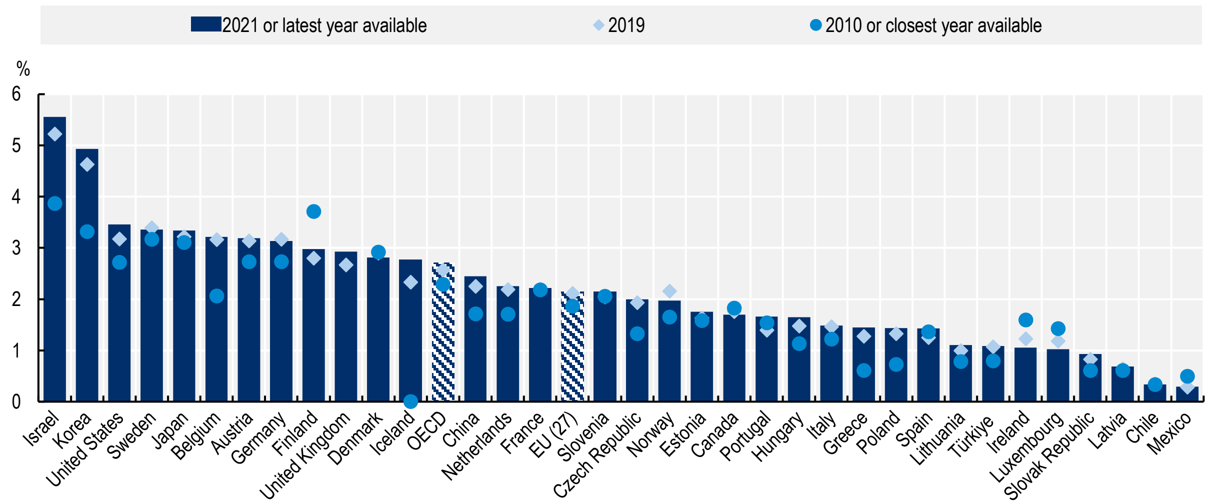


Source: OECD R&D statistics, February 2023. See OECD Main Science and Technology Indicators, http://oe.cd/msti, for most up-to-date indicators

StatLink https://stat.link/fksr1m

Across the OECD, Israel (5.6%) and Korea (4.9%) continued to display the highest levels of R&D intensity as a percentage of GDP (Figure 1.2). R&D intensity in the OECD area climbed from 2.5% in 2019 to 2.7% of GDP in 2021. Over the same period, R&D intensity as a percentage of GDP increased in the European Union (EU27) area from 2.1% to 2.2%, in the United States from 3.2% to 3.5%, and in the People's Republic of China (hereafter China) from 2.2% to 2.4%.

Figure 1.2. R&D intensity: Gross domestic expenditure on R&D as a percentage of GDP



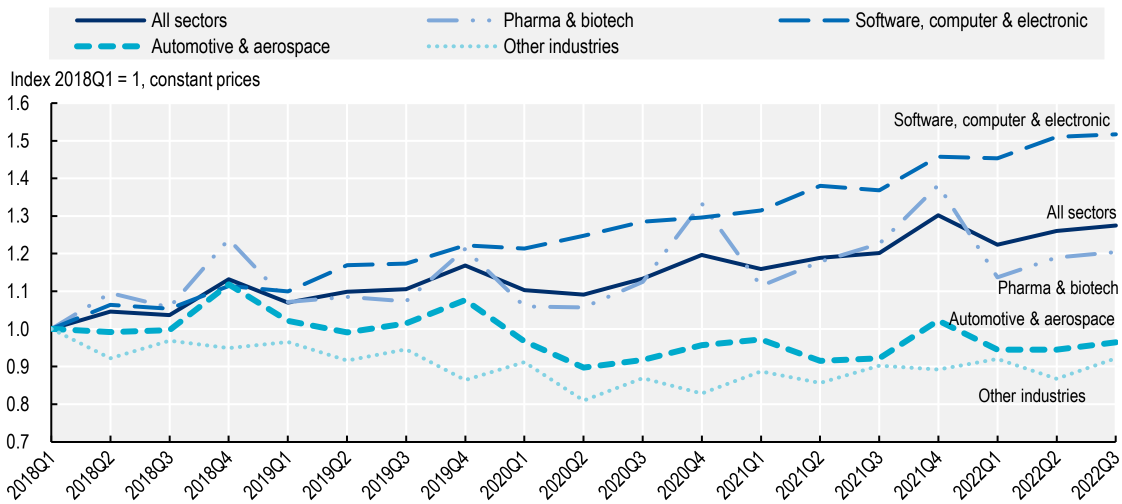
Note: 2021 data corresponds to 2020 for Chile, Colombia, Mexico, Türkiye and United Kingdom. Data for the United Kingdom only available for 2018-20 and preliminary. Following a major data revision by the UK statistical agency conducted in late 2022 and effective only from 2018, back series for previous years have been suppressed from the data available to OECD.
Source: OECD R&D statistics, February 2023. See OECD Main Science and Technology Indicators, http://oe.cd/msti, for most up-to-date indicators.

StatLink https://stat.link/indw0q

Since the private sector accounts for more than two-thirds of R&D expenditures in the OECD, a country's R&D intensity is heavily influenced by the R&D activities of its firms. The OECD Short-term Financial Tracker of Business R&D (SwiFTBeRD) dashboard delivers the timeliest possible insights on company-specific and sectoral quarterly and annual R&D data reported by several of the world's major R&D investors.[3] Analysis of R&D expense growth in 2021 confirms widespread improvement across the board for most companies following the initial pandemic shock in 2020 (Figure 1.3). Software, computer & electronic technology firms and (to a lesser extent) pharmaceutical and biotechnology firms continued to drive R&D expense growth, while automotive and aerospace (along with other industries) were still lagging in 2021. In the first half of 2022, year-on-year aggregate R&D expense growth in the software, computer & electronic technology sector remained at around 10%, while it was almost flat in other sectors. Given these trends, as Figure 1.3 shows, R&D expenses in the software, computer & electronic technology sector were more than 50% higher in mid-2022 as compared to the start of 2018. In the automotive and aerospace sector and other industries, by contrast, R&D expenses had yet to recover to their 2018 levels.

Figure 1.3. Industry R&D trends show variable growth by sector

Index 2018Q1 = 1, constant prices



Note: Reported values are deflated using the GDP price index of the OECD zone. Company reports of R&D expenses need not coincide with R&D expenditures as covered in official R&D statistics compiled according to the Frascati Manual (OECD, 2015). In order to compile the SwiFTBeRD data, the OECD implements a series of adjustments aimed at enhancing comparability, whenever the necessary information is available. Companies presenting their financial results in compliance with the International Financial Reporting Standards (IFRS) capitalise part of their development costs (under some criteria). In the data presented in SwiFTBeRD, capitalised development costs are added to reported R&D expenses, while amortisation of capitalised development expenditures are conversely excluded, provided that the information is available both in the annual and interim reports. In addition, when possible, expenses and impairment of purchased in-process R&D (as well as restructuring R&D costs) are excluded in the SwiFTBeRD figures in order to align as much as possible with R&D conducted in the reference period and deliver more meaningful indicators.
Source: OECD Short-term Financial Tracker of Business R&D (SwiFTBeRD) dashboard, Beta version, 7 December 2022, https://oecd-main.shinyapps.io/swiftberd/ (accessed 8 February 2023).

StatLink https://stat.link/uayc3b

STI policy responses to COVID-19

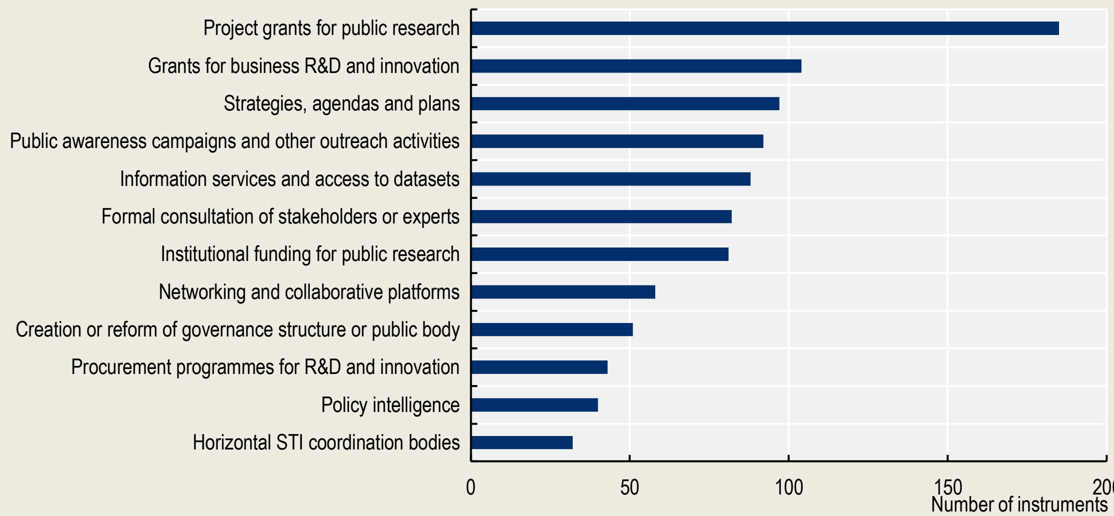
Governments launched hundreds of STI policy initiatives in the first year of the pandemic to develop research and innovation solutions. In the first six months of the pandemic, national public research-funding agencies and organisations announced they were providing more than USD 5 billion for public research-funding schemes targeting COVID-19 (OECD, 2021[2]). Box 1.1 provides a breakdown of the types of policy initiatives that were used.

Box 1.1. What sorts of STI policies did governments use to target COVID-19 and mitigate its effects?

The Science, Technology and Innovation Policy (STIP) Compass "COVID-19 Watch tracker"[1] has collected information on more than 900 STI policy initiatives launched between January 2020 and June 2021. Analysis shows these covered a wide range of target groups using a mix of policy instruments (Barreneche, 2021[4]), notably grant schemes targeting public research, as well as business R&D and innovation. "Soft" instruments, including public awareness campaigns, information services and stakeholder consultation were also used extensively (Figure 1.4).

Figure 1.4. Top 12 policy instruments used in STI policy initiatives targeting COVID-19

Number of policy instruments in the COVID-19 Watch portal of STIP Compass, by type of policy instrument



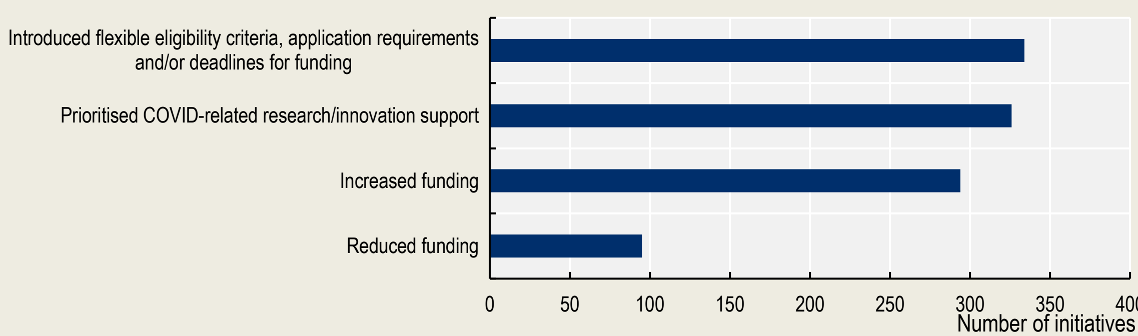
Source: EC-OECD STIP Compass, https://stip.oecd.org (accessed 7 February 2023).

StatLink https://stat.link/6pu7em

More than 90% of STI policy initiatives in the COVID-19 Watch database were launched in 2020.[2] Following this spate of standalone emergency policy measures in the early phases of the pandemic, governments shifted their response to adapting existing policy initiatives. As Figure 1.5 shows, countries participating in the EC-OECD STIP Survey in mid-2021 reported adapting around 15% of all STI policy initiatives to respond to COVID-19. Many programmes and policy initiatives introduced flexible eligibility criteria, application requirements and/or deadlines for funding. Many also prioritised support for research and innovation related to COVID-19. Finally, three times as many initiatives increased funding than decreased it.

Figure 1.5. Shifts in existing STI policies in response to COVID-19

Number of policy initiatives as reported in the EC-OECD STIP Survey, June 2021



Note: Data based on country responses to the EC-OECD STIP Survey 2021, specifically the following question in the "policy initiative fiche": "*Any shifts related to COVID-19*"?

Source: EC-OECD STIP Compass, https://stip.oecd.org (accessed 7 February 2023).

1. https://stip.oecd.org/stip/covid-portal.

2. Of the 932 policy initiatives in the COVID-19 Watch database, just 76 were initiated in the first 6 months of 2021.

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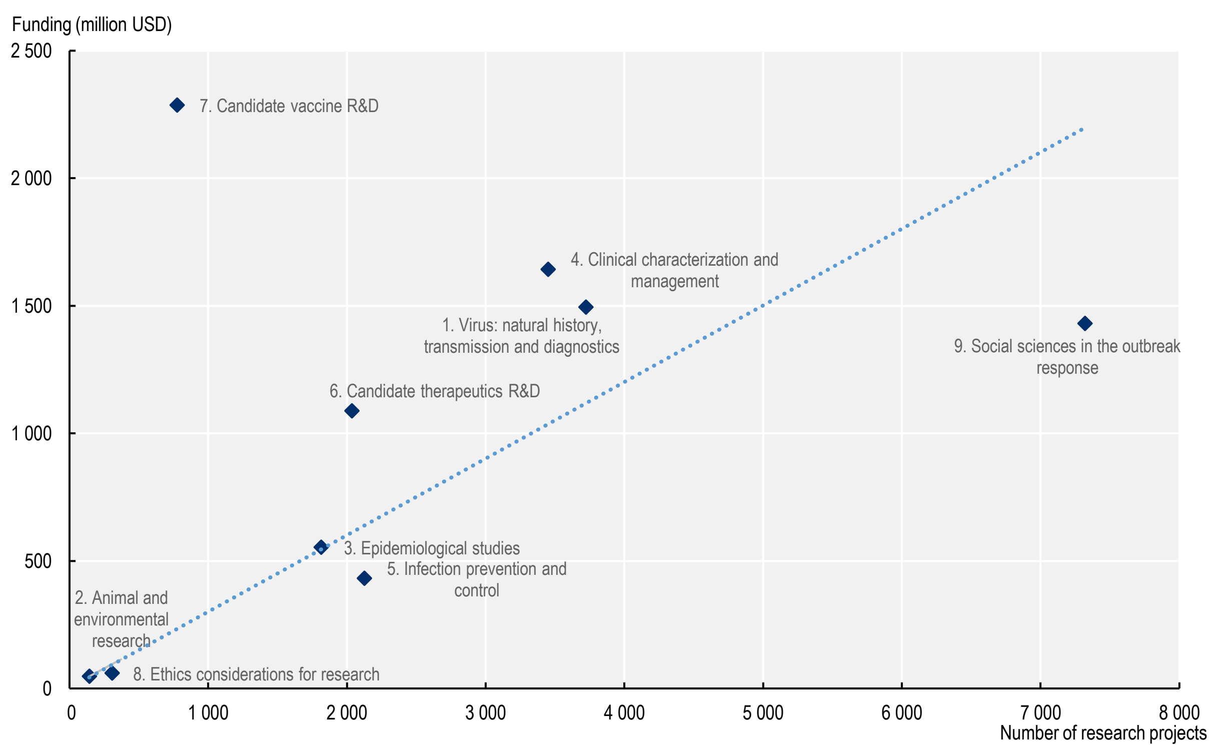
Translating policy initiatives into research funding

The research community translated much of this COVID-19 policy support into funded research projects covering a variety of topics. The UK Collaborative on Development Research (UKCDR)[4]/GloPID-R COVID-19 Research Project Tracker has collected data on almost 18 000 research projects with funding of over USD 8 billion between the start of the pandemic and September 2022.[5] The tracker maps research projects against the priorities identified in the World Health Organization (WHO) Coordinated Global Research Roadmap for COVID-19 (WHO, 2020[5]) to help funders and researchers prioritise resources for underfunded areas with the greatest research need. This mapping against the WHO priorities shows that 4% of research projects in the database target vaccine R&D yet account for 25% of the awarded funding, while 36% target the social sciences yet account for 16% of funding (Figure 1.6).[6]

Such comparisons should be interpreted with care. For example, it is well established that social science projects typically rely on less funding than their science, technology and engineering counterparts. There also exists evidence that the social sciences and humanities were less well organised than their biomedical counterparts to respond effectively to the demands of a complex crisis like COVID-19 (see Chapter 4 for further discussion on the subject). The real outlier, however, is the scale of support for vaccine research, as compared, for example, to research on candidate therapeutics, which accounted for around 12% of total funding (approximately USD 1 billion) and 10% of research projects, with an average project size of approximately half a million USD. This reflects the high priority given to the development and availability of vaccines, particularly in the early phases of the pandemic, where infection prevention was greatly emphasised. Ongoing OECD work on mapping government R&D project funding for COVID-19 provides a picture consistent with these findings (OECD, forthcoming[6]).

Figure 1.6. COVID-19 funded research projects mapped against WHO "research priorities"



Note: Some projects have been assigned to more than one WHO priority area. There are 20 272 projects included in total.
Source: OECD calculation, based on data from the UKCDR and Global Research Collaboration for Infectious Disease Preparedness (GloPID-R) COVID-19 Research Project Tracker, https://www.ukcdr.org.uk/covid-circle/covid-19-research-project-tracker/ (accessed 15 February 2023).

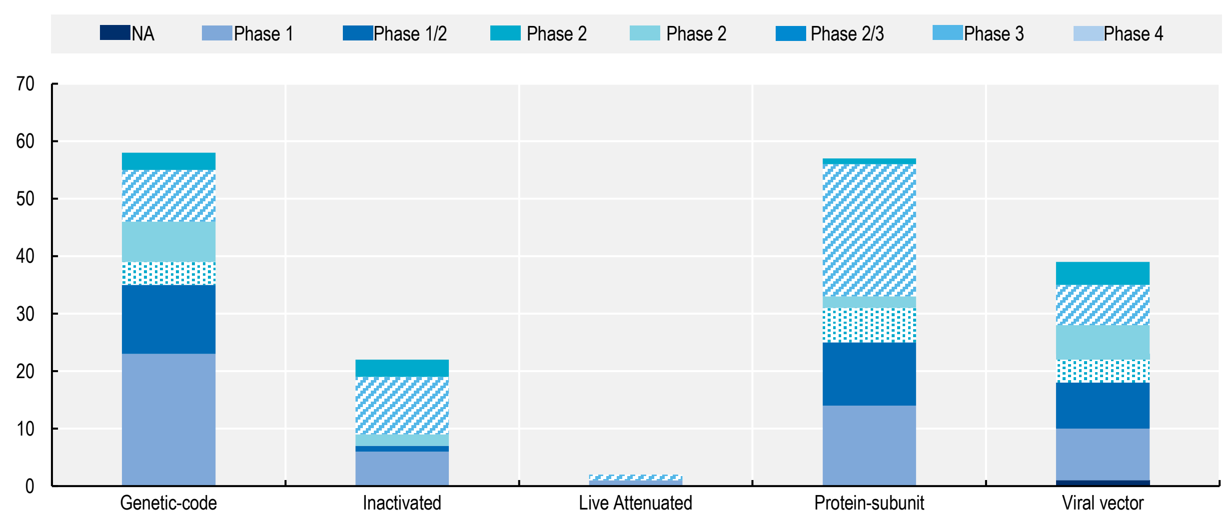
StatLink https://stat.link/icpan2

Translating research into COVID-19 knowledge and vaccines

The 2021 edition of the STI Outlook (OECD, 2021[2]) highlighted the rapid and massive response of the research community to the pandemic, as measured by bibliometric analysis and the progress of clinical trials. Already at the time of writing in late 2020, the first COVID-19 vaccines were in the final stages of approval and about to be launched. Two years on, several effective vaccines have been developed using different technologies (Figure 1.7) and tested and rolled out in record time. This is an outstanding demonstration of what can be done when academia and industry effectively combine resources (see Chapter 4). The creation of different – and often novel – vaccine platforms is also a welcome development that could have far-reaching benefits across medical science. It is estimated that COVID-19 vaccines had saved 20 million lives by mid-2022, although this number could have been greater if vaccine coverage had been more equitable (Watson et al., 2022[7]). The earliest COVID-19 vaccines continue to dominate the marketplace and there are now fewer new vaccines under development than in the first half of 2022 (Figure 1.8).

Figure 1.7. COVID-19 vaccine candidates, by technology platform and clinical trial phase

Number of vaccines under development



Note: The “live attenuated” technology platform corresponds to vaccines that use a weakened version of the virus that replicates without causing disease. “Inactivated” vaccines are a version of the actual virus grown and chemically inactivated. “Viral vector” vaccines are based on another virus with spike protein which has been disabled from replication. “Protein-subunit” vaccines are based on viral subunits expressed via various cell lines to stimulate immune response. “Genetic-code” vaccines use deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) to create antigens for the immune system to target. Definitions taken from https://sidp.org/resources/Documents/COVID19/Jeannettee%20Bouchard%20General%20Information%2012.28.2020.pdf.

Source: OECD calculations based on WHO, https://www.who.int/teams/blueprint/covid-19/covid-19-vaccine-tracker-and-landscape (accessed 6 February 2023).

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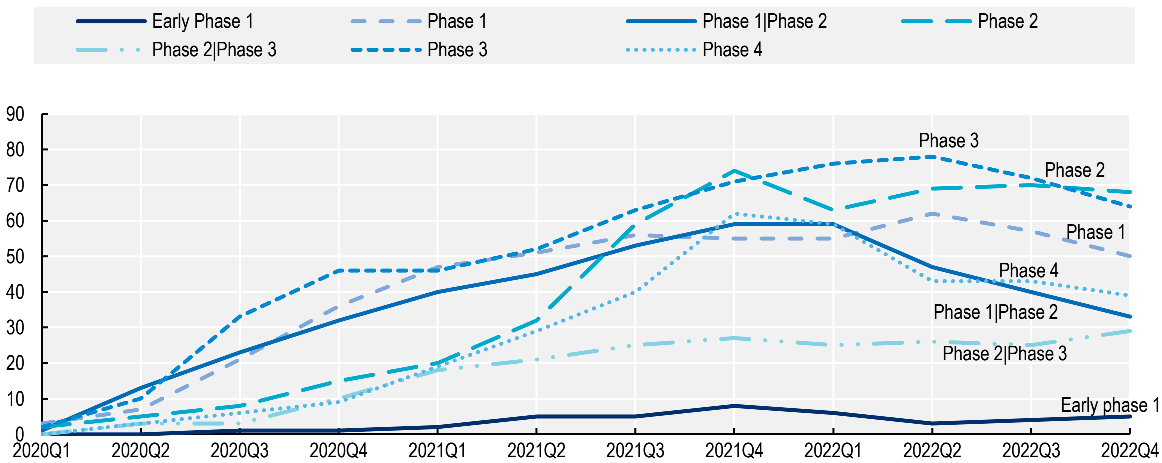
Figure 1.8. Trends in registered COVID-19 vaccine studies, by clinical trial phases

Numbers of clinical trials by phases, January 2020 to December 2022



Note: Biomedical clinical trials of experimental drug, treatment, device or behavioural intervention may proceed through four phases. Phase 1: Clinical trials test a new biomedical intervention in a small group of people (e.g. 20-80) for the first time to evaluate safety (e.g. determine a safe dosage range and identify side effects). Phase 2: Clinical trials study the biomedical or behavioural intervention in a larger group of people (several hundred) to determine efficacy and further evaluate its safety. Phase 3: Studies investigate the efficacy of the biomedical or behavioural intervention in large groups of human subjects (from several hundred to several thousand) by comparing the intervention to other standard or experimental interventions, as well as monitoring adverse effects and collecting information that will allow the intervention to be used safely. Phase 4: Studies are conducted after the intervention has been marketed. These studies are designed to monitor the effectiveness of the approved intervention in the general population and collect information about any adverse effects associated with its widespread use. Definition of phases from the WHO glossary: https://www.who.int/clinical-trials-registry-platform.
Source: OECD calculations based on United States National Institutes of Health (NIH), ClinicalTrials.gov, https://clinicaltrials.gov/ct2/results/map?term=AREA%5BInterventionType%5D+%28Drug+OR+Biological%29&cond=COVID-19&intr=vaccine (accessed 18 January 2023).

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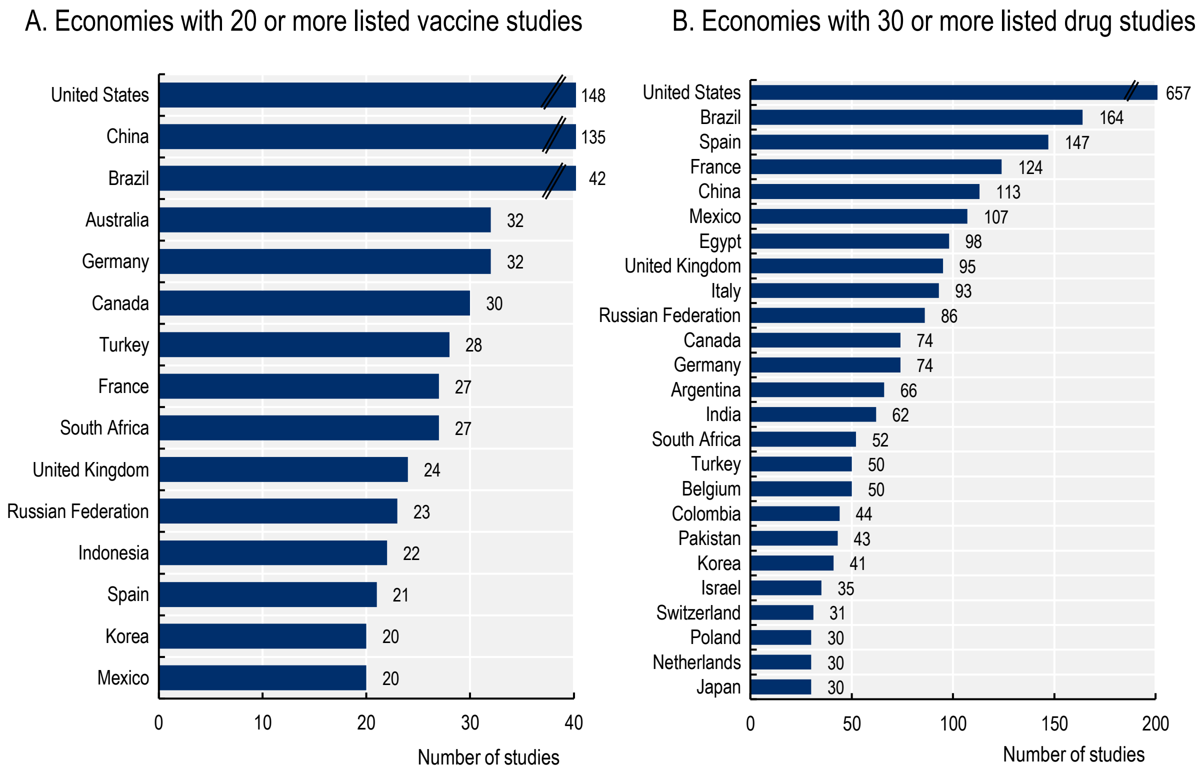
Figure 1.9 shows the number of COVID-19-related clinical studies, as registered with the United States National Institutes of Health (NIH) by September 2022. Panel A shows that the United States, followed by China, have by far the most COVID-19 vaccine clinical studies. Between them, they have more vaccine studies than the next nine ranked countries combined. Panel B shows the United States to be an outlier on COVID-19 drug studies with more than 650 studies, compared to 164 studies for second-placed Brazil. This concentration is partly explained by country size, but the data also show that clinical trials have been carried out widely across the world. A criticism of the biomedical response to COVID-19 is that there were too many uncoordinated clinical studies and too few clinical trials with sufficient participants to draw statistically significant conclusions (see Chapter 4). So the large number of clinical studies shown in Figure 1.9 should not necessarily be interpreted as a wholly positive development.

Figure 1.9. Registered COVID-19 vaccine and drug studies by economy, as of 6 February 2023



Note: The charts show the numbers of COVID-19 studies registered at the NIH (ClinicalTrials.gov). The International Committee of Medical Journal Editors requires trial registration as a condition of the publication of research results generated by a clinical trial. Multi-economy registered studies are counted in each economy. Note that the number of studies is not necessarily indicative of the breadth or depth of the studies conducted within each territory.
Source: NIH, ClinicalTrials.gov (accessed 6 February 2023).

StatLink https://stat.link/q80nsb

At the same time, vaccine competition between governments has been rife and influenced in part by geopolitical tensions, creating a global patchwork of vaccine approvals. By mid-2022, China had approved eight vaccines, all but one developed domestically; Russia had approved six vaccines, all developed domestically; and France, Japan and the United States had yet to approve any Chinese, Indian or Russian-developed vaccines (Table 1.1). The dominant vaccine narrative has been compared to the historical space or nuclear arms "races", despite the pandemic being a global challenge (Wilson Center, 2022[8]). The vaccine "nationalism" and "diplomacy" that some countries pursued raises serious concerns about strategic competition in other technology areas and the prospects for future STI co-operation on global challenges (like climate change). Chapter 2 further discusses this issue.

Table 1.1. Approval of selected vaccines in selected countries, as of July 2022

	United States	France	Japan	Mexico	Brazil	China	India	Indonesia	Russia	South Africa
Johnson & Johnson (USA)	√	√	√	√	√		√	√		√
Moderna (USA)	√	√	√	√			√	√		

Pfizer/BioNTech (USA/Germany)	√	√	√	√	√	√		√		√
Oxford/AstraZeneca (UK)		√	√	√	√			√		
Sinopharm/Beijing (China)				√		√		√		√
Sinovac (China)				√	√	√		√		√
CanSino (China)				√		√		√		
Covaxin (India)				√	√		√			
Sputnik V (Russia)				√	√		√	√	√	

Note: USA = United States; UK = United Kingdom.
Source: OECD analysis based on UNICEF COVID-19 Market Dashboard data, https://www.unicef.org/supply/covid-19-market-dashboard (accessed 25 September 2022).

Outlook on COVID-19 and STI

The COVID-19 pandemic is not yet over, and its far-reaching consequences will unfold well into the future. Further variants of concern could emerge, requiring a continuous stream of updated vaccines until vaccinology develops more universal protection (International Science Council, 2022[9]). Disparities in access, distribution and uptake of vaccines remain a major source of uncertainty, given that new variants are more likely to arise from unvaccinated and immunocompromised people. By mid-2022, the WHO estimated that almost one billion people in low-income countries remained unvaccinated.[7] This was not due to a lack of vaccine supply – as was the case in much of 2021 – but to rollout problems caused by operational and financial capacity gaps, insufficient political commitment, and vaccine hesitancy driven by misinformation and disinformation.

Multilateralism is key for effective responses to the pandemic

Effective multilateral actions are still required to provide technical and financial assistance that will help overcome the myriad domestic logistical hurdles facing COVID-19 vaccine deployment. To review experiences gained and lessons learned from the international health response to COVID-19, the WHO set up an Independent Panel for Pandemic Preparedness and Response in late 2020. The panel published its main report in May 2021, identifying weak links at every point in the chain and recommending a package of reforms to transform the system to enhance pandemic prevention, preparedness and response. A one-year review of progress that followed in May 2022 lamented the lack of investment, co-ordination and ambition to transform the system, resulting in limited and inequitable access to COVID-19 vaccines, tests and therapies (Johnson Sirleaf and Clark, 2022[10]). Estimates vary, but recent research suggests that more than one million lives could have been saved in 2021 alone if COVID-19 vaccines had been shared more equitably with low- and middle-income regions (Ledford, 2022[11]). More recently, limited supplies and the high costs of COVID-19 antivirals have similarly restricted their flow to low-income countries (Ledford, 2022[12]).

Efforts have been made to expand equitable access to COVID-19 vaccines, notably through firms' non-profit agreements (e.g. the Oxford-AstraZeneca partnership), voluntary licensing arrangements (e.g. the Medicines Patent Pool), and the scale-up of local manufacturing capacity in low- and middle-income countries (e.g. plans by Moderna and BioNTech to set up manufacturing in Africa). However, the global architecture to provide access to vaccines, diagnostics and genomic sequencing – notably the Access to COVID-19 Tools (ACT) Accelerator, which includes COVAX – has not met expectations, owing to insufficient funding, wealthier-country hoarding and logistical challenges, among other factors (Johnson Sirleaf and Clark, 2022[10]).

Several OECD countries have announced substantial STI investments to improve pandemic prevention, preparedness and response. For example, Japan recently set up the Strategic Center of Biomedical Advanced Vaccine Research and Development for Preparedness and Response (SCARDA), which will invest in vaccine research on a range of pathogens (including coronaviruses) using a range of technologies for vaccine delivery. With an initial investment of USD 2 billion over five years, SCARDA aims to produce diagnostic tests, treatments and vaccines that will be ready for large-scale production within the first 100 days following the identification of a pathogen with pandemic potential (Mallapaty, 2022[13]). Investments have also been made in antiviral therapeutics. For example, the US National Institute of Allergy and Infectious Diseases launched the Antiviral Drug Discovery Centers for Pathogens of Pandemic Concern in 2021, endowed with USD 1.2 billion to fund basic research on developing antivirals for seven virus families (Kozlov, 2022[14]). Drawing on a philanthropic donation of AUS 250 million (Australian dollars), the Cumming Global Centre for Pandemic Therapeutics in Australia was launched in 2022 to create drugs within weeks or months of future infectious disease outbreaks (Nelson, 2022[15]). What characterises these new centres is the range of drug platforms they plan to exploit to deal rapidly and in multiple ways with an array of microbial threats.

These are welcome new investments in OECD countries, but a co-ordinated response is also needed to promote longer-term vaccine and therapeutic innovation that includes technical, production and quality-control capacities in low-income countries (International Science Council, 2022[16]). The uneven distribution of research infrastructure capacities at the global level has prevented equitable access to resources and data in many parts of the world, contributing to a disconnect between needs and resources (see Chapter 4). Moreover, the study of COVID-19 variants is largely concentrated in high-income and upper-middle-income countries, even though several dominant variants were first identified in low- and middle-income countries.[8] If global vaccination coverage remains unequal, it will be important to develop research capacity that includes more low-income countries, in order to investigate the emergence of variants (UKCDR and GloPID-R, 2022[17]). Research funders have recognised the problem, allocating around USD 200 million globally for COVID-19 projects aiming to strengthen research capacity. Most of these projects focus on reinforcing laboratory capacity in low- and middle-income countries (UKCDR and GloPID-R, 2022[18]). Such a strengthening of research capacity is an important contribution to health-crisis preparedness, but should be extended to provide effective global action for other ongoing and future crises, notably the climate crisis and the need for green transitions. As highlighted in Chapter 4, many countries and organisations have started their own evaluations of their response to COVID-19, and STI performance and future preparedness should be an important focus of such exercises.

The pandemic is a sociopolitical challenge that creates multiple risks and uncertainties

Like all health crises, COVID-19 is a broader sociopolitical challenge, but was widely perceived at the outset as a mainly biomedical challenge. In most countries, the biomedical community and its relevant research-funding institutions took the lead in establishing national research agendas. These were too narrowly focused and failed to address all aspects of the crisis from a scientific perspective (see Chapter 4). Furthermore, the pandemic's health impacts have gone well beyond those associated with the SARS-CoV-2 virus: public health interventions targeting COVID-19 often caused disruptions in healthcare delivery for other conditions, including cancer and heart disease, while access to immunisation services for common childhood illnesses fell in many low- and middle-income countries (UKCDR and GloPID-R, 2023[19]). The WHO (2022) also estimates that the global prevalence of anxiety and depression increased by 25% during the first year of the pandemic.

"Long COVID" is another uncertainty, with a persisting lack of consensus on a clear definition of the condition, its clinical characterisation and management, and appropriate support for sufferers. According to data from UKCDR and the GloPID-R COVID-19 Research Project Tracker (UKCDR and GloPID-R, 2022[20]), at least USD 218 million targeted long COVID research as of September 2022, with projects largely concentrated in Europe (48%) and North America (39%).

Finally, mis- and disinformation have been particularly problematic globally (see Chapter 4 and (OECD, 2022[21]), with studies showing a directional relationship between online misinformation and vaccine hesitancy (e.g. (Pierri et al., 2022[22]). As highlighted in Chapter 4, this is a complex problem with no easy solution. Policy responses range from improving the digital and scientific literacy of citizens and policy makers, to promoting active involvement by behavioural and social scientists to provide the necessary background for communicating relevant and useful information to different communities.

STI and Russia's war of aggression against Ukraine

Both Russia and Ukraine are relatively minor players in the international STI landscape, so that the war has had few direct impacts on STI activities in OECD countries. Russia's relative scientific decline in recent decades has made it easier for OECD countries to sever their ties without seriously undermining their own scientific efforts (Johnson Sirleaf and Clark, 2022[10]). The European Union quickly excluded Russia from Horizon Europe following the invasion. Some months later, the United States announced its intention to wind down government-to-government research collaboration with Russia, and advised US agencies and government labs to curtail interaction with the leadership of universities and institutions affiliated with the Russian government (Hudson, 2022[23]).

Science "sanctions" like these are unprecedented, and form part of a wider campaign of economic and trade penalties that are meant to deter Russia (Hudson et al., 2022[24]). It is too early to assess their impacts on Russian science, but there exist STI areas where Russia excels and has strong ties with STI activities by OECD countries, which have been adversely affected by these sanctions. In the space sector, for example, where Russia has deep and extensive capabilities (Undseth and Jolly, 2022[25]), the ExoMars project, a EUR 1.3 billion (euros) joint Europe-Russia mission, has been severely delayed. In Arctic research – much of which is crucial to understanding and monitoring climate change – European scientists have had to suspend collaboration with their Russian counterparts owing to restrictions imposed by their funding agencies or institutions (Gaind et al., 2022[26]).

Besides these disruptions in particular STI fields, the indirect impacts on STI are far greater. The projected economic slowdown in 2023, and the highest rates of inflation seen since the 1980s, could impact STI expenditures. Rising debt service burdens are also set to compound challenges for public finances (OECD, 2022[1]), which could put further pressure on public funding of R&D. The goal of reducing reliance on fossil-fuel supplies from Russia has also lent new urgency to STI investments in clean energy and energy efficiency. Fossil-fuel dependency on Russia has more immediate impacts, however, with scientific infrastructures in Europe – notably particle accelerators, high-power lasers, gamma beams, and supercomputing facilities and data centres – facing massively increased energy bills. This is leading some infrastructures to cut back on experiments (Owens, 2022[27]), (Zubașcu, 2022[28]). The spectre in late-2022 of energy rationing and even rolling blackouts has not materialised, however, although it has drawn greater attention to reducing the carbon footprint of science.[9]

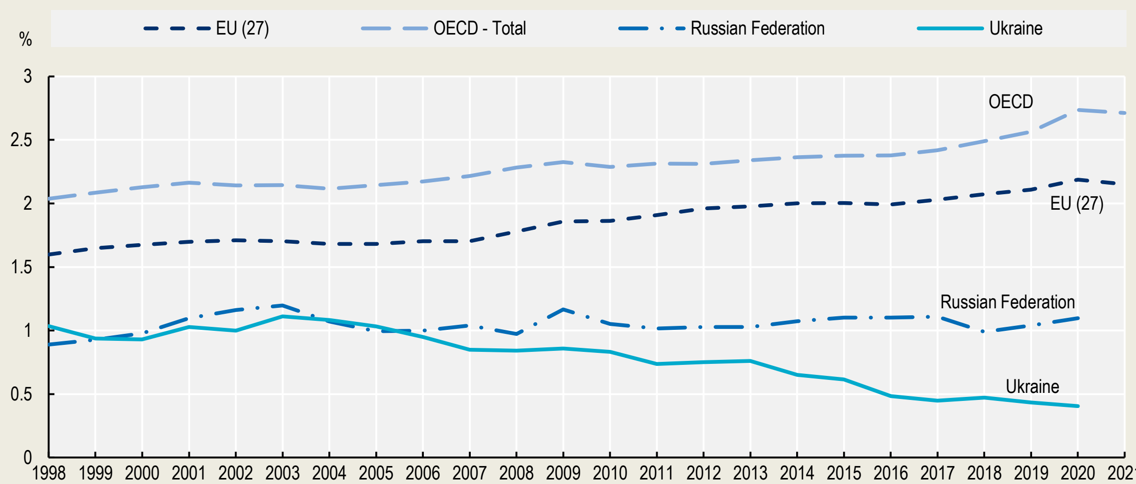
Impacts on STI activities in Ukraine

The impacts of the war on Ukraine's STI activities have been devastating. Many of its research institutions have been bombed, and around one-quarter of its research workforce fled the country in the early months of the conflict (Nature, 2022[29]). By October 2022, with Russian attacks on Ukraine's critical civilian infrastructures, like electricity and water, scientific experiments had become almost impossible. Box 1.2 provides a snapshot of Ukraine's science system in recent years, showing a system in transition prior to Russia's aggression.[10]

Box 1.2. Ukraine: A science system in transition, with core strengths

For several years prior to Russia's war of aggression in Ukraine, science and research in Ukraine had been in transition, with significant structural changes taking place in the face of strong budgetary pressure. Domestic expenditure on R&D as a percentage of GDP fell by about one-third between 2013 and 2018 (Figure 1.10). The number of researchers shrank from over 52 000 full-time equivalents in 2013 to 41 000 in 2018. This evolution was marked by a steep drop in researchers working in business and government institutions, which was only partly offset by an increase in researchers from higher education institutions.

Figure 1.10. Domestic R&D expenditure as a percentage of GDP (Ukraine, Russia, EU27 and OECD)



Note: OECD R&D statistics and UNESCO Institute for Statistics (UIS) for Ukraine, February 2023.

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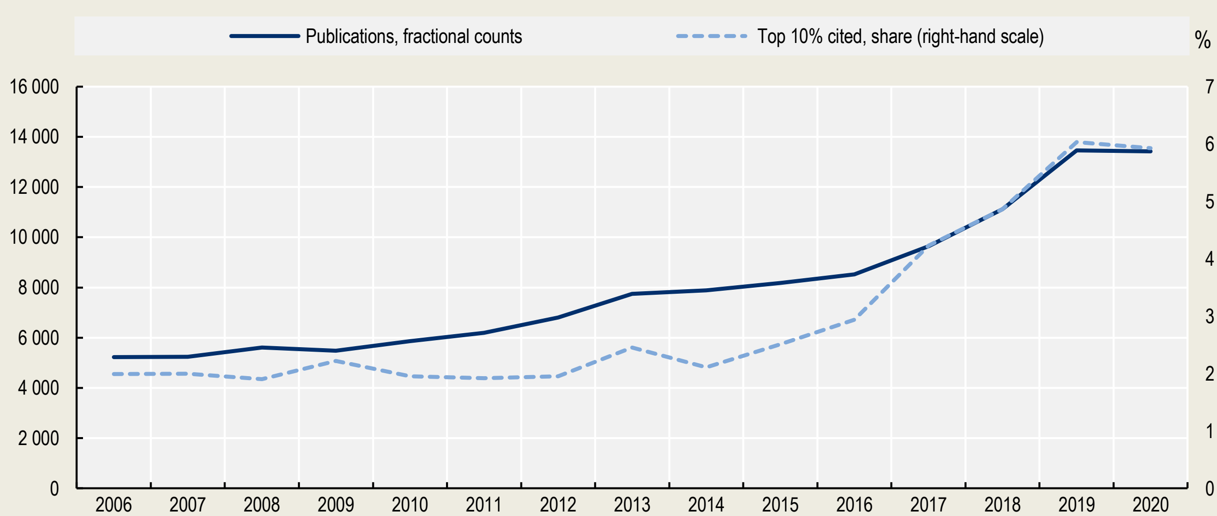
This reorientation towards higher education, together with an increase in international collaborations, helps explain an impressive rise in both the number and quality of Ukrainian scientific publications, from only 2% among the global top 10% most cited in their fields in 2006 to 6% in 2020 (Figure 1.11).

Figure 1.11. Quantity and citation impact of scientific production in Ukraine, 2006-20



Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 5.2021, September 2021, https://public.flourish.studio/story/1266872/; https://public.flourish.studio/story/1458190/; and https://public.flourish.studio/story/1458190/ (accessed on 23 November 2022).

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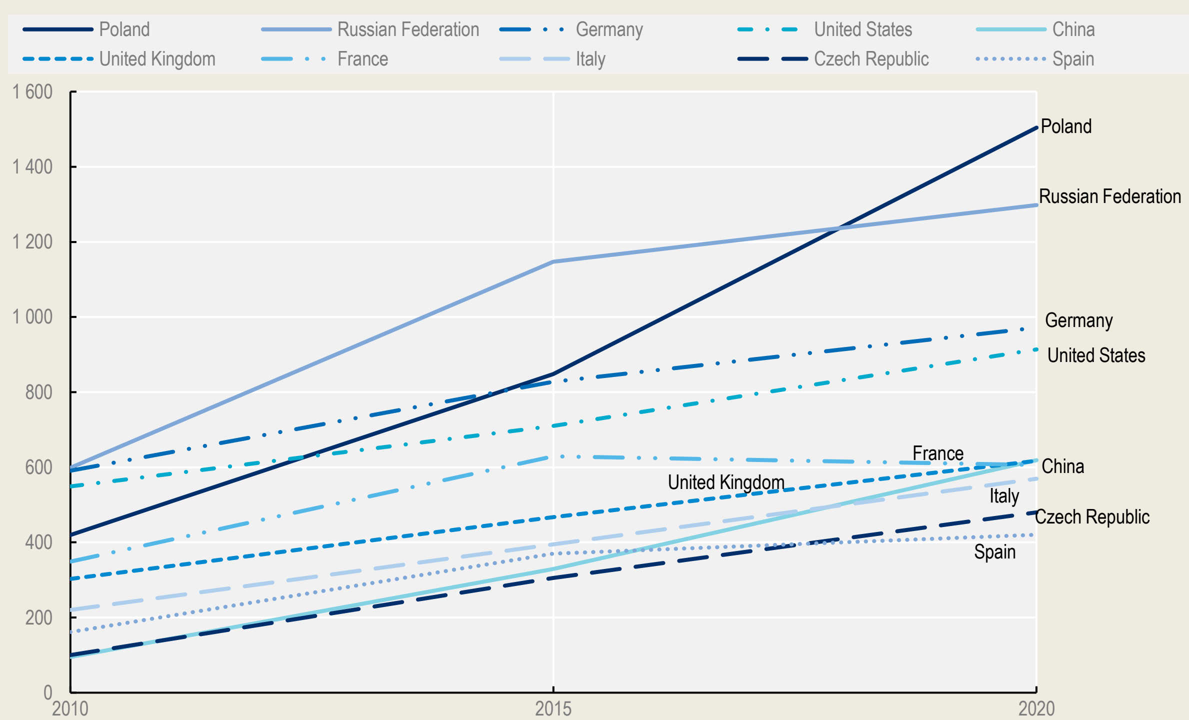
Ukrainian scientific output shows above-average specialisation and expertise (proxied by citation impact) in areas such as computer science and energy (Ukrainian nuclear engineers are involved in new nuclear build programmes around the world). Although less specialised, Ukrainian scientific output also excels in the areas of Earth and planetary sciences and environmental science, although engineering is the largest field in terms of total output. All these domains are closely linked to Ukrainian industry and are crucial to economic development. As reported in the EC-OECD STIP Compass, Ukraine's main thematic STI policy strategies in 2021 focused on aerospace[11] and artificial intelligence (AI).[1]

A significant proportion of Ukraine's scientific publication output has resulted from international collaborations and partnerships. Since 2014, Ukraine has managed to halt the progressive decline in international collaboration seen in previous years, which likely played an important role in raising the overall competitiveness of its science. There has been a strategic focus in Ukraine on building international partnerships, as well as shifts in collaboration patterns. Russia-based scientists used to be the most frequent partners for Ukraine-based authors, but Polish-based scientists have emerged more recently as preferred partners (Figure 1.12).

Figure 1.12. Ukraine's top scientific collaboration partners, 2010, 2015 and 2020

Whole counts: Number of documents co-authored with partner country



Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 5.2021, September 2021, https://public.flourish.studio/visualisation/9410350/ (accessed 23 November 2022).

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As reported in the 2021 edition of the EC-OECD STIP Compass,[2] one of the key structural problems hindering Ukrainian research and innovation activity prior to the war was the persistent net outflow of talented scientists and inventors. This led to a debate on ways to support these valuable human resources in the country and prevent "brain drain". Indeed, analysis of changes in affiliations of scientific authors over 2010-20 reveal that Ukraine had a bilateral deficit with most countries where high mobility was observed, particularly Russia. The war is certain to change the longer-term mobility patterns of many Ukrainian students and scientists, with long-lasting impacts.

1. https://stip.oecd.org/stip/interactive-dashboards/policy-initiatives/2021%2Fdata%2FpolicyInitiatives%2F99993318.
2. https://stip.oecd.org/stip/interactive-dashboards/countries/Ukraine.
Source: (OECD, 2022[30]).

International support for Ukrainian STI

Many countries and scientific institutions have put in place various arrangements to support Ukraine's science system (OECD, 2022[30]). These include temporary measures to host Ukrainian students and researchers, providing safe havens in which they can continue their studies and conduct research. For example, the European Commission's Horizon Europe programme made available EUR 25 million early in the crisis to facilitate and enable this support, and address the immediate and urgent humanitarian challenge.[12] The European Commission has also launched a one-stop-shop for information and support services provided to Ukraine-based researchers and researchers fleeing Ukraine.[13] On the innovation front, the European Innovation Council has agreed to provide a total EUR 20 million in funding to the Ukrainian innovation community. It will provide up to EUR 60 000 in direct financial support to at least 200 Ukrainian technological start-ups that remain and work in Ukraine, as well as to those that relocate to the European Union during the war (Council, 2022[31]).

Solidarity is pervasive at the global level, as demonstrated by the inventory of offers of assistance and statements of support from science organisations.[14] For instance, the Polish Academy of Sciences, with support from the US National Academies of Science, has launched an initiative to help Ukrainian researchers settle in neighbouring Poland.[15] Many refugee scientists and students have already been accepted into Polish research institutions. This offers an opportunity to step up scientific partnerships between these two countries, with immediate benefits for Poland and longer-term possibilities for Ukraine. However, Poland will require support and solidarity from other countries and the European Union if it is to effectively perform this temporary hosting role. This includes support for those who choose to return to Ukraine and promoting new sustainable, long-term partnerships between research institutions, to be maintained once the war is over (OECD, 2022[30]).

As highlighted in Box 1.2, Ukraine has longstanding "brain drain" challenges, which the war could exacerbate. There is a long history of scientists leaving their home countries during times of conflict or political crisis, and then struggling to return or contribute effectively as a diaspora once the crisis is over. In an ultra-competitive international science system, where talent is at a premium, many of the best Ukrainian scientists or students may be tempted to stay in their new homes rather than return to institutions that have been subjected to the ravages of war. At the individual level, this would be a very legitimate and understandable choice. The long-term policy aim should be to support genuine brain circulation and partnership between neighbouring countries, rather than pursuing brain gains at the expense of other countries (OECD, 2022[30]).

The OECD has highlighted the following key considerations for policy makers (OECD, 2022[30]):

- Considering the risks posed by "brain drain" to the future of science in Ukraine, OECD countries should aim to promote genuine brain circulation, and the establishment of sustainable and productive long-term partnerships with Ukrainian scientific institutions.[16]
- Individual mobility and international networks can provide the basis for productive future partnerships between Ukrainian research institutes and universities and their counterparts across the world.

- Policy measures to support refugee scientists from Ukraine should be designed from the outset to ensure they are able to maintain strong links with their home institutions and colleagues, so that the current brain exodus can be rapidly reversed once the war is over.
- Members of the Ukrainian scientific diaspora should be considered as a strategic asset both for their country of origin and their country of destination. With appropriate support, they can play an important role in brokering or building partnerships.
- Digital tools and open access to scientific data and publications can provide the basis for much research to continue remotely, even when research institutions are closed or scientists are also contributing to the war effort.

A growing "securitisation" of STI policy?

Russia's war of aggression against Ukraine is expected to lead to increased expenditures on defence R&D. However, perceived security threats go well beyond traditional defence concerns, extending to a range of issues that have implications for STI policy. These include:

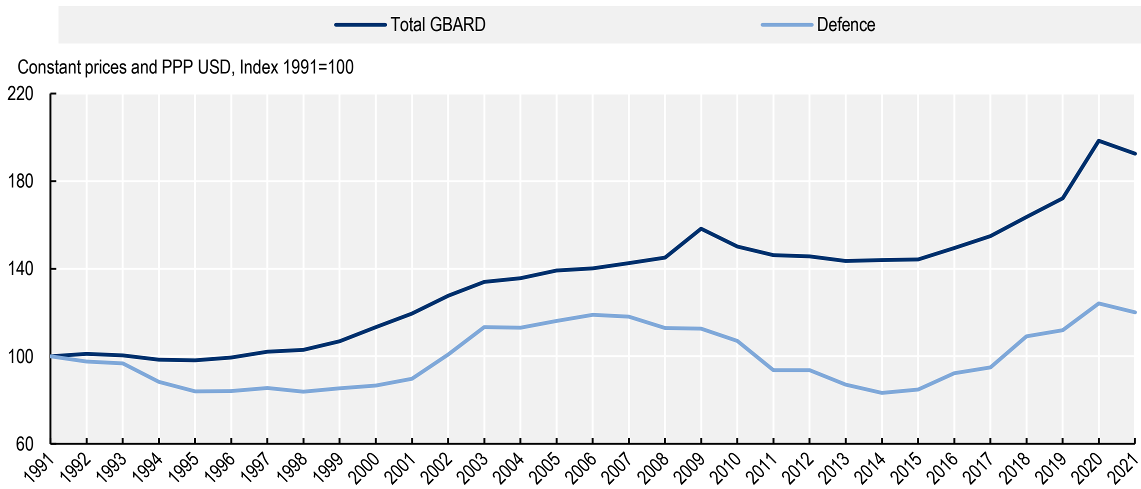
- using STI to reduce systemic risks, e.g. to enhance food security, energy security, health security and cybersecurity
- managing technological change responsibly to reduce a range of risks, e.g. those associated with AI, synthetic biology and neurotechnology
- mitigating and adapting to the climate crisis, which is increasingly framed in terms of the threats it poses to national security
- reducing vulnerabilities from trade dependencies in high-tech and other strategic goods, leading to a push for "technology sovereignty" and "open strategic autonomy".

Together with the impacts of the pandemic, these pressures have drawn attention to risk, uncertainty and resilience as conditions and concerns for STI policy. They have contributed to a growing "securitisation" of STI policies, where economic competitiveness rationales for policy intervention interact with rationales emphasising national security, sustainability transitions and (to a much lesser extent) inclusion. Chapter 3 discusses the rationales for sustainability transitions and their implications for STI policies. This chapter discusses selected security concerns, specifically regarding defence R&D expenditures, biosecurity and research security. Chapter 2 covers how security concerns related to technology dependencies are increasingly framing STI policy agendas through concepts such as "technology sovereignty" and "open strategic autonomy".

Defence R&D spending

Russia's war of aggression against Ukraine has cast a spotlight on the role of science and technology in defence. Discovering, developing and utilising advanced knowledge and cutting-edge systems is fundamental to maintaining or achieving a technological edge for purposes of defence and deterrence. OECD statistics on GBARD (OECD, 2022[3]) provide some insights on the extent to which governments direct public funds to R&D for military purposes. They show that defence R&D, which has grown the least in real terms since 1991, has been experiencing a sustained recovery in recent years (Figure 1.13). With total defence expenditures expected to increase in several OECD countries in the coming years, the recovery in defence R&D expenditures could gather pace.

Figure 1.13. Trends in total and defence government R&D budgets 1991-2021



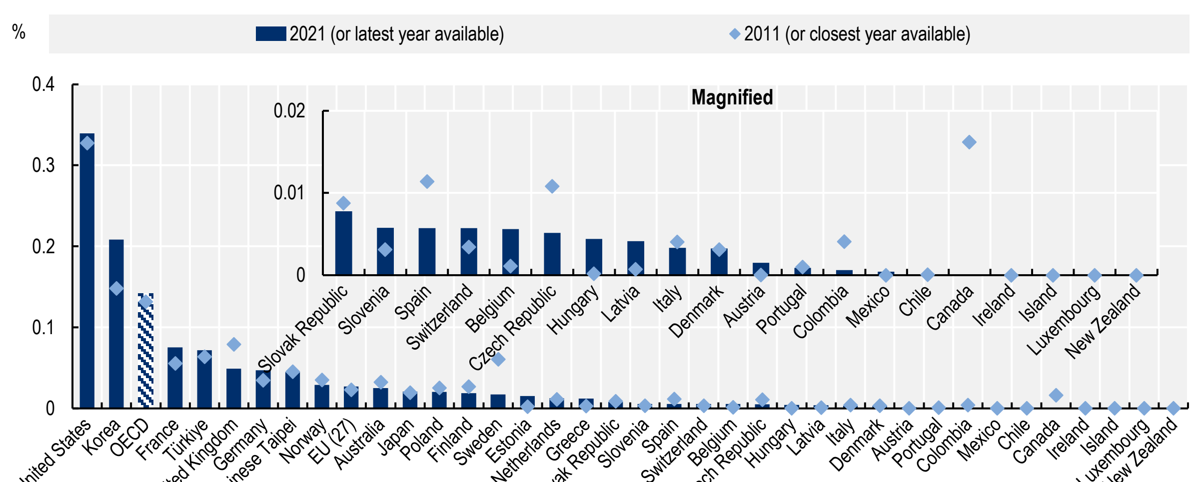
Note: The OECD estimation includes all Member countries of the OECD except Costa Rica.
Source: OECD R&D statistics, September 2022 (accessed 27 November 2022). See OECD Main Science and Technology Indicators Database, http://oe.cd/msti, for most up-to-date OECD indicators.

StatLink https://stat.link/ki7h8b

Across the OECD, an estimated 0.15% of GDP is dedicated to defence R&D budgets (OECD, 2022[3]). To put this figure in context, this represents about 7.5% of the North Atlantic Treaty Organisation guideline for total defence expenditure as a share of GDP.[17] The distribution of military R&D budgets is highly skewed: the United States reports the largest R&D budget support for defence as a percentage of GDP, followed by Korea, France and the United Kingdom (Figure 1.14). In Europe, many countries are planning to increase expenditure on defence; a few countries, such as Germany and Poland, have already announced a large increase (0.5-1% of GDP per year) for 2022/23 (OECD, 2022[32]).

Figure 1.14. R&D budgets for defence in selected countries

Percentage of GDP



Note: The OECD estimation includes all Member countries of the OECD except Costa Rica,
Source: OECD calculations based on OECD R&D statistics, September 2022 (accessed 23 November 2022). See OECD Main Science and Technology Indicators Database, http://oe.cd/msti, for most up-to-date OECD indicators.

StatLink https://stat.link/9nzbpl

Biosecurity

Synthetic biology[18] is a promising field that could help tackle current and future challenges, including through treating infectious and genetic diseases (Khan et al., 2022[33]), preventing food shortages (Mudziwapasi et al., 2022[34]) and mitigating the impacts of climate change (DeLisi, 2019[35]). At the same time, the field comes with inherent risks, centred on dual-use research and deliberate misuse. These risks cannot be eliminated – only managed. Yet there is consensus across the academic literature that public bodies are underprepared for the risks stemming from rapid advances in synthetic biology (OECD, forthcoming[36]). An engineered pandemic-class agent (Bakerlee, 2021[37]) with a higher case fatality rate and transmissibility than SARS-CoV-2 could overwhelm the insufficient detection and response systems that exist today (Bell and Nuzzo, 2021[38]), potentially leading to a breakdown of critical food, water and power distribution systems, and local civilisational collapse. Possible countermeasures include untargeted metagenomic sequencing to enable early detection of emerging pandemics[19] and improvements in response capacities – for example, by stockpiling personal protective equipment, and using safe pathogen-killing lights and improved ventilation to block pathogen transmission.[20] Besides detection and response capacities, prevention countermeasures are also required, including measures to delay the proliferation of pandemic-class agents (Box 1.3). Managing these risks is a balancing act between supporting scientific advancements for the betterment of humanity and implementing appropriate measures against biosecurity threats (OECD, forthcoming[36]).

Box 1.3. Preventive measures to counter risks from synthetic biology

Part of the concern around rapid advances in synthetic biology is that non-state actors may have easier access to technologies or viral agents. Following the 1995 chemical weapon attack in the Tokyo subway and the 2001 Anthrax attack in the United States, the discourse shifted to non-state actors yet regulatory gaps remain, primarily relating to prevention (Rabitz, 2014[39]). Additionally, dual-use research that can serve civil and defence aims remains largely unaddressed, and there currently exist no internationally recognised guidelines for covering high-risk dual-use research.

Key technologies of concern include DNA synthesis and virus assembly, gene editing and gene drives, and cell-free and life-similar biotechnology. Taking just DNA synthesis and virus assembly as an example, detailed step-by-step virus assembly protocols (Xie et al., 2021[40]) allow an increasing number of individuals to assemble numerous viruses from a genome sequence. Today, perhaps 30 000 individuals can generate infectious samples of influenza viruses using standard laboratory equipment, and perhaps one-tenth as many can generate corona-, adeno- and paramyxoviruses.

Viral agents are far more accessible than nuclear arms, but apart from smallpox — which due to its size and complexity, can only be assembled by perhaps 100 individuals globally — there exist no credible blueprints for pandemic-capable agents that a malicious actor could use to ignite a new pandemic. However, this information could soon be provided by well-meaning scientists. For example, ongoing efforts such as the Global Virome Project[1] are working to discover and characterise novel viruses (Sandbrink et al., 2022[41]) by performing identification experiments that assess whether a virus is capable of causing a pandemic, then sharing them in a public list rank-ordered by perceived threat level (SpillOver, 2022[42]). Other labs aim to enhance the infectiousness of highly lethal but poorly transmitted viruses through “gain-of-function” experiments (Herfst et al., 2012[43]), without independent oversight. If the genome sequences of sufficient pandemic-capable pathogens are shared publicly, many thousands of individuals will immediately gain the ability to kill many millions.

Countermeasures are possible to prevent this scenario from happening. For example, a well-designed “pandemic test-ban treaty” could ban pandemic virus identification experiments globally, preventing respectable laboratories from sharing credibly hazardous results. In an era when scientists can design nucleic acid vaccines in a couple of days – as was the case with the COVID-19 Moderna and BioNTech vaccines – these experiments are arguably unnecessary to develop vaccines rapidly.

Another counter-measure would be to introduce universal and secure screening of synthetic DNA orders. The assembly of engineered pathogens requires synthetic DNA that can be ordered by mail. The International Gene Synthesis Consortium,[2] a group of gene synthesis companies that voluntarily vet their customers and screen synthetic gene orders to identify potentially dangerous sequences, is only responsible for 80% of such orders. Establishing universal and secure DNA synthesis screening could prevent unauthorised access to dangerous sequences. Ongoing efforts are under way to provide a freely available screening system,[3] which could then be integrated into all DNA synthesis devices.

1 https://www.globalviromeproject.org.
2 https://genesynthesisconsortium.org.
3 https://www.securedna.org/main-en.
Source: (OECD, forthcoming[36]).

Research security

Some governments and non-state actors are making increasingly forceful efforts to unfairly exploit and skew the open research environment towards their own interests. Such efforts have become more apparent as geopolitical tensions have mounted, and many countries now consider unauthorised information transfer and foreign interference in public research as serious national and economic security risks. Governments are implementing measures to improve research security (see Box 1.4) while at the same time emphasising the norms and principles that constitute good scientific practice – such as academic freedom, openness, honesty and accountability – and regulate international research collaboration – including reciprocity, equity and non-discrimination. A lack of shared and respected international regulations and norms can lead not only to a misappropriation of research, but also to certain types of research being selectively conducted in countries that do not impose legal or ethical restraints (OECD, 2022[44]).

Box 1.4. Measures supporting research security and integrity

Responsibilities for research security and integrity are distributed across multiple actors, operating at different scales in the international research ecosystem. These include national governments, research-funding agencies, research institutions, universities, academic associations and intergovernmental organisations.

Many governments have developed guidelines and checklists to increase awareness of risks to research security and integrity, frequently accompanied by policies and measures to mitigate these risks. It is important these are proportionate and based on sound risk identification and assessments, as not every research institution or research project will face the same level or type of risk. These guidelines should also be regularly revisited and revised, as necessary. Some national policies identify specific "sensitive" countries they consider liable to foreign interference, but many take country-agnostic approaches.

In some countries, intelligence agencies, law enforcement agencies, research institutions and universities have increased co-operation and information exchange to help researchers identify and manage risks, and strengthen security in international collaboration. However, maintaining institutional autonomy in risk management and decision-making is key, not only to effectively identify risk but also to gain crucial buy-in across the research sector. Several funding agencies have integrated risk assessment and management in their funding application and review processes. Meanwhile, universities are developing rules and guidelines to mitigate risks to research security, and protect the integrity and freedom of scientific research.

At the intergovernmental level, the OECD has published a report on integrity and security in the global research ecosystem (OECD, 2022[44]) and launched a web portal on research security.[1] Group of Seven (G7) countries, for their part, have established a working group on the security and integrity of the research ecosystem. The G7 is also planning to develop a common set of principles to help protect the research and innovation ecosystem from risks to open and reciprocal research collaboration (G7-Summit, 2022[45]). Finally, the European Commission recently published a toolkit on how to mitigate foreign interference in research and innovation (European Commission, 2022[46]).

1. https://stip.oecd.org/stip/research-security-portal.
Source: (OECD, 2022[44]).

Maintaining the balance between open and trust-based scientific collaboration, and protective but potentially restrictive regulations, is a major challenge. Over-regulation or excessive intervention can undermine the freedom of scientific enquiry and exchange. For example, while national governments have routinely defined research on chemical, biological, radiological, nuclear and explosive technologies as dual-use, and historically used conventional export control systems to prevent knowledge transfer, it is less easy to control the transfer of data, information and know-how from scientific research carried out without a specific practical aim. This means that basic research has traditionally been exempt from export controls. At the same time, knowledge from many areas of fundamental research can arguably be considered as potentially dual-use. For instance, AI or quantum computing have the potential for both civilian and military use, in addition to being the focus of intense economic competition between companies, countries and regions.

Outlook

There is a growing sense of multiple crises triggering turbulence, instability and insecurity in contemporary societies. Crises are building up one after another and interacting in unpredictable ways, with impacts on economies, politics, the environment and global affairs. Even seemingly singular crises like the COVID-19 pandemic are complex, with cascading effects that have proven difficult to predict and resolve. This "polycrisis" (Homer-Dixon et al., 2022[47]) or "permacrisis"[21] situation has presented decision makers with a high degree of volatility, uncertainty, complexity and ambiguity. Policy needs to be more anticipatory, systemic, inclusive and innovative to manage crises, and contribute to society's capacity for resiliency and adaptation to shocks. However, such policy qualities depend on government capacities which are often lacking, and will take time and considerable investment to develop.

To a significant extent, STI provides economies and societies with built-in resiliency capacity. However, it can only perform this role effectively if it is well-prepared to respond to known risks and unknown uncertainties. Of course, good preparation requires long-term investments in R&D, skills, and research and technical infrastructures, but these alone are insufficient. It also needs strong relationships in "normal times" among those who should mobilise rapidly to deal with crisis situations (de Silva et al., 2022[48]), as well as a strong strategic intelligence capacity to identify, monitor and evaluate emerging risks and responses.

The global nature of crises also calls for vibrant multilateralism and international solidarity. The COVID-19 response experience was mixed in this regard, demonstrating what could be done rapidly through international co-operation but also its limits, particularly in the uneven international rollout of vaccines and therapeutics. Vaccine nationalism and diplomacy are perhaps emblematic of international co-operation-competition dynamics that are likely to characterise the response to other crises, notably climate change (see Chapter 3). Such dynamics will continue to shape the ways in which research and innovation can contribute to global crisis responses.

Finally, growing securitisation of STI offers opportunities, but also risks. On the one hand, framing global problems like climate change, biodiversity loss and food insecurity as national security risks – on account of their wide-ranging and unpredictable effects – further raises their profiles as problems requiring urgent domestic action, including in STI. On the other hand, it could divert STI from targeting other goals related to sustainability transitions and social inclusion, as well as escalate international tensions. Part 2 discusses this issue further.

References

Adepoju, P. (2022), "African coronavirus surveillance network provides early warning for world", *Nature Biotechnology*, Vol. 40/2, pp. 147-148, https://doi.org/10.1038/d41587-022-00003-3. [52]

Bakerlee, C. (2021), *Mother Nature is not 'the ultimate bioterrorist'*, STAT, https://www.statnews.com/2021/01/08/mother-nature-is-not-the-ultimate-bioterrorist/ (accessed on 24 February 2023). [37]

Barreneche, A. (2021), *Tracking science and innovation policies in response to COVID-19*, https://stiplab.github.io/datastories/covid/covid_blog.html (accessed on 24 February 2023). [4]

Bell, J. and J. Nuzzo (2021), *Global Health Security Index: Advancing Collective Action and Accountability Amid Global Crisis*, Global Health Security Index, https://www.ghsindex.org/wp-content/uploads/2021/12/2021_GHSindexFullReport_Final.pdf (accessed on 24 February 2023). [38]

Biasin, M. et al. (2021), "UV-C irradiation is highly effective in inactivating SARS-CoV-2 replication", *Scientific Reports*, Vol. 11/1, https://doi.org/10.1038/s41598-021-85425-w. [51]

Council, I. (2022), *Conference on the Ukraine Crisis: Responses from the European higher education and research sectors*, https://doi.org/10.24948/2022.04. [31]

de Silva, M. et al. (2022), "How did COVID-19 shape co-creation?: Insights and policy lessons from international initiatives", *OECD Science, Technology and Industry Policy Papers*, No. 134, OECD Publishing, Paris, https://doi.org/10.1787/e11c5274-en. [48]

DeLisi, C. (2019), "The role of synthetic biology in climate change mitigation", *Biology Direct*, Vol. 14/1, https://doi.org/10.1186/s13062-019-0247-8. [35]

European Commission (2022), "Tackling R&I foreign interference: staff working document", https://op.europa.eu/en/publication-detail/-/publication/3faf52e8-79a2-11ec-9136-01aa75ed71a1/language-en (accessed on 24 February 2023). [46]

G7-Summit (2022), *Annex to the G7 Science Ministers` Communiqué 2022: Further Implementation and G7 Science Working Groups*, https://www.bmbf.de/SharedDocs/Downloads/de/2022/220613-g7-annex.pdf?__blob=publicationFile&v=4 (accessed on 24 February 2023). [45]

Gaind, N. et al. (2022), "Seven ways the war in Ukraine is changing global science", *Nature*, Vol. 607/7919, pp. 440-443, https://doi.org/10.1038/d41586-022-01960-0. [26]

Herfst, S. et al. (2012), "Airborne Transmission of Influenza A/H5N1 Virus Between Ferrets", *Science*, Vol. 336/6088, pp. 1534-1541, https://doi.org/10.1126/science.1213362. [43]

Homer-Dixon, T. et al. (2022), "A call for an international research program on the risk of a global polycrisis", https://cascadeinstitute.org/technical-paper/a-call-for-an-international-research-program-on-the-risk-of-a-global-polycrisis/ (accessed on 24 February 2023). [47]

Hudson, R. (2022), *US to 'wind down' research collaboration with Russia*, Science|Business, https://sciencebusiness.net/news/us-wind-down-research-collaboration-russia (accessed 4 October 2022). (accessed on 24 February 2023). [23]

Hudson, R. et al. (2022), "The conduct of science in times of war", *Science Business discussion paper*, Science|Business, https://sciencebusiness.net/report/conduct-science-times-war (accessed 4 October 2022). [24]

International Science Council (2022), *Conference on the Ukraine Crisis: Responses from the European higher education and research sectors - A Conference Report*, International Science Council, https://doi.org/10.24948/2022.04. [9]

International Science Council (2022), *Unprecedented & Unfinished: COVID-19 and Implications for National and Global Policy*, International Science Council, https://doi.org/10.24948/2022.03. [16]

Johnson Sirleaf, E. and H. Clark (2022), *Transforming or Tinkering? Inaction lays the groundwork for another pandemic*. [10]

Khan, A. et al. (2022), "Combating Infectious Diseases with Synthetic Biology", *ACS Synthetic Biology*, Vol. 11/2, pp. 528-537, https://doi.org/10.1021/acssynbio.1c00576. [33]

Kozlov, M. (2022), "Why scientists are racing to develop more COVID antivirals", *Nature*, Vol. 601/7894, pp. 496-496, https://doi.org/10.1038/d41586-022-00112-8. [14]

Ledford, H. (2022), "COVID vaccine hoarding might have cost more than a million lives", *Nature*, https://doi.org/10.1038/d41586-022-03529-3. [11]

Ledford, H. (2022), "Donated COVID drugs start flowing to poor nations — but can't meet demand", *Nature*, https://doi.org/10.1038/d41586-022-02939-7. [12]

Mallapaty, S. (2022), "Japan's $2-billion initiative to prep pandemic vaccines in 100 days", *Nature*, Vol. 610/7930, pp. 20-20, https://doi.org/10.1038/d41586-022-03000-3. [13]

Mudziwapasi, R. et al. (2022), "Unlocking the potential of synthetic biology for improving livelihoods in sub-Saharan Africa", *All Life*, Vol. 15/1, pp. 1-12, https://doi.org/10.1080/26895293.2021.2014986. [34]

Nature (2022), "Ukraine's scientists need help to rebuild their research system", *Nature*, Vol. 609/7925, pp. 7-7, https://doi.org/10.1038/d41586-022-02760-2. [29]

Nelson, F. (2022), "Billion-dollar project aims to prep drugs before the next pandemic", *Nature*, https://doi.org/10.1038/d41586-022-02776-8. [15]

OECD (2022), “Building back a better innovation ecosystem in Ukraine”*, OECD Policy Responses on the Impacts of the War in Ukraine*, OECD Publishing, Paris, https://www.oecd.org/ukraine-hub/policy-responses/building-back-a-better-innovation-ecosystem-in-ukraine-85a624f6/ (accessed on 6 March 2023). [54]

OECD (2022), “Integrity and security in the global research ecosystem”*, OECD Science, Technology and Industry Policy Papers*, No. 130, OECD Publishing, Paris, https://doi.org/10.1787/1c416f43-en. [44]

OECD (2022), *OECD Economic Outlook, Volume 2022 Issue 1*, OECD Publishing, Paris, https://doi.org/10.1787/62d0ca31-en. [32]

OECD (2022), *OECD Economic Outlook, Volume 2022 Issue 2*, OECD Publishing, Paris, https://doi.org/10.1787/f6da2159-en. [1]

OECD (2022), *OECD Main Science and Technology Indicators: Highlights – March 2022*, https://www.oecd.org/sti/msti-highlights-march-2022.pdf (accessed on 24 February 2023). [3]

OECD (2022), *Public communication and engagement in science: lessons learned from COVID-19*, https://www.oecd.org/sti/inno/public-communication-engagement-in-science.htm (accessed on 24 February 2023). [21]

OECD (2022), “The future of science in Ukraine: Actions now will affect post-war recovery”*, OECD Policy Responses on the Impacts of the War in Ukraine*, OECD Publishing, Paris, https://doi.org/10.1787/afbd05df-en. [30]

OECD (2021), *OECD Science, Technology and Innovation Outlook 2021: Times of Crisis and Opportunity*, OECD Publishing, Paris, https://doi.org/10.1787/75f79015-en. [2]

OECD (forthcoming), “Existential risks in synthetic biology: considerations and scenarios”. [36]

OECD (forthcoming), *Measuring governments’ R&D funding response to COVID-19 with project data: Preliminary analysis from the OECD Fundstat initiative*. [6]

Owens, B. (2022), “Energy crisis squeezes science at CERN and other major facilities”, *Nature*, Vol. 610/7932, pp. 431-432, https://doi.org/10.1038/d41586-022-03257-8. [27]

Pierri, F. et al. (2022), “Online misinformation is linked to early COVID-19 vaccination hesitancy and refusal”, *Scientific Reports*, Vol. 12/1, https://doi.org/10.1038/s41598-022-10070-w. [22]

Rabitz, F. (2014), *Regulatory Gaps in the Global Governance of Synthetic Biology*. [39]

Sandbrink, J. et al. (2022), “Mitigating Biosecurity Challenges Associated with Zoonotic Risk Prediction”, *SSRN Electronic Journal*, https://doi.org/10.2139/ssrn.4035760. [41]

SpillOver (2022), *SpillOver: Viral Risk Ranking*, https://spillover.global (accessed on 24 February 2023). [42]

Sun, T. et al. (2022), “Challenges and recent progress in the governance of biosecurity risks in the era of synthetic biology”, *Journal of Biosafety and Biosecurity*, Vol. 4/1, pp. 59-67, https://doi.org/10.1016/j.jobb.2022.02.002. [49]

Thompson, T. (2021), “Real-world data show that filters clean COVID-causing virus from air”, *Nature*, https://doi.org/10.1038/d41586-021-02669-2. [50]

UKCDR and GloPID-R (2023), *Indirect health impacts*, https://www.ukcdr.org.uk/wp-content/uploads/2022/07/2-Tracker-Highlights-Template_Indirect-health-impacts.pdf (accessed on 24 February 2023). [19]

UKCDR and GloPID-R (2022), *Long COVID*, https://www.ukcdr.org.uk/wp-content/uploads/2022/09/UKCDR-140922-Tracker-Highlights-Long-Covid.pdf (accessed on 24 February 2023). [20]

UKCDR and GloPID-R (2022), *New variants*, http://chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.ukcdr.org.uk/wp-content/uploads/2022/09/UKCDR-140922_new-variants.pdf (accessed on 24 February 2023). [17]

UKCDR and GloPID-R (2022), *Research Capacity Strengthening*, https://www.ukcdr.org.uk/wp-content/uploads/2022/09/UKCDR_140922_Research-Capacity-Strengthening.pdf (accessed on 24 February 2023). [18]

Undseth, M. and C. Jolly (2022), "A new landscape for space applications: Illustrations from Russia's war of aggression against Ukraine", *OECD Science, Technology and Industry Policy Papers*, No. 137, OECD Publishing, Paris, https://doi.org/10.1787/866856be-en. [25]

Waltz, E. (2022), "How nasal-spray vaccines could change the pandemic", *Nature*, Vol. 609/7926, pp. 240-242, https://doi.org/10.1038/d41586-022-02824-3. [53]

Watson, O. et al. (2022), "Global impact of the first year of COVID-19 vaccination: a mathematical modelling study", *The Lancet Infectious Diseases*, Vol. 22/9, pp. 1293-1302, https://doi.org/10.1016/s1473-3099(22)00320-6. [7]

WHO, W. (2020), "A Coordinated Global Research Roadmap: 2019 Novel Coronavirus". [5]

Wilson Center (2022), *Reframing Vaccine Diplomacy Amid Strategic Competition: Lessons from COVID-19*. [8]

Xie, X. et al. (2021), "Engineering SARS-CoV-2 using a reverse genetic system", *Nature Protocols*, Vol. 16/3, pp. 1761-1784, https://doi.org/10.1038/s41596-021-00491-8. [40]

Zubașcu, F. (2022), *Energy crisis is starting to hit Europe's big science labs*, Science|Business, https://sciencebusiness.net/news/energy-crisis-starting-hit-europes-big-science-labs (accessed on 24 February 2023). [28]

Notes

[1] In the context of this chapter, "securitisation" refers to the reframing of regular policy issues, such as climate change, migration, and emerging technologies, into matters of "security".

[2] In the EU27 area, business R&D performance was the main reason for an aggregate fall in R&D expenditures. This is because the structure of business R&D in the European Union is more concentrated in industries that were more negatively impacted by the COVID-19 crisis (see below).

[3] Estimates of real growth in R&D expenses for the ensemble of firms in the OECD SwiFTBeRD panel map very closely the evolution of official business expenditure on R&D estimates over periods in which these are available. For example, the final 2020 estimates of the September 2022 MSTI release confirm the "nowcasts" made in the March 2021 release for 2020.

[4] UKCDR (https://www.ukcdr.org.uk/) is a group of UK Government departments and research funders working in international development research. UKCDR aims to amplify the value and impact of research for global development by promoting coherence, collaboration and joint action among UK research funders.

[5] This makes the UKCDR/GloPID-R COVID-19 Research Project Tracker (https://www.ukcdr.org.uk/covid-circle/covid-19-research-project-tracker/) one of the most comprehensive databases on COVID-19 research projects, covering a wide breadth of research disciplines. However, because of limited data availability on funding, it significantly underestimates the awarded total research funding.

[6] 776 projects targeting "candidate vaccine R&D" were awarded USD 2.3 billion, with another USD 1.4 billion going to 7 320 projects targeting "social sciences in the outbreak response". This means that the average project size for vaccine research was USD 3 million, compared to USD 195 000 for social sciences project – i.e. more than 15 times larger.

[7] The development of oral or nasal vaccines could be a game-changer for promoting global access. It could prevent even mild cases of illness and block onward transmission (Waltz, 2022[53]).

[8] As Omicron spread across the globe, South African labs were the first to detect it and flag it to the world. The Network for Genomic Surveillance in South Africa first spotted the mutated variant in sequencing data from Botswana (Adepoju, 2022[52]).

[9] In France, for example, the Agence Nationale de la Recherche is drawing up an "energy sobriety" plan that will incorporate sustainability criteria in its project funding assessments.

[10] In the context of the preparation of Ukraine's National Recovery and Development Plan in May-June 2022, the OECD contributed ideas on how Ukraine's science, technology and innovation system could be reformed to better contribute to the post-war reconstruction of its economy and society. These are summarised in (OECD, 2022[54]).

[11] https://stip.oecd.org/stip/interactive-dashboards/policy-initiatives/2021%2Fdata%2FpolicyInitiatives%2F99993866.

[12] https://euraxess.ec.europa.eu/ukraine.

[13] This European Research Area for Ukraine (ERA4Ukraine) portal brings together initiatives at the EU level, per country and from non-governmental groups (https://euraxess.ec.europa.eu/euraxess/news/era4ukraine-one-stop-shop-support-researchers-ukraine).

[14] This is being compiled by the International Science Council (https://council.science/current/news/statements-international-scientific-community-conflict-ukraine/).

[15] https://www.nationalacademies.org/supporting-ukraines-scientists-engineers-and-health-care-workers.

[16] An example of promoting brain circulation with Ukraine is an initiative of the German Federal Ministry of Education and Research (BMBF), which aims to establish "German-Ukrainian Cores of Excellence" (CoE), i.e. centres for cutting-edge research in Ukraine. The goal is to establish bilateral research units under the leadership of a top researcher (preferably of Ukrainian origin) with the involvement of young Ukrainian scientists, and to transfer them to Ukraine, provided that the security situation is safe. The initiative aims to integrate Ukrainian scientists as a group while maintaining close ties with Ukrainian partner institutes. In this way, the CoE aim to counteract the current brain drain and contribute to the stabilisation and recovery of Ukrainian science. An initial call was published in 2019, and since 2021, 12 German-Ukrainian scientific teams have been developing concepts for establishing future CoE. The best of these will be funded in an implementation phase, which is expected to start in 2024. This BMBF initiative will be complemented by other (medium-term) co-operation approaches. These aim to enhance research cooperation, develop local scientific capacities, support reform processes and promote the integration of Ukrainian science into the European Research Area. A major priority is research co-operation in the field of energy and green hydrogen to facilitate the rapid (re)construction of a sustainable energy system in Ukraine.

[17] Distinguishing R&D from other military expenditures is challenging, partly because public procurement contracts for defence systems may not allow disentangling sums allocated for R&D purposes from sums spent on actual deliveries. Spending on classified military R&D projects is also likely to go unreported, leading some OECD countries not to report any defence R&D figures at all.

[18] Synthetic biology is defined as a multidisciplinary field that "integrates systems biology, engineering, computer science, and other disciplines to achieve the 'modification of life' or even the 'creation of life' via the redesign of existing natural systems or the development of new biological components and devices" (Sun et al., 2022[49]).

[19] For example, the Nucleic Acid Observatory project (https://www.naobservatory.org/) aims to build a reliable early warning system by looking for exponentially increasing nucleic acids in wastewater from travel hubs, using untargeted metagenomic sequencing.

[20] Passive mechanisms such as improved ventilation using HEPA filters (Thompson, 2021[50]) or pathogen-killing lights are a proven way to reduce transmission. Applying sufficient low-wavelength germicidal lights to inactivate over 90% of viruses within a second would reliably block the spread of the most contagious known pathogens. Preliminary studies have shown that low-wavelength germicidal lights are safe for humans and other multicellular organisms while efficiently killing pathogens like SARS-CoV-2 (Biasin et al., 2021[51]).

[21] This is the Collins Dictionary's "Word of the Year 2022", which they define as "an extended period of instability and insecurity" (https://blog.collinsdictionary.com/language-lovers/a-year-of-permacrisis/).

2 Science, technology and innovation policy in times of strategic competition

Technological leadership has long underpinned the economic prosperity and security of OECD countries and has typically involved some measure of protection of technologies from strategic competitors. The growing ascendancy of China in frontier technologies has ushered in a new era of intensified strategic competition, particular in critical technologies that will underpin future economic competitiveness and national security. Governments are putting in place measures to (i) reduce STI interdependency risks and restrict international technology flows; (ii) enhance industrial performance through STI investments; and (iii) strengthen international STI alliances among like-minded economies. These measures could disrupt integrated global value chains and the deep and extensive international science linkages that have built up over the last 30 years. Coupled with a growing emphasis on “shared values” in technology development and research, they could lead to a “decoupling” of STI activities at a time when global challenges require global solutions underpinned by international STI co-operation. A major test for multilateralism will be to reconcile growing strategic competition with the need to address global challenges like climate change.

Key messages

- Technological leadership has long underpinned the economic prosperity and security of OECD countries. Leadership has inevitably involved some measure of protection of technologies from strategic competitors, but such efforts today are complicated by the interdependent and multinational nature of contemporary technological innovation.
- The People's Republic of China (hereafter China) has accumulated increasingly sophisticated technological capabilities over the last two decades and is already a market leader in areas like 5G and at the forefront in others, including batteries and photovoltaics. While China is tightly embedded in global value chains and international science networks, its growing technological ascendancy, made possible by the stability and opportunity the international order provides, has ushered in a new era of intensified strategic competition.
- For liberal market economies, China's ascendancy raises three main areas of concern, each of which is expected to underpin future economic and national security: (i) rising competition in critical technologies that are expected to underpin future economic competitiveness; (ii) diverging values and interests between China and liberal market economies, challenging the existing international rules-based order; and (iii) growing recognition of vulnerability from a lack of diversification in technology supply-chains.
- As economic and security policy agendas show signs of growing convergence, concepts like "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 emerged as frames for science, technology and innovation (STI) policy. This framing could – and is indeed intended to – disrupt existing technology ecosystems. It could also have unintended effects – for example, on co-operation in basic science.
- The chapter focuses chiefly on STI-related policies in China, the European Union and the United States. It shows that countries use, often in combination, three main types of policy intervention to strengthen their technology sovereignty and strategic autonomy:

    1. protection measures, such as export controls, foreign direct investment screening, negative lists and research security measures, to restrict international technology flows and reduce supply-chain vulnerabilities
    2. promotion measures, such as industrial policies, to strengthen domestic industrial capabilities and performance and reduce dependencies on foreign suppliers
    3. projection measures, such as international STI alliances and technical standards, to intensify STI co-operation around shared values and interests and diversify technology supply chains.

- Policy discussions on interdependency vulnerabilities often cite two prime examples: semiconductors and critical minerals. The chapter describes how OECD countries and China are investing heavily in innovation in both areas, using a mix of protection, promotion and projection measures to strengthen their relative positions.
- These policies may sacrifice some of the gains derived from specialisation, economies of scale, and the diffusion of information and know-how. They could also undermine future co-operation on global grand challenges. A major test for multilateralism will be to reconcile growing strategic competition with the need to address collectively global challenges like climate change.

Introduction

China's ascendancy in science and technology has brought many benefits. It has contributed significantly to the world's stock of knowledge through its scientific research and has accelerated innovation in technology areas that are critical to sustainability transitions. It is already a market leader in some technologies, such as 5G, and at the forefront in others, including batteries and wind turbines. These successes are underpinned by significant growth in R&D expenditures, with China now employing the largest number of researchers globally. They have also been made possible by the stability and opportunity the international order provides.

China's growing technological capabilities have also ushered in a new era of intensified strategic competition with liberal market economies. Policy concerns stem from growing competition in critical technologies that are expected to underpin future economic competitiveness and national security, diverging values and interests between China and liberal market economies that challenge the existing international rules-based order, and growing vulnerability from supply-chain interdependencies. These concerns have prompted technology leaders, such as the European Union and the United States, to seek greater technological sovereignty and strategic autonomy vis-à-vis China, with the aim of reducing technology supply-chain vulnerabilities and checking China's ambition to lead in critical technologies like artificial intelligence (AI).

The COVID-19 pandemic and Russia's war of aggression against Ukraine have also shone a spotlight on global interdependencies, and their benefits and risks. For instance, solutions to the pandemic have drawn upon extensive international co-operation in science and technology. But the pandemic has also disrupted global supply chains on goods ranging from face masks to semiconductors, leading to critical shortages in many OECD countries. The war in Ukraine has exposed disruption vulnerabilities in the supply of Russian hydrocarbons and Ukrainian grains that engendered unprecedented increases in global gas and food prices, with destabilising knock-on economic effects. Both crises have amplified previously existing concerns about a heavy reliance on non-diversified supply chains.

To reduce their mutual technology dependencies, China, the European Union and the United States – which between them account for most of the world's advanced science and technology developments and production[1] – have recently introduced initiatives to strengthen domestic STI capabilities and reduce international technology dependencies. Technology-fuelled industrial policy, underpinned in part by COVID-19 recovery investments, has become newly fashionable, combining security concerns with economic renewal and the need for green transitions. This is most visible in semiconductors, but also extends to other technology fields.

Such policy efforts to reduce technology dependencies could disrupt integrated global value chains, and the deep and extensive international science linkages that have built up over the last 30 years. Coupled with a growing emphasis on "shared values" in technology development and research, these developments could lead to a "decoupling" of STI activities, particularly between the European Union and the United States on the one hand, and China on the other. This is at a time when global challenges, notably climate change, require global solutions underpinned by international STI co-operation. China, the European Union and the United States are each establishing various overlapping and sometimes competing international fora and platforms to co-operate on technology development, governance and diffusion. However, these are not global, and a major test for multilateralism will be to reconcile growing strategic competition with the need for international co-operation to address global challenges.

The chapter is based on a literature review of some of the main trends and policy responses related to growing strategic competition. It begins with a brief overview of strategic competition and its growing influence on STI policy. The increasing "securitisation"[2] of STI is part of a policy push for greater strategic autonomy, whose meaning remains contested, but which broadly aims to (i) reduce STI interdependency risks and restrict international technology flows; (ii) enhance industrial performance through STI investments; and (iii) strengthen international STI alliances among like-minded economies. The chapter includes sections discussing each of these policy goals. This is followed by a section that describes how China, the European Union and the United States are pursuing these policy goals to reduce their vulnerabilities in semiconductors and critical minerals. A final section draws some lessons and presents a brief outlook for STI policy in times of strategic competition.

Strategic autonomy in research and innovation

Technology is central to today's geopolitical competition (The White House, 2022[1]), and technological leadership has long underpinned the economic prosperity and security of OECD countries. Leadership has inevitably involved some measure of protection of technologies – particularly military technologies, but also civilian ones with dual-use potential – from strategic competitors. These efforts are complicated by the interdependent and multinational nature of contemporary technological innovation, with R&D processes for developing new technology more collaborative and globally distributed than in the past. This means many technologies have diverse origins and rely heavily on other technologies with owners, users and stakeholders in multiple countries. Many also have dual-use potential (National Academies of Sciences, Engineering, and Medicine, 2022[2]).

At the same time, economic and security thinking are converging, with countries increasingly concerned about vulnerabilities arising from excessive dependence on others. This has led to increasing government intervention in the economy – particularly in China – and new policy measures to enhance self-sufficiency and resilience. As a rising economic power, China is faced with an imperative to acquire and develop technologies to climb the global value chain and escape the middle-income trap.[3] China has implemented comprehensive industrial policy measures to support "national champions" and engaged in overseas acquisitions to bridge the technological gap (Wigell et al., 2022[3]). However, these are seen by liberal market economies as distortions to the competitive playing field that undermine the rules and norms of the global economy (Goodman and Robert, 2021[4]).

Supply-chain vulnerabilities and geopolitical tensions related to China's ascendancy have led to growing policy interest in "technology sovereignty", which refers to a polity's capacity to act strategically and autonomously in an era of intensifying global technology-based competition (Edler et al., 2021[5]). 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 (Crespi et al., 2021[6]), (March and Schieferdecker, 2021[7]). Countries' capacity to successfully develop, integrate and use emerging and disruptive technologies in military applications is a traditional measure of their strategic autonomy (Soare and Pothier, 2021[8]), but this capacity also applies to many commercial technologies, particularly those with dual-use potential.

This intensified era of geopolitical competition is putting pressure on the rules and institutions that govern the international economy. In its latest national security strategy (The White House, 2022[1]), the United States government notes challenges to the post-Second World War rules-based system. These rules have always been subject to dynamic change, driven by the evolving interests of powerful countries and changing global norms (Edler et al., 2021[5]). As China strives for technological leadership, it also seeks to define what these new "rules of the road" should look like. This makes the technological race between China and liberal market economies a competition between different systems and values (Soare and

Pothier, 2021[8]), (Edler et al., 2021[5]). This difference lies at the core of strategic competition, since the nature of different political systems determines how technologies are developed and used, and their success will define the broader appeal of these systems in the longer term (Schmidt et al., 2022[9]).

Three types of policy intervention for strengthening strategic autonomy

The policy literature (e.g. (Helwig, Sinkkonen and Sinkkonen, 2021[10]; March and Schieferdecker, 2021[7]; Goodman and Robert, 2021[4])) identifies three main types of policy intervention for strengthening technology sovereignty and strategic autonomy – i.e. protection, promotion and projection, sometimes referred to as the “3Ps” (Figure 2.1):

1. *protection: restricting technology flows and reducing dependency risks*, e.g. through regulatory policies like export controls, supply-chain diversification measures, etc.
2. *promotion: enhancing domestic innovation capabilities and performance*, e.g. through holistic innovation policies, mission-oriented innovation policies, national industrial strategies, etc.
3. *projection: extending and deepening international STI linkages*, e.g. through international technology alliances, active participation in international standards setting bodies, etc.

The challenge facing policy makers is to strike an appropriate balance between these types of policy intervention in their country context. For example, much of the current technology sovereignty debate in the United States centres on the balance between protection and promotion measures, with advocates of a more active industrial policy (promotion) highlighting its centrality for meeting growing technology competition from China. In practice, single policy initiatives, such as national industrial policies, can incorporate elements of all three types of policy intervention. Along these lines, the European Commission (European Commission, 2021[11]) has signalled the need for a coherent mix of industrial, research and trade policies that can facilitate partnership and collaboration with like-minded countries in pursuit of strategic autonomy. These policy areas are often quite independent of one another, and their orchestration presents co-ordination and governance challenges for policy makers (Edler et al., 2021[5]), (Araya and Mavinkurve, 2022[12]). Ultimately, no single formula exists, and an appropriate policy mix will vary depending on countries, technology areas and industrial sectors. This calls for a targeted, risk management-based approach informed by assessments of threats, risks and opportunities.

Figure 2.1. Three types of policy intervention to strengthen technological strategic autonomy

The sections that follow cover each of these types of policy intervention. They explore the issues at stake and point to policy initiatives from China, the European Union and the United States, which together account for most of the world's science and innovation activities. Specific policy initiatives often combine different types of intervention, and this is highlighted throughout. Table 2.1 lists the main policy initiatives covered. To provide some context, the following section first presents a few selected headline indicators on the science and innovation performance of China, the European Union and the United States.

Table 2.1. Selected recent policy initiatives that incorporate protection, promotion or projection

China	Made in China 2025; 14th Five-Year Plan; Dual Circulation Strategy; Military-Civil Fusion; Government Guidance Funds; China Standards 2035; Belt and Road Initiative
European Union	NextGenerationEU; New Industrial Strategy for Europe; New European Innovation Agenda; Important Projects of Common European Interest; Chips Act for Europe; EU-US Trade and Technology Council
United States	CHIPS and Science Act; Inflation Reduction Act; Infrastructure Investment and Jobs Act; Quad; Indo-Pacific Economic Framework for Prosperity; Group of Seven (G7) Partnership for Global Infrastructure and Investment

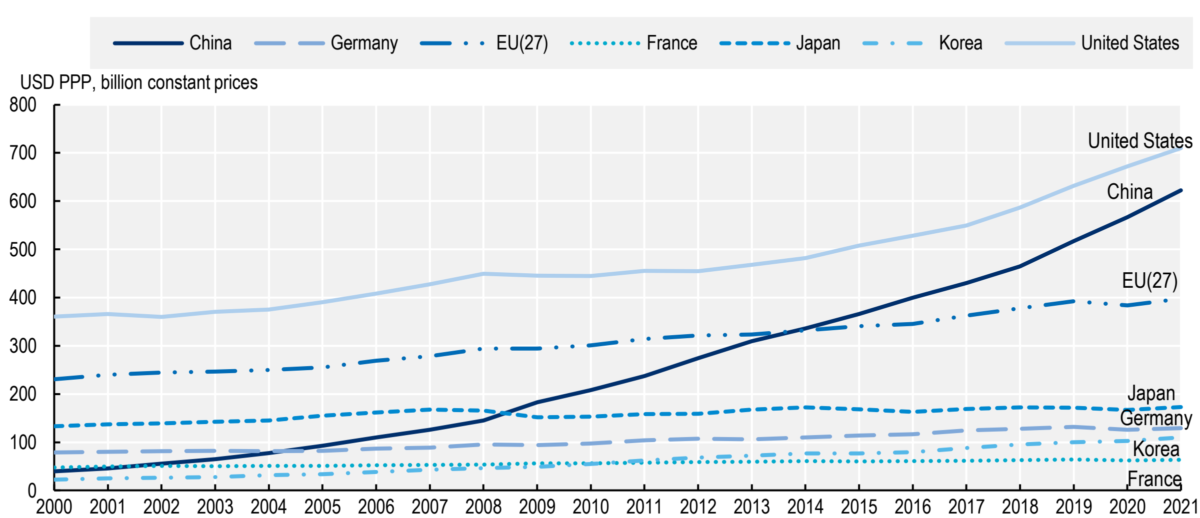
Note: The table makes no claim to comprehensiveness, and the policy initiatives listed are limited to examples covered in later sections of this chapter. Note that many of these initiatives cover more than one type of policy intervention (protection, promotion and projection).

How do China, the European Union and the United States compare? Some selected headline indicators

The United States remains the largest absolute spender on R&D in the world, followed by China, which overtook the European Union in 2014 (Figure 2.2). China's R&D intensity grew from 1.71% in 2010 to 2.45% in 2021. This exceeds the R&D intensity of the European Union (2.15%,) but is still somewhat below the level of the United States (3.46%).

Figure 2.2. Gross domestic expenditure on R&D (GERD), selected economies, 2000-21

US dollar (USD) billion in constant purchasing power parity (PPP) prices



Source: OECD R&D statistics, February 2023. See OECD Main Science and Technology Indicators, http://oe.cd/msti, for most up-to-date indicators (accessed on 8 February 2023).

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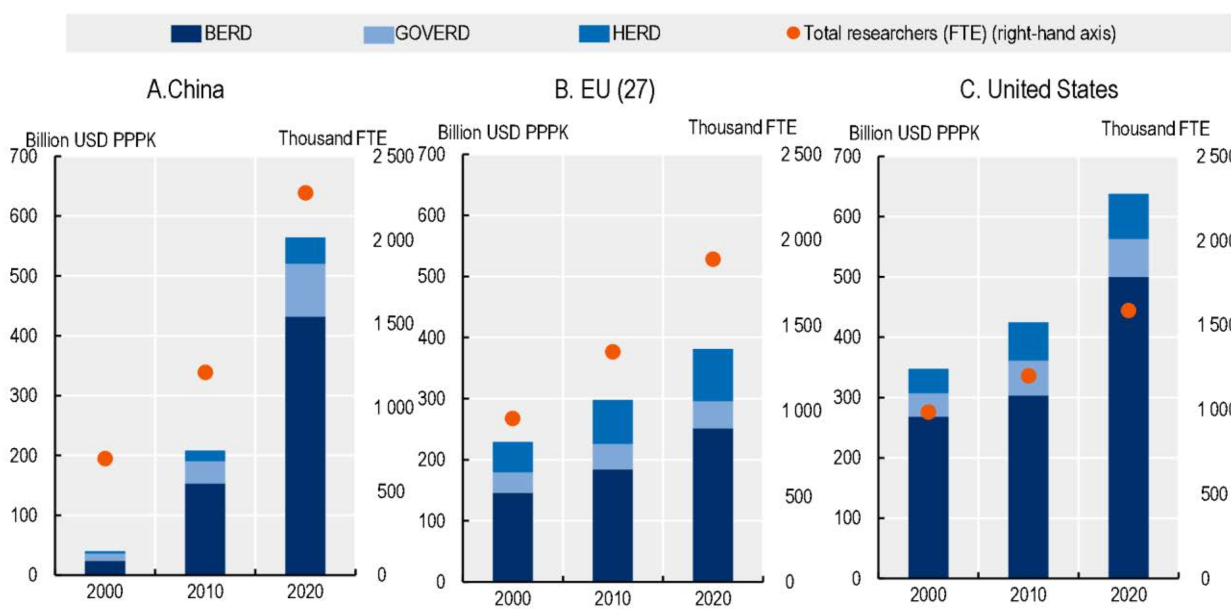
Figure 2.3 shows the absolute R&D expenditures of China, the European Union and the United States over the last two decades. The scale of China's expenditures today suggest it has critical mass to innovate at the frontier. The business sector accounts for the largest expenditures on R&D in all three areas by far, though the proportion has increased in China in recent decades, from 60.0% in 2000 to 76.6% in 2020. The government sector is the second-largest R&D performer in China, accounting for 15.7% of GERD in 2020, although this is a significant decline compared to 20 years earlier, when it accounted for 31.5%. The higher education sector is the smallest, accounting for just 7.7% of GERD in 2020, a proportion largely unchanged from 20 years earlier (8.6%). This situation is somewhat reversed in the European Union and the United States, where the higher education sector is more prominent than the government sector, with a growing share of GERD over the last 20 years.

Figure 2.3 also shows that China had 2.28 million researchers in 2020 – the largest number of researchers in the world, compared to 1.89 million in the European Union and 1.59 million in the United States.[4] While researcher numbers have grown markedly in all three areas over the last two decades, they have more than tripled in China over the past 20 years, marking the greatest expansion compared to other countries. To put this into perspective, China still had only 3.0 researchers per 1 000 in total employment in 2020, which is around one-third of the European Union level, suggesting considerable room for further expansion.

Figure 2.3. R&D expenditures by sector and total full-time employed (FTE) researchers

USD billion in 2015 PPP prices and 1 000 FTE



Note: 2020 R&D expenditure data are provisional for the United States, and estimated for China and the EU27; 2020 researchers' data for the United States corresponds to 2019.
Source: OECD R&D statistics, September 2022. See OECD Main Science and Technology Indicators Database, http://oe.cd/msti, for most up-to-date OECD indicators.

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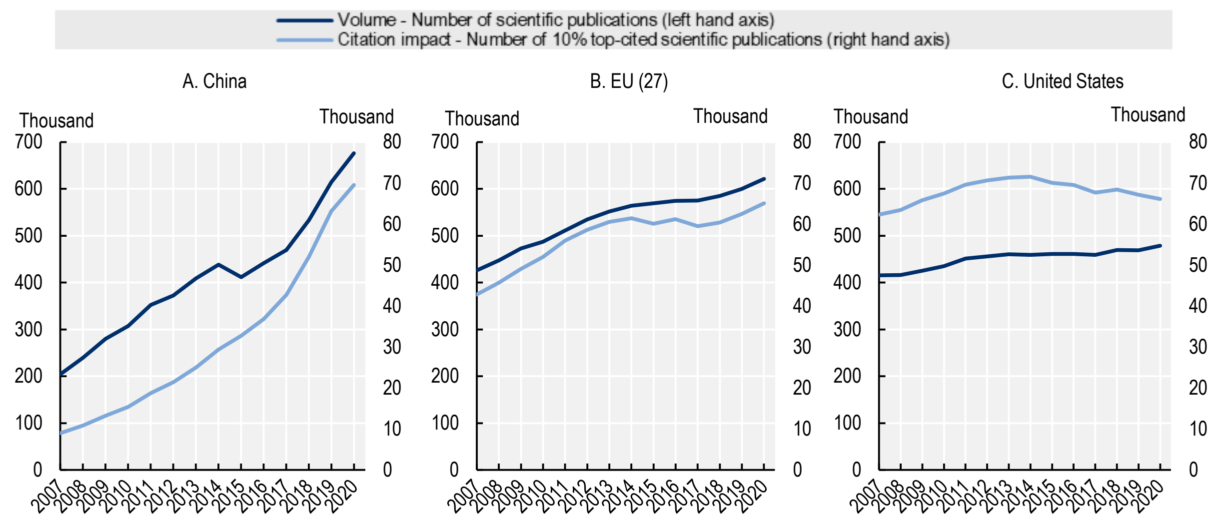
China's increases in R&D expenditures and personnel have translated into a higher volume and citation impact of scientific publications. Figure 2.4 shows that China produced more scientific publications in 2020 than either the European Union or the United States. It also produced more top-cited scientific publications in 2020. The European Union also increased its volumes of scientific publications and the number of top-cited, though by a smaller margin than China. Increases in the United States were much smaller, although starting from a high level of performance.

Turning to patents, China accounted for 13% of IP5 patent families[5] in 2017-19 compared to just 1% in 1998-2000, surpassing Germany as the third-largest patenting country according to this measure (Figure 2.5). Over the same period, the proportion of IP5 patent families originating in the United States fell from 26% to 19%. Japan remains the top patenting country, accounting for 26% of IP5 patent families in 2017-19, a proportion that is largely unchanged from 1998-2000, when it accounted for 28%. As the preferred measure of internationalisation of innovative activities, inventive performance and diffusion of knowledge, the data on IP5 patent families suggest that China has accumulated increasingly sophisticated technological capabilities over the last two decades thanks to its R&D investments.

Figure 2.4. Trends in volume and citation impact of scientific publications, selected economies



Note: Peer-reviewed scientific publications convey the research findings of scientists worldwide. Subsequent citations by other authors provide an indirect but objective source of information about the quality of research outputs, as implied by their use by the scientific community itself. Despite limitations, such as that citations do not take into account the use of the scientific information by inventors or practitioners who are less likely to publish in peer-reviewed journals, they provide one of the available quality adjustments to raw counts of documents. Their relevance can be considered to be higher in the context of the higher education sector. The indicator of scientific excellence indicates the amount (in %) of a unit's scientific output that is part of the set of the 10% most-cited papers within their respective scientific fields (see https://www.oecd.org/sti/inno/Bibliometrics-Compendium.pdf).

Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 6.2022, September 2022.

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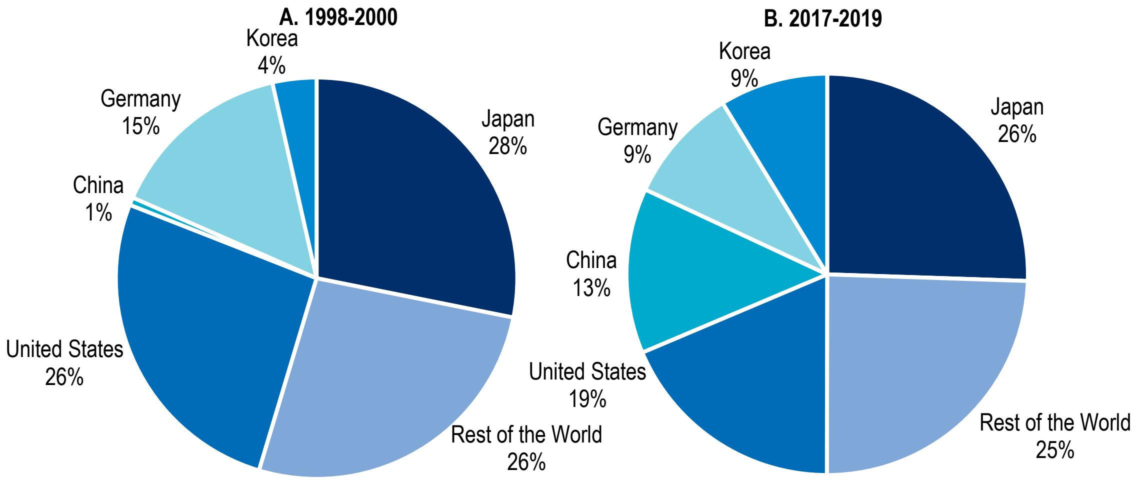
Figure 2.5. Distribution of IP5 patent families for selected countries and the rest of the world

Percentage of IP5 patent families originating in the different countries and regions that make up the total



Note: Data refer to families of patent applications filed within the Five IP offices (IP5), by earliest filing date, according to the applicant's location.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats (accessed 9 February 2023).

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Protection: Restricting knowledge flows and reducing risks from interdependency

The first type of strategic autonomy policy intervention concerns protection, for example, in the form of barriers to open knowledge and technology flows where there is growing recognition of risks to national security. The COVID-19 crisis and Russia's war of aggression against Ukraine have also brought interdependency risks to the fore, raising questions about the resilience of a global production model grounded on international fragmentation and just-in-time logistics. A shift in the balance between the security of supply and efficiency considerations could lead to a reconfiguration of supply chains and the use of suppliers at less distant locations. This reconfiguration could affect the sourcing of high-tech products and components, particularly where there are vulnerabilities from key suppliers based in countries with different geopolitical priorities (OECD, 2022[13]).

The growing research security agenda outlined in Chapter 1 shows that these concerns extend to basic research, which has traditionally fallen outside of formal controls. International science collaboration has blossomed in the last 20 years, particularly between OECD countries and China. Yet there exists a real possibility that rising geopolitical tensions could limit these linkages and lead to a decline in international science co-operation in the future.

This section is divided into two parts. The first provides a few selected headline indicators to show the growth and extent of interdependencies between economies, particularly China, the European Union and the United States. The second part looks more closely at recent policy trends that aim to reduce vulnerabilities from interdependencies and considers what they could mean for future research and innovation activities.

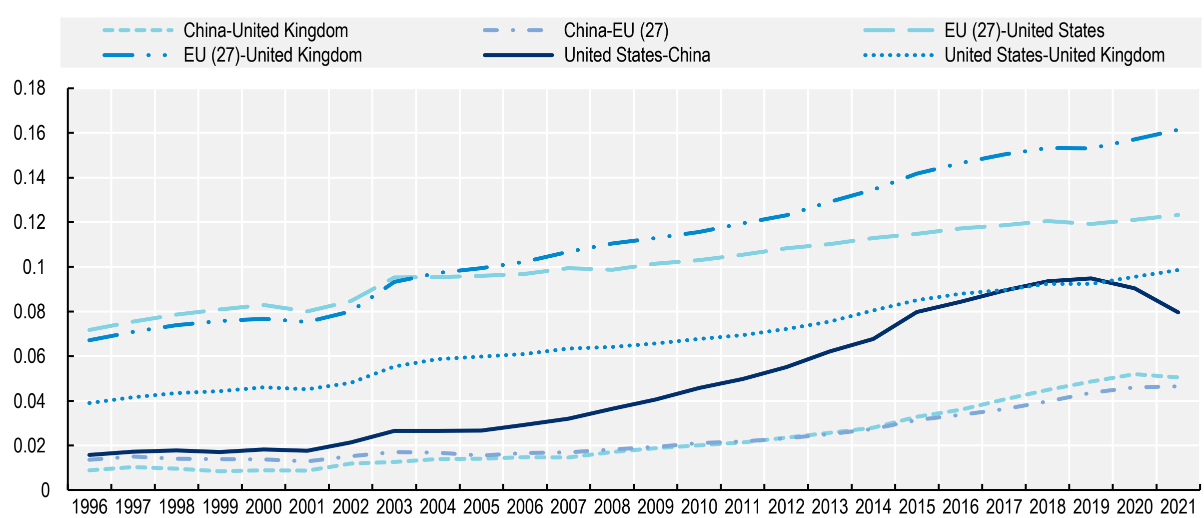
Getting a measure of STI interdependency

Since the end of the Cold War, several types of STI linkages have deepened and expanded. These include international science collaboration, international mobility of scientists and engineers, and global value chains in high R&D-intensive economic activities, as briefly described below.

International science collaboration

Science depends on the global knowledge commons for progress, and around one-fifth of scientific publications are co-authored internationally. As China's scientific capabilities have grown in recent years, it has developed strong research links with OECD countries. Data on collaboration based on scientific publications – calculated using whole counts of internationally co-authored documents – shows international collaboration between China and the United States grew rapidly over the last few decades (Figure 2.6). In fact, between 2017-19, US co-authorship with China was more prevalent than with the United Kingdom. This has since fallen quite sharply, allegedly owing to pandemic travel restrictions and denial of visas that restricted Chinese students and scholars from travelling overseas (Wagner and Cai, 2022[14]). Most of the decline – which started in 2020 and accelerated in 2021 – is in engineering and natural sciences fields, which account for the bulk of bilateral research collaboration between China and the United States (Figure 2.7). In the meantime, collaboration in other research fields, such as life and health sciences and social sciences and humanities, continued to grow over the same period. These patterns could be early signs of China-US disengagement from bilateral collaboration in research fields that are critical to strategic competition. They could also signal that bilateral collaboration in other areas, such as medicine and environmental sciences, where strategic competition is less prominent, could continue to grow.

Figure 2.6. Bilateral collaboration intensity trends in scientific publications, 1996-2021



Note: The indicator of bilateral collaboration intensity between two economies is calculated by dividing the number of scientific publications by authors with affiliations in both economies (whole counts) by the square root of the product of the publications for each of the two economies (whole counts). This indicator is therefore normalised for publication output. Publications refer to all citable publications, namely, articles, reviews and conference proceedings.
Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 6.2022, February 2023

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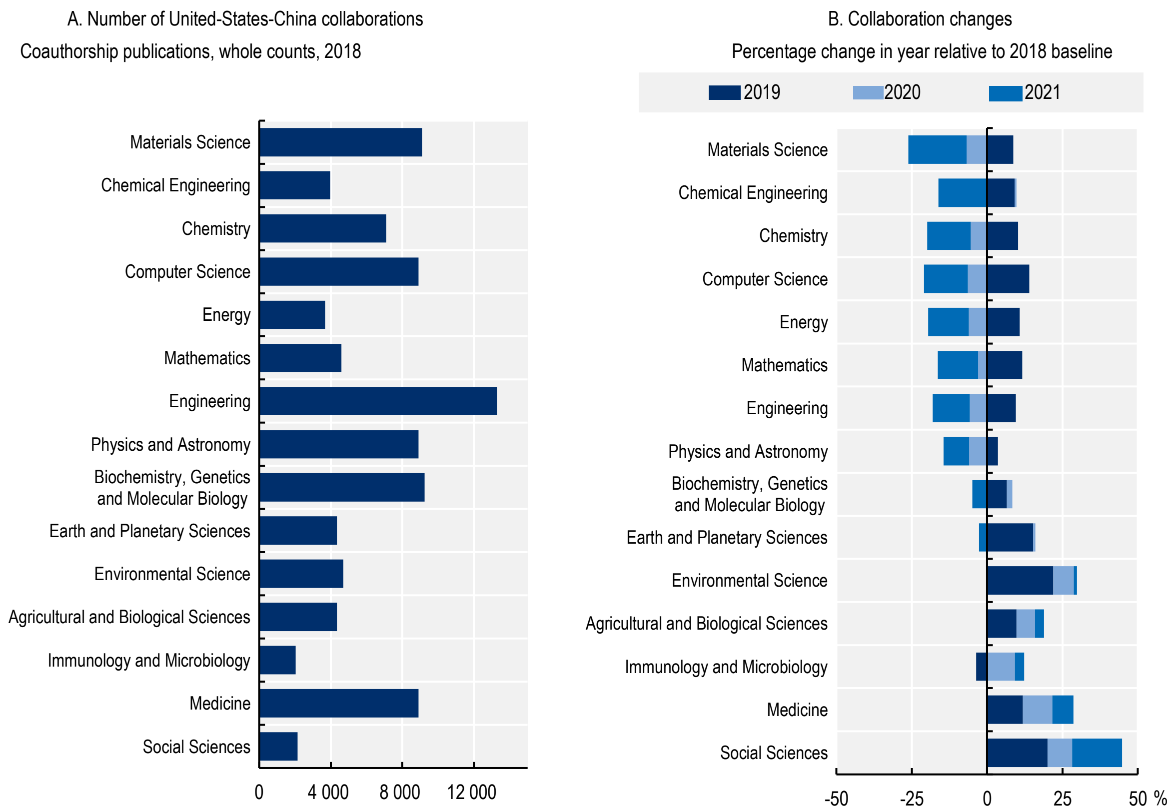
Figure 2.7. Top 15 fields of collaboration between the United States and China



Note: 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 top-15 in the chart corresponds to those fields where more than 2 000 US-China co-authorship publications were recorded in 2018 (whole counts). Panel A shows the number of 2018 collaborations, in absolute terms. Panel B shows the changes in collaborations for each year versus the previous year, as a percentage of 2018 collaborations.
Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 6.2022, February 2023.

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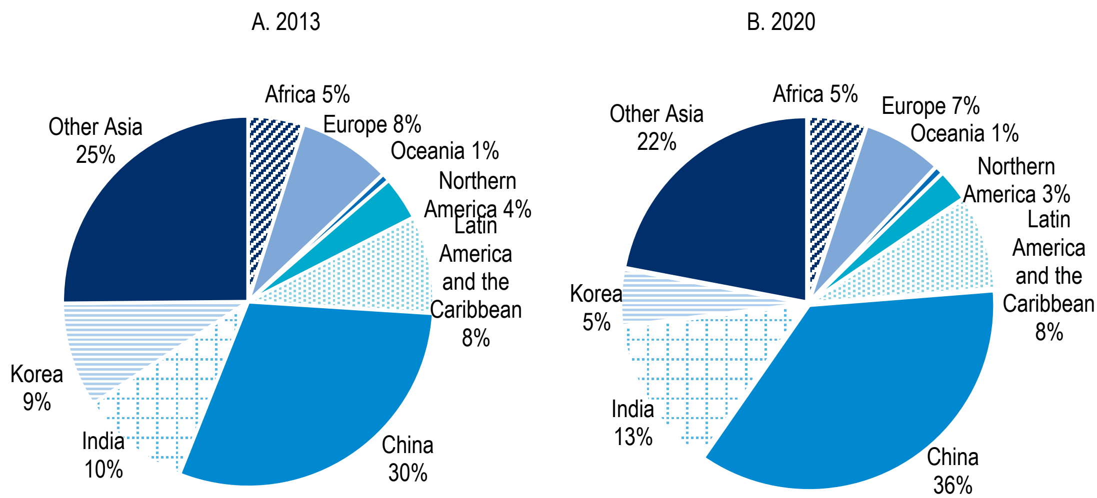
Foreign-born human resources for science and technology

Some of the largest research performers in OECD countries rely heavily on foreign-born PhDs and postdocs to perform their R&D. In the United States, for example, foreign-born workers comprised 19% of the science, technology, engineering and mathematics (STEM) workforce in 2019, up from 17% in 2010; 45% of workers in science and engineering occupations at the doctorate level were foreign-born, with the highest shares among computer and mathematical scientists. Around half of foreign-born workers in the United States whose highest degree was in a science and engineering field are from Asia, with India (22%) and China (11%) as the leading birthplaces (National Science Board, 2022[15]). Indeed, China and India make up almost half of foreign-born students in the United States (Figure 2.8). Data on net flows of scientific authors show recent declines in the United States, becoming a net outflow in 2021 (Figure 2.9). Net inflows of scientific authors into China mirror these declines to some extent, which points to Chinese scientists returning from the United States. The European Union's growing attractiveness for scientific authors is partly a result of Brexit, with EU scientists returning from the United Kingdom.

Figure 2.8. Foreign-born origin studying in the US tertiary education system

Percentage of foreign-born students from different countries and regions that make up the total



Source: (OECD, 2023[16]) (accessed 11 October 2022).

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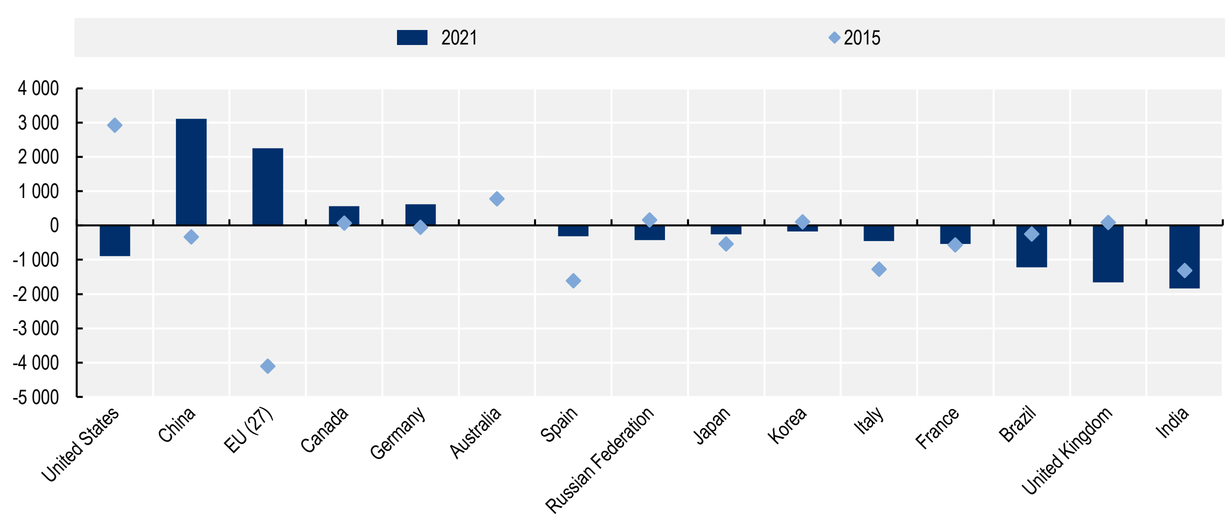
Figure 2.9. Net flows of scientific authors, top publishing countries, 2015 and 2021

Entries minus exits realised in the reference year



Note: Estimates are based on differences between annual fractional inflows and outflows of scientific authors for the reference economy, as indicated by a change in the main affiliation of a given author with a Scopus ID over the author's indexed publication span. An inflow is computed for year t and economy c if an author who was previously affiliated to another economy is first seen to be affiliated to an institution in that economy and year. Likewise, an outflow is recorded when an author who was affiliated to c in a previous period is first observed to be affiliated in a different economy in year t. In the case of affiliations in more than one economy, a fractional counts approach is used. In the case of multiple publications per author in a given year, the last publication in any given year is used as reference, while others are ignored.
Source: OECD calculations based on Scopus Custom Data, Elsevier, Version 6.2022, September 2022.

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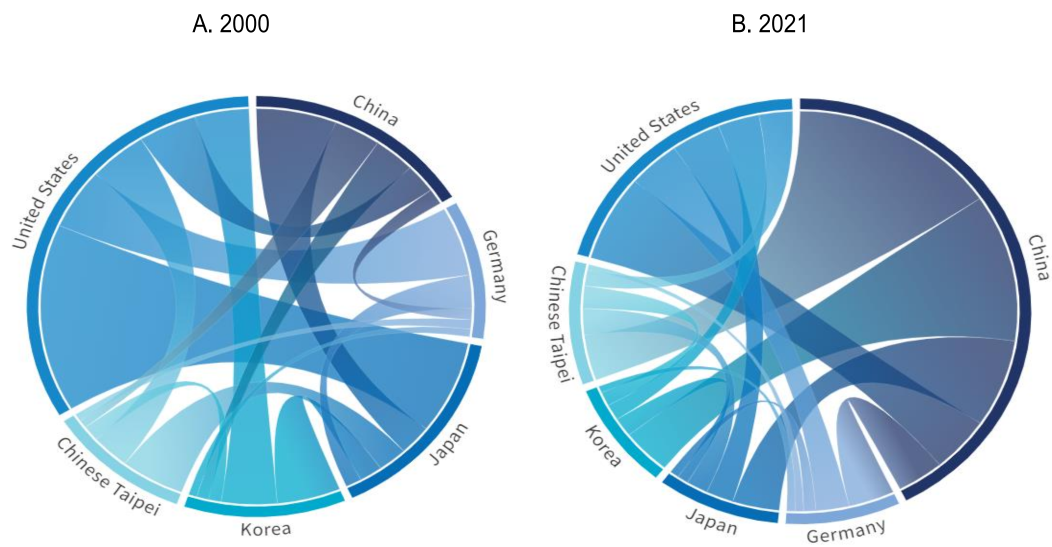
Global value chains in high R&D-intensive sectors

Changes in recent decades in the major importers[6] of intermediate products in high and medium-high R&D-intensive economic activities highlight how economies have become increasingly interconnected in global value chains. At the beginning of the 21st century, the United States was the largest importer of intermediate products in high and medium-high R&D-intensive economic activities, with Japan its most significant supplier. Twenty years later, China has become the largest importer (and exporter) of such intermediate products. It is also the main supplier to its neighbouring economies (Japan, Korea and Chinese Taipei) and the second-largest supplier to the United States, after Mexico (Figure 2.10). These interdependencies would make potential decoupling between China and OECD countries highly disruptive and costly.

Figure 2.10. Flows of intermediate products in high and medium-high R&D-intensive economic activities, selected economies

Import flows, in USD current prices



Note: Intermediate products in high and medium-high R&D-intensive economic activities are defined in https://www.oecd-ilibrary.org/science-and-technology/oecd-taxonomy-of-economic-activities-based-on-r-d-intensity_5jlv73sqqp8r-en. They include products from the following industrial International Standard Industrial Classification of All Economic Activities, Fourth version (ISIC 4) sectors: D20 Chemicals and chemical products; D21 Basic pharmaceutical products and pharmaceutical preparations; D26 Computer, electronic and optical products; D252 Weapons and ammunition; D27 Electrical equipment; D28 Machinery and equipment n.e.c.; D29 Motor vehicles, trailers and semi-trailers; D302A9 Railroad equipment and transport equipment n.e.c.; D303 Air and spacecraft and related machinery; D304 Military fighting vehicles; D325 Medical and dental instruments and supplies. Panel B: 2021 data for Korea corresponds to 2020. This selection of imports flows represented 20 % of the World imports of intermediate products in high and medium-high R&D-intensive economic activities in 2021.
Source: (OECD, 2023[17]) (accessed 6 February 2023).

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Reconfiguring interdependencies?

Managing international co-operation in science

The figures on international scientific collaboration illustrate that researchers from different countries work together regardless of governments' ideological positions. Scientific discovery occurs in an interconnected ecosystem that draws upon collective intellect, know-how, talent, financial resources and infrastructure from around the world. The impressive growth in China's scientific capabilities over the last two decades make it an attractive partner for many researchers in OECD countries, and vice versa. Furthermore, global challenges like the COVID-19 pandemic, climate change and other complex socio-economic issues cannot be tackled without international research collaboration (OECD, 2022[18]).

At the same time, it is likely that global research networks have yet to internalise fully the implications of growing technological sovereignty, particularly in research areas with dual-use potential. Declining collaboration between China and the United States in natural sciences and engineering since 2020 could accelerate (Figure 2.7). While much uncertainty remains, excessively risk-averse policies could trigger a more abrupt and extensive intellectual decoupling and disengagement. The policy challenge for OECD member countries is to enable their researchers to continue robust and principled academic engagement while protecting their interests and standing up for their values in a complex geopolitical environment (see Chapter 1). This will not be easy, and managing the risks and benefits of internationalisation will need to be informed by frequent data-driven mapping of research relationships to determine which areas are essential for more open science, and which are not (Joseph et al., 2022[19]). Researchers will also need to diversify their international linkages, drawing on support from research-funding agencies, which could do more to deepen their contacts with a wider range of partner organisations globally (Deutsche Forschungsgemeinschaft, 2022[20]).

Securitising high-tech commercial flows

The rapid pace of product and financial market integration at the global level, combined with the relentless pursuit of efficiency gains through global supply chains, have brought economic benefits but also exposed vulnerabilities to disruption, as shown during the COVID-19 pandemic. Increasing complexity has introduced logistical fragility into global supply chains, with mounting geopolitical tensions raising the risk of coercion to extract gains from partner countries elsewhere in the chain (OECD, 2021[21]).

As Figure 2.10 shows, China's growth and integration into the world economy has seen manufacturing firms in OECD countries use China increasingly as a source of high-tech inputs and a platform for final assembly. This has caused growing technological interdependency between China and OECD economies (e.g. in semiconductors), but also raised concerns about supply-chain vulnerabilities in critical technologies. In parallel, China has accumulated increasingly sophisticated technological capabilities and is already a market leader in some areas – such as 5G – and at the forefront in others, including AI, drones and other technologies with potential military applications (Goodman and Robert, 2021[4]).

These developments have raised national security concerns among OECD countries, leading to a growing "securitisation" of high-tech commercial flows. This is evidenced in the increasing use of barriers to direct market access, such as negative lists, export controls[7] and tightened foreign direct investment (FDI) screening, and indirect barriers, like national standards. OECD economies are also looking at options to diversify supply chains, making them more resilient and less vulnerable to disruptions and shocks. This could entail boosting global capacities to produce multiple reliable and sustainable sources of materials and inputs, intermediate goods and finished goods in priority sectors, as well as enhance logistics infrastructure capacity (US Department of State, 2022[22]).

Whether these new arrangements will end up being as efficient as current ones is an open question, but they could see distinct and decoupled technology ecosystems emerge in China and liberal market economies (European Chamber of Commerce in China and Mercator Institute for China Studies, 2021[23]).[8] The resulting re-division of the world into blocs separated by barriers will likely sacrifice some of the gains from specialisation, economies of scale, and the diffusion of information and know-how (OECD, 2022[13]).[9] It will also lead to competition that may undermine future co-operation on global grand challenges, and could signal the weakening of any notion of economic interdependency acting as a bulwark against future conflict.

Promotion: Enhancing industrial performance through STI investments

The second type of strategic autonomy policy intervention concerns promotion – notably in the form of holistic industrial policy, in which STI policy plays a prominent part. A revival of industrial policy has been the subject of active debate for more than a decade (e.g. (Rodrik, 2014[24]; Warwick, 2013[25]; Criscuolo et al., 2022[26])), particularly in light of the need for rapid sustainability transitions and the competitiveness threat posed by China's industrial policies. While the industrial and innovation policy mix in most OECD economies remains largely focused on R&D, tax incentives and earlier-stage investment support, there has been a resurgence in targeted interventions that are rationalised by geopolitical tensions, supply-chain concerns and various "green" targets (DiPippo, Mazzocco and Kennedy, 2022[27])[10]. Decarbonisation, in particular, calls for what has been termed an "industrial revolution against a deadline", where relying on price signals alone may mean the technological change needed to reach net-zero happens too late (Tagliapietra and Veugelers, 2020[28]) (see Chapter 3).

Most economists accept there exist sound theoretical rationales for industrial policies but are sceptical of governments' abilities to achieve well-targeted, timely and effective interventions in practice, mostly on account of informational asymmetries between the public and private sectors, and the political risks of policy capture by powerful insiders and special interests. Rodrik (2014[24]) argues that these hurdles are not insurmountable and in fact apply to most areas of government policy. Rather, the debate concerns the design of industrial policies, as well as the strong need for their evaluation and regular reassessment (Warwick, 2013[25]).

In this regard, the OECD has outlined a framework for formulating industrial policy mixes that emphasises the potential complementarities between instruments along several lines (Criscuolo et al., 2022[29]; Criscuolo et al., 2022[26]). These include the distinction between horizontal and targeted policies, demand-pull and supply-push instruments, and policies that improve firm performance and those that affect the framework conditions for innovation. Chapter 3 outlines a similarly broad research and innovation ecosystem framework, focusing on holistic STI policies for promoting sustainability transitions. Mission-oriented innovation policies (MOIPs) incorporate a similar ecosystem perspective, but with a narrower focus on fulfilling a specific mission, such as achieving net-zero greenhouse gas (GHG) emissions by 2050. MOIPs are the subject of Chapter 5. This section briefly outlines the industrial strategies and some of their main policy instruments in China, the European Union and the United States.

China's "indigenous innovation" drive

Despite its remarkable economic success, China is still at risk of being caught in the middle-income trap. To escape this prospect, the Chinese government has launched several high-level initiatives over the years to promote technology development and the upgrading of its manufacturing base.[11] The "indigenous innovation" campaign launched in 2006 as part of the Guidelines on National Medium- and Long-term Programme for Science and Technology Development (2006-20) highlighted China's resolve to catch up with advanced industrialised nations and reflected a renewed focus on state intervention in technology development (Arcesati, Hors and Schwaag Serger, 2021[30]). The guidelines sought to support a comprehensive system of implementation by co-ordinating policies on R&D investment, tax incentives, financial support, public procurement, intellectual property and education (OECD, 2017[31]). Another watershed moment came in 2015 with the launch of the Made in China 2025 industrial policy, which shifted the focus from catching up to leapfrogging OECD countries at the innovation frontier, with a view to turning China into an STI "superpower" by 2049.

Since then, China has made rapid progress towards becoming a global leader in some technology areas. It has already forged ahead in fields such as 5G networks, and secured a strong position in areas like AI and electric-vehicle batteries (Zenglein and Holzmann, 2019[32]). It invests heavily in research, and its R&D intensity has already surpassed that of the EU27 (see Figure 2.2). The government also deploys some unique industrial policy instruments, especially government guidance funds, the state-owned financial sector, non-financial state-owned enterprises and the party-state's political guidance of private firms, to develop domestic technological capabilities.[12] As a whole, this industrial policy support means that China spends far more on supporting its industries than any other economy, an amount estimated at more than twice the level of the United States in dollar terms in 2019 (DiPippo, Mazzocco and Kennedy, 2022[27]).

Rising tensions with the United States in recent years have caused China's perspective on globalisation and interdependence to shift, with "technology security" emerging as a core dimension of the Chinese government's all-encompassing national security concept (Arcesati, Hors and Schwaag Serger, 2021[30]). Faced with an increasingly turbulent and unpredictable external environment, the Chinese government is looking to innovate its way out of many of the challenges it faces, and extols the importance of indigenous innovation as crucial to becoming self-reliant (China Power Team, 2021[33]). The 14th Five-Year Plan for National and Economic Social Development 2021-25) and its underpinning Dual Circulation Strategy, both of which are described below, aim to achieve self-sufficiency in core technologies and reduce China's reliance on foreign technologies such as advanced semiconductors, where it has critical dependencies.

The most recent initiatives covered in this chapter are Made in China 2025, the 14th Five-Year Plan, the Dual Circulation Strategy and Military-Civil Fusion, all briefly outlined in Box 2.1. These important initiatives are both highly general and concise, setting key goals, directions, priorities and frameworks. They are usually followed by more detailed and implementation-oriented action plans utilising tools and measures such as government investments, R&D programmes, demonstration projects, tax incentives, financing support and human-resource policies (OECD, 2017[31]). In fact, China has a very comprehensive set of STI planning documents from high-level strategies to the sectoral level, and many are replicated at the province level. China's government uses a sophisticated "strategic intelligence" system to monitor and scan domestic and foreign STI policies, strategies, inputs and outputs, and provides strategic advice to decision makers. The system draws on extensive databases managed by the Institute of Scientific and Technical Information of China, a research institute under the Ministry of Science and Innovation. The institute gathers and disseminates data covering domestic patents, talents, and the achievements of major science and technology-funding programmes. It also gathers and disseminates "open-source" intelligence on foreign STI sources, trends and achievements, promoting technology transfer from foreign sources to national industries (Center for Security and Emerging Technology, 2021[34]; Arcesati, Hors and Schwaag Serger, 2021[30]).

Box 2.1. Selected Chinese industrial policy initiatives

Made in China 2025

Launched in 2015, Made in China 2025 was an important milestone in Chinese STI policy as the first of a series of national ten-year strategic initiatives covering the long-term comprehensive development of China's manufacturing industry (OECD, 2017[31]). Its aim is to build a world-class innovation system and achieve global dominance in key technologies, to achieve major breakthroughs over the next decades (Zenglein and Holzmann, 2019[32]). While Made in China 2025 called for a broader upscaling of manufacturing capabilities, it prioritised progress in ten key industries.[1] It identified nine paths for achieving its ambition, including making various enhancements to Chinese innovation capabilities, promoting digitalisation, and targeting priority technologies and products. Within these nine paths, it further identified eight directions for implementation related to system reform, fair market competition, finance, tax, human resources, SMEs, international openness and co-ordination mechanisms. A technology roadmap for priority technologies and products was also published in 2015, and later updated (OECD, 2017[31]).

14th Five-Year Plan (2021-25)

While China's five-year plans are wide-ranging, its 14th Five-Year Plan for National Economic and Social Development places technology and innovation at the heart of China's modernisation drive (Arcesati, Hors and Schwaag Serger, 2021[30]). It echoes many of the ambitions outlined in Made in China 2025, emphasising the goal of reducing China's reliance on foreign technology as quickly as possible through industrial modernisation and domestic technological innovation efforts, to become ultimately a global leader in strategic emerging industries, frontier technology and basic science (Grünberg and Brussee, 2021[35]). The 14th Five-Year Plan includes a commitment to formulating and implementing strategic scientific plans and projects related to national security and economic development, focusing on seven areas. It promises to establish a number of national laboratories and to support the development of new types of research universities and institutes. It also commits to boosting spending on basic research, an area where China has historically lagged (China Power Team, 2021[33]). It aims to develop and implement a ten-year action plan for basic research, acknowledging its role in the development of indigenous breakthroughs in key science and technology fields. The plan incorporates innovation indicators, including a commitment to increasing R&D expenditures by 7% per year, almost doubling innovation patents over the plan's five-year period, and increasing the digital economy's share of GDP to 10% by 2025 (Xinhua News Agency, 2021[36]). For the first time, the Five-Year Plan also includes a medium-term outlook (until 2035).

Dual Circulation Strategy

The Dual Circulation Strategy is China's overarching plan for economic development and global integration. Its name derives from the dual goals of strengthening innovation capabilities domestically (via "internal circulation") while maintaining global ties (via "external circulation") (Bilgin and Loh, 2021[37]). It is enshrined in the 14th Five-Year Plan and seeks to solve China's core development challenges in the next decades, ranging from domestic issues (such as insufficient innovation capacity, income disparity and environmental degradation) to external risks (such as growing protectionism and technological dependence) (Brown, Gunter and Zenglein, 2021[38]). The strategy aims to do this by (i) reducing external demand as a driver of economic growth, by boosting domestic consumption; (ii) positioning China as a global manufacturing powerhouse in high value-added products; (iii) attaining higher levels of self-sufficiency in key areas, by enhancing innovation; and (iv) ensuring access to critical inputs, by diversifying supply chains and funnelling investment into specific sectors (China Power Team, 2021[33]). As China becomes more self-reliant through this strategy, it could provide the grounds for greater decoupling. On the other hand, the Dual Circulation Strategy does not aim for complete autarky, and foreign technology and capital are viewed as vital for China to become more self-sufficient and upgrade its economic structure (Bilgin and Loh, 2021[37]).

Military-Civil Fusion

Inspired in part by the success of the United States in developing productive linkages between its civil and defence technology ecosystems, China has been pursuing a Military-Civil Fusion initiative for several years. This was subsequently mainstreamed in 2018 as part of its 13th Five-Year Plan. The initiative 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. It has expansive ambitions, from enhancing co-operation in big data infrastructures to mobilising national defence (Kania and Laskai, 2021[39]).

1. The key industries are as follows: Information Technology (AI, IoT, smart appliances); Robotics (AI, machine learning); Green Energy and green vehicles (energy efficiency, electric vehicles); Aerospace equipment; Ocean Engineering and high-tech ships; Railway equipment; Power equipment; New materials; Medicine and medical devices; and Agriculture machinery.

The European Union's "open strategic autonomy" agenda

While expenditures by the European Commission on STI and industry policies are a fraction of those of EU Member States, they have a strong influence on the direction of European policies. EU policy has played a central part in promoting the concept of "open strategic autonomy" in Europe as part of the green and digital "twin transitions" agenda. EU Member States have different views on the meaning and implications of strategic autonomy. Some prefer a European industrial policy that targets specific sectors, while others prefer more horizontal measures that create the conditions for innovation (Lewander et al., 2021[40]). On the eve of the COVID-19 pandemic, the European Commission presented a new industrial strategy to support the twin green and digital transitions, make EU industry more competitive globally, and enhance Europe's open strategic autonomy (European Commission, 2020[41]). It updated the strategy in 2021 to reflect lessons from the pandemic, notably the need for a better understanding of Europe's strategic dependencies, how they may develop in the future and the extent to which they could lead to vulnerabilities. The industrial strategy proposed strengthening and diversifying external trade on the one hand, and strengthening Europe's innovation capacity in key strategic areas on the other, using tools such as Important Projects of Common European Interest (IPCEIs) (see Box 2.2), industrial alliances, and funding from Horizon Europe and the European Defence Fund (EDF) (European Commission, 2021[11]).

In response to the COVID-19 pandemic, the European Union launched the NextGenerationEU fund in 2020, worth EUR 750 billion (euros) (in 2018 prices). The purpose of the fund is to mitigate the economic and social impact of the pandemic, and make European economies and societies more sustainable, resilient and better prepared for the challenges and opportunities of the green and digital transitions. The Recovery and Resilience Facility (RRF) is the key instrument at the heart of NextGenerationEU. The European Union views the RRF as a unique opportunity to accelerate the development and transformation of STI systems in Member States. The (European Commission, 2022[42]) has estimated the overall expenditure for research and innovation in Member States' recovery and resilience plans at around EUR 44.4 billion, typically representing between 4% and 13 % of a country's RRF allocation. These investments target the green transition, digital technologies and health, and are accompanied by STI policy reforms in some countries.

Although the European Commission continues to channel much of its support for research and innovation through Horizon Europe and the structural funds, the toolkit of its innovation policy has expanded over the years to cover the whole innovation chain. This had led to new initiatives, including the European Innovation Council, established in 2021 with a budget of EUR 10 billion over seven years.[13] The European Commission adopted a New European Innovation Agenda in 2022 to position Europe at the forefront of what is described as a new wave of "deep-tech" innovation. Deep tech is rooted in cutting-edge science, technology and engineering, and calls for breakthrough R&D and large capital investments. The agenda outlines dedicated actions to improve access to finance for European start-ups and scale-ups; experiment new ideas through regulatory sandboxes; help create "regional innovation valleys", including in lagging regions; attract and retain talent in Europe; and improve the STI policy framework (European Commission, 2022[43]). Many of the actions are based on existing measures, which will be extended or better linked to other measures.

Box 2.2. Important Projects of Common European Interest (IPCEIs)

The Treaty on the Functioning of the European Union provides the possibility to approve state aid for IPCEIs. While these provisions have been used very rarely until recently, there is now strong momentum to use IPCEIs more extensively to achieve the European Union's quest for strategic autonomy (Szczepański, 2020[44]). IPCEIs are ambitious cross-border breakthrough innovation and infrastructure projects led by EU Member States, which identify the scope of the project, select participating companies and agree on project governance. Since Member States' support constitutes state aid under EU rules, IPCEIs have to be notified to the European Commission for assessment and must meet various criteria for approval (European Commission, 2021[45]). The IPCEI on microelectronics was the first to be approved in 2018, followed by an IPCEI on batteries in 2019. A second IPCEI on batteries was approved in 2021 and aims to support research and innovation throughout the battery value chain – from extraction of raw materials, through the design and manufacturing of battery cells and packs, to the recycling and disposal in a circular economy – with a strong focus on sustainability (European Commission, 2021[45]). A further IPCEI on the hydrogen-technology value chain was approved in 2022, covering the generation of hydrogen, fuel cells, storage, transportation and distribution of hydrogen, and end-users applications, particularly in the mobility sector (European Commission, 2022[46]). To give a sense of the scale and coverage of IPCEIs, the second battery initiative was established by 12 Member States, which will provide up to EUR 2.9 billion in funding, to be complemented by an expected EUR 9 billion in private investments; the hydrogen initiative involves 15 Member States providing up to EUR 5.4 billion in public funding, with an expected private-sector investment of EUR 8.8 billion.

Growing emphasis on dual-use technologies

Well before Russia's war of aggression against Ukraine, it was already apparent that the European security environment had shifted, with Europe's democratic systems challenged by a mix of hybrid threats (European Commission, 2021[47]). The European Commission 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 (EEAS, 2022[48]). Many critical technologies for security and defence increasingly originate in the civilian domain, and use critical components with dual-use possibilities. The European Commission published the "Action Plan on Synergies between civil, defence and space industries" in 2021, which aims to enhance complementarities between civil and defence EU 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 (European Commission, 2021[49]). It followed this up in 2022 with its "Roadmap on critical technologies for security and defence". The roadmap identifies technologies critical for EU security and defence. It seeks to ensure that defence considerations are better incorporated in civilian European research and innovation programmes, and vice versa. It also aims to promote from the outset an EU-wide strategic and co-ordinated approach for critical technologies for security and defence, and to reduce strategic dependencies and vulnerabilities in the value and supply chains associated with these technologies (European Commission, 2022[50]).

In practice, plans like these have translated into increasing co-operation and co-ordination between civil programmes like Horizon Europe and defence initiatives like the EDF, to make more effective use of resources and technologies and create economies of scale (European Commission, 2020[51]; European Commission, 2020[41]; Finkbeiner and Van Noorden, 2022[52]). Established in 2021 with a budget of EUR 8 billion over seven years, the EDF promotes R&D co-operation between public research (typically research and technology organisation, rather than universities) and firms. It supports competitive and collaborative projects throughout the entire R&D cycle, including design, prototyping and testing.[14] The action plan also includes the new Observatory on Critical Technologies for the space, defence and related civil sectors, which will begin work in 2023. The observatory will identify, monitor and assess critical technologies, including their potential application and related value and supply chains, and any root causes of strategic dependencies and vulnerabilities (European Commission, 2022[50]).

United States: A "modern American industrial strategy"

Although the United States has tended to eschew a formal national industrial strategy, publicly funded R&D and procurement in defence-related sectors have historically underpinned development and US leadership in many technologies, including integrated circuits, GPS and the internet. Breakthroughs like these are the result of civil-military integration involving a world-class network of US universities and firms collaborating closely, for example, through federal organisations like the Defense Advanced Research Projects Agency (Kania and Laskai, 2021[39]). China's recent ascendancy in emerging critical technologies like 5G has led several American policy makers and analysts to question whether this approach is sufficient for the 21st century, amid calls for a more active national industrial strategy that serves not only economic development interests, but also national security (Guile et al., 2022[53]). Following this line of argument, the United States needs to take a more formal, systemic and integrated approach to industrial policy if it is to prevail in its technological rivalry with China. Such an approach should cover all economic sectors that contribute to the country's overall technical capabilities and production resilience, and aim to enhance the innovation-enabling "operating environment" in which firms, institutions and individuals work (Atkinson, 2020[54]; Allison et al., 2021[55]; SCSP, 2022[56]).

Somewhat along these lines, the Biden Administration has signed three major bills with bipartisan support:

- The CHIPS and Science Act (2022) is discussed below (Box 2.3). Briefly, it aims to ensure the United States maintains and advances its scientific and technological edge by investing in R&D, skills and manufacturing in semiconductors, as well as in other technological areas such as nanotechnology, clean energy, quantum computing and AI. It also aims to unlock STI opportunities beyond a few regions on the coasts and targets those groups who have been historically left out (The White House, 2022[57]). The US Department of Commerce (2022[58]) has since published a USD 50 billion implementation strategy for the "CHIPS for America Fund", which will disburse a large tranche of the act's funding. The National Science Foundation has also established a technology, innovation and partnerships directorate to strengthen the commercialisation of research and technology.[15]
- The Inflation Reduction Act (2022) targets small businesses through measures that include (i) doubling the refundable R&D tax credit for small businesses, from USD 250 000 to USD 500 000; (ii) issuing domestic content requirements and offering targeted tax incentives to spur the growth of American supply chains across technologies like solar, wind, carbon capture and clean hydrogen; (iii) supporting the deployment of distributed zero-emission technologies through a new "Clean Energy and Sustainability Accelerator", which will prioritise over 50% of its investments in disadvantaged communities; and (iv) assisting rural electric cooperatives by funding clean energy and energy efficiency upgrades (The White House, 2022[59]).
- The Infrastructure Investment and Jobs Act (2021) aims to strengthen domestic production to revitalise the US industrial base. It includes commitments to build zero-emission vehicles and their components domestically, using grants to support battery and battery component manufacturing, manufacturing facilities, and retooling and retrofitting of existing facilities. It also aims to invest in advanced energy manufacturing facilities and clean energy demonstration projects in communities where coal mines or power plants have been shut down (The White House, 2021[60]).

According to The White House (2022[61]), a strong vision of a "modern American industrial strategy" unifies these laws. This strategy commits to making substantial public investments in three key areas, namely infrastructure, innovation and clean energy. It seeks to "crowd in" private investment and spur innovations that work towards achieving core economic and national security interests. These laws are all multi-year mobilisation efforts but are expected to spur investments at a historical scale, totalling USD 3.5 trillion over the next decade when counting both public capital and private investment.

The industrial strategy strongly emphasises developing manufacturing capabilities, since these create well-paid jobs, decrease supply-chain vulnerabilities, and are the basis for building and maintaining technological leadership. As such, they are part of the strategy to contribute to a more resilient and secure US economy, better positioning the United States to weather future shocks. Addressing inequality is a critical part of the approach, and many of the strategy's instruments target disadvantaged groups and areas. Moreover, for all its emphasis on developing domestic technological and manufacturing capabilities, the strategy recognises the importance of international partnerships to fulfil its mandate (The White House, 2022[61]).

Strengthening international STI alliances

The third type of strategic autonomy policy intervention is rooted in the projection of national interests in international regulations, norms, standards and alliances. The confluence of issues related to trade, technology and democracy has broadened perspectives on the role of technology in shaping and driving new international alignment and alliance patterns (Soare and Pothier, 2021[8]). At one level, these alliances are forged between like-minded democracies, such as OECD countries, which can gain (for example) from regulatory co-operation to jointly set global technology standards based on shared values (Bauer and Erixon, 2020[62]). At another level, they aim to project competing norms and values globally through technology investments and assistance, particularly in low- and middle-income economies. Examples of related policies include China's Belt and Road Initiative (BRI), and the G7 Partnership for Global Infrastructure and Investment initiative.

In some respects, these efforts at alliance-building represent a "recoupling" with like-minded and trustworthy allies – sometimes referred to as "friend-shoring". Strategic autonomy should not be conflated with isolationism, and no single country has all the technological capabilities required to successfully compete in the global economy and preserve its national security. Countries can amplify their domestic innovation strengths through well-chosen strategic alliances, while at the same time enhancing their own national security by supporting the technological capabilities of others.

This section starts with China, highlighting the science and technology aspects of its ambitious BRI and its recent push to shape international technological standards. It then turns to new technology alliances forged by the European Union and the United States.

China's Belt and Road Initiative and standardisation push

Belt and Road Initiative (BRI)

Initially launched in 2013, the BRI is China's signature foreign policy initiative, surpassing the post-Second World War Marshall Plan as the largest global infrastructure project ever undertaken. Chinese banks and businesses have invested billions of dollars under the BRI to fund and develop telecommunications infrastructure, power plants, ports and highways in dozens of countries. Its scope has since expanded to include a Digital Silk Road aiming to improve recipient countries' telecommunications networks, AI capabilities, cloud computing, and e-commerce and mobile payment systems (among other high-tech areas), as well as a Health Silk Road aiming to put China's vision of global health governance into action (Council on Foreign Relations, 2021[63]). China is also using the BRI, particularly its Digital Silk Road component, to complement its efforts to promote domestic standards in international standards organisations and industry groups (see below) and advance regulatory harmonisation. By 2021, the BRI encompassed over 140 countries, representing close to 40% of global output and 63% of the world's population (Huang, 2022[64]).

The BRI includes STI activities that address developmental challenges, particularly in agriculture, energy and health care. Already in 2016, the Ministry of Science and Technology, the National Development and Reform Commission, the Ministry of Foreign Affairs and the Ministry of Commerce jointly released the Plan on Cooperation in Science, Technology and Innovation under the BRI (MOST (China Ministry of Science and Technology), 2017[65]). Science and Technology Daily (2022[66]) reports that by the end of 2021, China had engaged in STI co-operation with 84 countries through the BRI, supporting 1 118 joint research projects and establishing 53 joint laboratory projects. Furthermore, more than 30 bilateral or multilateral technology transfer centres between China and other countries had been built thanks to the BRI. Since 2016, the BRI has supported the exchange and training of around 180 000 science and technology personnel in China, and over 14 000 young scientists for short-term research work. While it is difficult to estimate the costs of these activities, Chen (2019[67]) estimates that the Chinese Academy of Sciences alone had already provided around USD 268 million to STI projects associated with the BRI by 2019, a figure that is likely much larger today.[16]

The Chinese Academy of Sciences also established in 2018 the Alliance of International Science Organizations (ANSO), a non-profit, non-governmental international scientific organisation that aims to support the needs and scientific capacity-building of the Global South through partnerships and co-operation with its member countries and institutions. ANSO currently has 67 members from 48 countries, including 27 national academies, 23 universities, 10 national research institutes and agencies, and 7 international organisations. It funds and organises fellowships and scholarships, training programmes and collaborative research, and offers awards and prizes to both individuals and organisations. Its budget is modest – around USD 13 million in 2021, most of which funded scholarships and collaborative research projects.[17]

China Standards 2035

Standards are critical to innovation: they provide a foundation for technology development and interoperability, and safeguard global market access to technologies (Blind, 2013[68]). Following the Made in China 2025 strategy, the Chinese government launched China Standards 2035 in 2018. This strategy aims to optimise the governance of standardisation in China, enhance its effectiveness and improve the level of internationalisation of China's standards.[18] In particular, it aims to improve the traditionally weak interaction between standardisation and technological innovation in China, and establish a formal mechanism to link scientific and technological projects and standardisation work (Xinhua News Agency, 2021[36]). This will be important for China as it seeks to develop R&D ecosystems that elevate whole-sector capacities, particularly in critical and emerging industries like AI, quantum computing and biotechnology (Wu, 2022[69]). China Standards 2035 also aims to promote compatibility between Chinese standards and the international standards systems, including through mutual recognition and co-ordinated development of domestic and foreign standards. The strategy also promotes standards co-operation within the BRI (Xinhua News Agency, 2021[36]).

International standards emerge from a variety of sources, with international standard-setting organisations playing important roles.[19] Firms collaborate internationally with other players (including competitors) within these organisations to develop and adopt standards created through co-ordinated technical efforts (Shivakumar, 2022[70]). Thanks to their technological supremacy, US firms have taken the lead in creating and setting international standards in these fora for much of the post-Second World War era. However, as China's innovation capacity grows in key technologies, its capability to influence international standards is also set to increase (Wigell et al., 2022[71]). This is creating considerable uncertainty, as the United States (and other like-minded countries) and China have different styles of engagement and hold different values. While participants in these bodies include a mix of government and private-sector researchers from member countries, the US approach has been to let the private sector take the lead, leveraging its extensive technical expertise and experience, and its knowledge of market need and demands (Goodman and Robert, 2021[4]). By contrast, China (and to some extent, the European Union) takes a more government-led approach, which some interpret as a politicisation of what has been widely perceived until now as a technocratic process. Technical standards also set the norms that govern the privacy and security of different technologies, particularly digital technologies. Since these have so far been based on the values and norms of liberal market economies, there are concerns that China's increasing domination in standard-setting organisations could pose a strategic risk to their integrity owing to diverging values (Wigell et al., 2022[71]). These tensions have led to fears that the role of international standard-setting organisations in establishing fair and credible standards will be undermined, ultimately damaging technological progress and market competition (Shivakumar, 2022[70]).

New alliances involving the European Union and the United States

Both the United States and the European Union have made recent pronouncements on the importance of international engagement to promote democracy-affirming norms and values, and reduce risks to national security inherent in technologies with dual-use potential. For example, in its industrial strategy plans, The White House acknowledges the importance of supply chain diversification, including through efforts to “friend-shore” some production (The White House, 2022[61]).

EU-US Trade and Technology Council

Having convened for the first time in 2021, the EU-US Trade and Technology Council aims to promote the responsible use of technologies, in line with democratic values and protection of human rights. It seeks to enhance trans-Atlantic co-operation on a range of issues, including export controls and FDI screening, in defence of national security, secure supply chains (especially with regard to semiconductors) and technology standards, including co-operation on AI. In all, it aims to ensure joint leadership in setting global norms for emerging and other critical technologies, and counter authoritarian influence in the digital and emerging technology space (EU-US Trade and Technology Council, 2021[72]). The council has established ten working groups to explore co-operation on these topics, in full respect of each side’s regulatory autonomy.[20]

Other regional groupings

The Quad is a loose grouping between Australia, India, Japan and the United States that promotes shared democratic values and respect for universal human rights in the ways technology is designed, developed, governed and used (The White House, 2021[73]). Its focus includes critical and emerging technologies (for which it recently issued “Principles for Critical Technology Supply-Chain Security”, organised around the pillars of security, transparency, autonomy and integrity),[21] climate-change mitigation and adaptation, and space technologies. The Quad also launched the Quad Vaccine Partnership in 2021 to advance equitable access to safe and effective vaccines in the Indo-Pacific region (Huang, 2022[64]). The Quad operates through expert working groups and international meetings, including biennial leaders’ summits.

A new, larger grouping covering the Asia-Pacific region was launched in 2022, known as the Indo-Pacific Economic Framework for Prosperity.[22] One of its chief aims is to diversify supply chains to ensure secure access to semiconductors, critical minerals and clean energy technology (The White House, 2022[74]). The United States also announced the Americas Partnership for Economic Prosperity in 2022 to help supply chains in the region be more resilient against unexpected shocks, and to promote innovation in both the public and private sectors (The White House, 2022[75]).

Group of Seven (G7)

The G7’s agenda has long covered STI issues, and the initiatives outlined here are among the latest in a long line. The largest initiative to date is the Partnership for Global Infrastructure and Investment (PGII), announced during the 2022 G7 Leaders’ Summit. The partnership aims to mobilise USD 600 billion in global infrastructure investments by 2027, with up to EUR 300 billion in investments channelled through the European Union’s Global Gateway initiative,[23] and USD 200 million coming from the United States (The White House, 2022[76]). Through blended finance, the PGII seeks to mobilise public and private resources in pursuit of values-driven, high-quality and sustainable infrastructure development. The European Union’s Global Gateway initiative focuses on digital, climate and energy, transport, health, and education and research, and is underpinned by a values-based approach promoting democratic values, high standards, strong governance and transparency (Liao and Beal, 2022[77]). The US initiative focuses on clean energy, secure digital networks and infrastructures, advancing gender equality and health security

(The White House, 2022[78]). Both initiatives emphasise the competitiveness benefits of these investments for their domestic firms, in addition to their job creation potential. Both also call for a whole-of-government approach, given the levels of investments involved and their expansive coverage.

Other recent relevant G7 initiatives include the Working Group on the Security and Integrity of the Global Research Ecosystem, which was established to develop principles, best practices, and a virtual academy and toolkit for research security and integrity (G7-Summit, 2022[79]); and a new Climate Club to accelerate climate action and increase ambition, with a particular focus on the industrial sector (G7, 2022[80]).

Strengthening strategic autonomy in action: Semiconductors and critical minerals

Policy discussions on technological sovereignty and vulnerabilities from interdependency often cite two prime examples: semiconductors and critical minerals. OECD countries and China are investing heavily in both areas, using a mix of protection, promotion and projection policies, as described below.

Semiconductors

Semiconductors are the building blocks of digital technologies and are most widespread in telecoms, computers and other consumer electronics, as well as motor vehicles and medical devices (OECD, 2021[21]). Semiconductor production is fragmented and specialised in a highly cost-efficient global supply chain, which begins with chip design[24] and continues through semiconductor manufacturing, testing, assembly and packaging, before reaching end-user companies that incorporate the chips into their products. No country or region has control over the entire value chain as each actor performs different steps of the production process according to their comparative advantages (Varas, 2021[81]). However, those segments involving manufacturing, assembly and testing are more concentrated,[25] mainly because of the enormous upfront investment costs in building state-of-the-art production facilities. While the United States once dominated semiconductor production, many of its firms moved to a “fabless” production model some time ago (or were established as such from the outset, e.g. Qualcomm), outsourcing their chip designs to contract manufacturing companies that specialise in operating foundries for third parties (European Commission, 2022[82]). Today, Korea and Chinese Taipei are typically in the middle of the supply chain: their semiconductor foundries import silicon wafers and equipment from Japan, Europe and the United States to produce chips that are then exported to China for integration into consumer goods, which are then re-exported to OECD countries (OECD, 2019[83]).

A major driver of innovation in the sector is miniaturisation of microprocessors that squeeze an ever-increasing number of transistors into a given area to make them faster and more power-efficient. The most advanced chips currently in production have a length of 5 nanometres (nm), which is expected to fall to 2nm by 2026. PCs and mobile phones are the main drivers of miniaturisation, and their high production volumes help to sustain the high cost of technology development and state-of-the-art production facilities. Chipmakers typically invest about one-third of their revenues in R&D and equipment. The cost of building a leading-edge fabrication plant can be as high as EUR 20 billion (with an additional EUR 5 billion per year to operate the plant). Only two companies, TSMC (Chinese Taipei) and Samsung (Korea), currently manufacture chips at 5nm, while Europe had no foundries that manufacture components below 22nm in 2021 (European Commission, 2021[11]).

The high concentration of semiconductor manufacturing in Asia raises concerns about vulnerability to production disruptions. The effect of such disruption would be more consequential because the semiconductor industry is an upstream industry. i.e. it supplies inputs to a wide range of other industries (Haramboure et al., forthcoming[84]). Recent semiconductor shortages, related to exceptional demand and supply shocks associated with the COVID-19 pandemic, have only served to exacerbate supply-chain concerns. Similarly, Asian countries look to reduce vulnerabilities tied to their dependence on US chip design and the most advanced European photolithography equipment. While somewhat behind global leaders in producing the most advanced chips, China is concerned about export controls, such as those recently announced by the United States to restrict its ability to obtain advanced computing chips, develop and maintain supercomputers, and manufacture advanced semiconductors (US Department of Commerce, 2022[85]).

Until recently, the bulk of public budgetary support in OECD countries has been upstream, targeting the R&D activities of semiconductor firms with research grants and R&D tax incentives. This reflects their specialisation in research-intensive segments of semiconductor supply chains.[26] By contrast, China has used massive subsidies to reduce its reliance on imports and its vulnerability to unilateral US export control restrictions, earmarking as much as USD 200 billion over a ten-year period under its Made in China 2025 plan to strengthen domestic research and manufacturing capabilities across the whole supply chain (EPRS, 2022[86]).[27] Coupled with pressures from semiconductor shortages and renewed interest in industrial policies to promote inclusive economic competitiveness and national security, this sort of support has kicked-off a “subsidy race”, with all of the main players (i.e. the United States, the European Union, Korea, Chinese Taipei and Japan) recently launching ambitious initiatives to promote their domestic semiconductor industries. By way of example, Box 2.3 outlines recent “chips acts” emanating from the European Union and the United States. Initiatives like these still focus on R&D investments, but also feature other industrial policy incentives, such as those that promote manufacturing (e.g. through subsidies for building and running fabrication facilities)[28] or seek to attract overseas investment and talent.

Box 2.3. Recent “chips acts” in the United States and the European Union

United States CHIPS and Science Act

Signed into law in August 2022, the CHIPS and Science Act provides USD 52.7 billion for semiconductor research, development, manufacturing and workforce development. This includes USD 13.2 billion for R&D and workforce development, and USD 500 million to advance international information and communications technology (ICT) security and semiconductor supply-chain activities. The act stipulates the establishment of a technology, innovation and partnerships directorate at the National Science Foundation, which was established in late-2022 to focus on fields like semiconductors and advanced computing, advanced communications technology, advanced energy technologies, quantum information technologies and biotechnology. It also expands fundamental and use-inspired research at the Department of Energy's Office of Science, and the National Institute of Standards and Technology. Besides supporting research, the act also seeks to strengthen the commercialisation of research and technology, for example, through a 25% investment tax credit covering capital expenses for the manufacturing of semiconductors and related equipment. To spur regional economic development bringing together businesses, universities and local communities, the act has earmarked USD 10 billion for the creation of regional partnerships that will develop technology, innovation and manufacturing sectors (The White House, 2022[57]).

European Chips Act

The European Chips Act, adopted by the European Commission in February 2022, seeks to strengthen the European Union’s semiconductor ecosystem, ensure the resilience of supply chains, reduce external dependencies and double the European Union’s global market share in semiconductors to 20% by 2030 (European Commission, 2022[87]). The act is expected to mobilise more than EUR 43 billion in public and private investments, with EUR 11 billion coming from repurposing existing funds under the European Union’s Horizon Europe and Digital Europe programmes (Zubașcu, 2022[88]). The act focuses on five strategic objectives: (i) strengthen research and technological leadership;

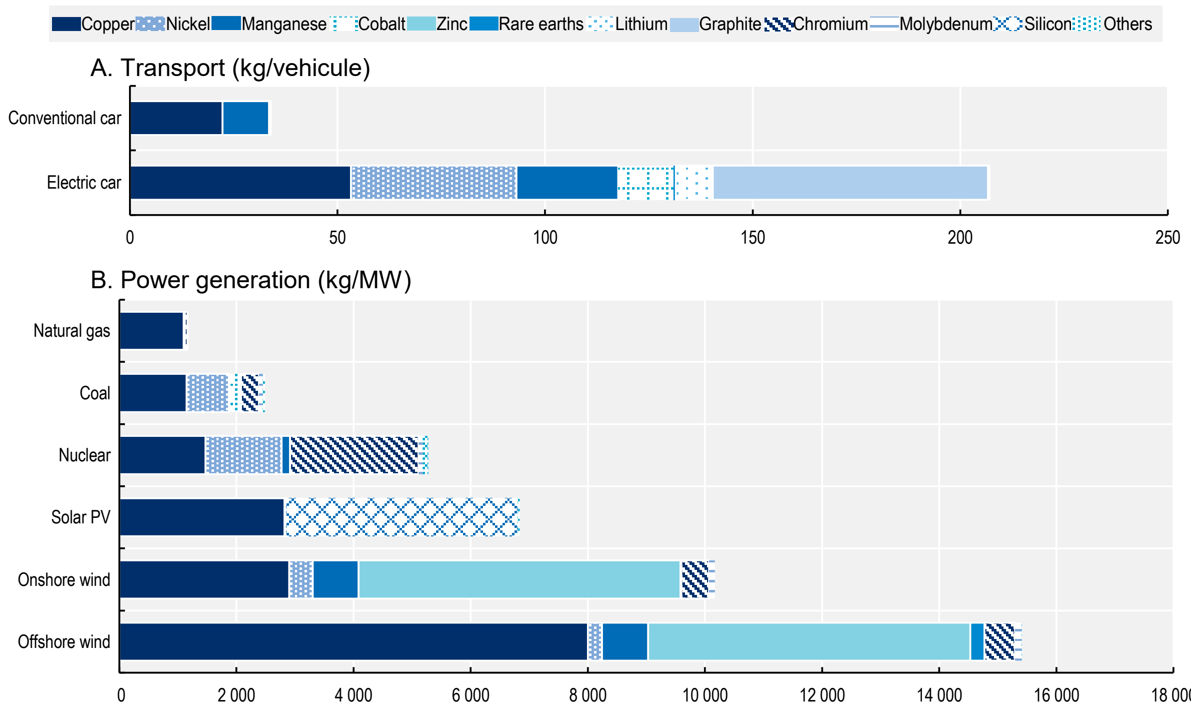
(ii) build and reinforce Europe’s capacity to innovate in the design, manufacturing and packaging of advanced chips; (iii) put in place a framework to increase production by 2030; (iv) address skill shortages and attract new talent; and (v) develop an in-depth understanding of global semiconductor supply chains (European Commission, 2022[87]). It proposes a three-pillar structure: Pillar 1 is intended to bolster large-scale technological capacity-building and innovation in the EU chips ecosystem, improving the transition ”from lab to fab”; Pillar 2 focuses on improving EU security of supply by attracting investment and enhancing production capacities within the European Union; and Pillar 3 aims to set up a monitoring and crisis response mechanism. Pillar 1, which is most relevant to this chapter, aims to reinforce Europe’s leadership in research; enable access across Europe to chip design tools, and pilot lines for prototyping and testing innovative chips technologies; promote education, skills and talent in microelectronics; and support a network of competence centres across Europe to promote innovative design and use of semiconductors systems (EPRS, 2022[86]). The act is still under review and is slated to be passed sometime in 2023.

Conducting the entire semiconductor manufacturing process in a single jurisdiction is neither feasible nor economically desirable (OECD, 2019[83]), and “strategic autonomy” cannot be reached without trusted international partners (Duchâtel, 2022[89]). The US CHIPS and Science Act is notable in this regard because it allocates USD 500 million over five years towards a CHIPS for America International Technology Security and Innovation Fund, which is intended to help the United States and like-minded governments co-ordinate their security and supply-chain activities (Valigra, 2022[90]).

Critical minerals

Many clean energy technologies rely on critical minerals such as copper, lithium, nickel, cobalt and rare-earth elements.[29] One of the major uses of these critical minerals is the production of permanent magnets for motors (e.g. in electric vehicles and wind turbine generators), where demand is expected to grow faster than for any other sector, driven by the strong uptake of clean energy technologies. According to the International Energy Agency (IEA) (IEA, 2021[91]), a typical electric car requires six times more mineral inputs than a conventional car, while an onshore wind plant requires nine times more mineral resources than a gas-fired plant for the same capacity (Figure 2.11). Moreover, in its “Net-Zero Emissions by 2050 Scenario”, the IEA estimates that mineral inputs for the production of energy-related infrastructure and end-use equipment will be up to six times higher in 2040 than today. Rare-earth permanent magnets are also used, for example, in ICT equipment (e.g. laptops, mobile phones and cameras) and medical resonance imaging equipment. They are also crucial for modern weaponry, including combat aircraft, drones and missile guidance systems (Alves Dias et al., 2020[92]; Matthews, 2022[93]).

Figure 2.11. Mineral intensity of selected clean and fossil energy technologies

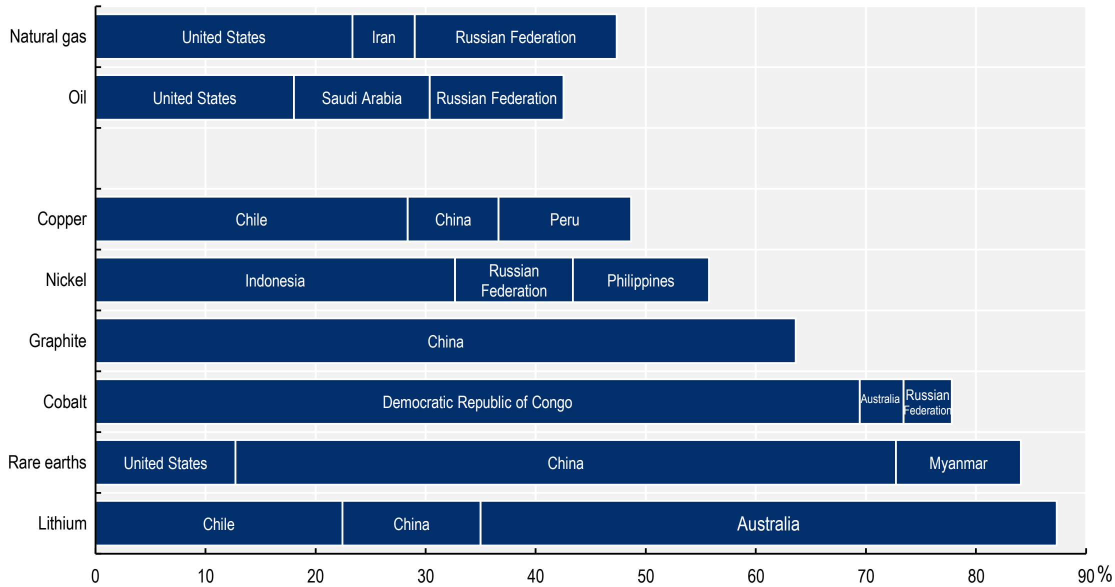


Note: Steel and aluminium are not included. The values for vehicles are for the entire vehicle, including batteries, motors and glider. The intensities for an electric car are based on a 75 kilowatt-hour (kWh) nickel manganese cobalt (NMC) 622 cathode and graphite-based anode. The values for offshore wind and onshore wind are based respectively on the direct-drive permanent magnet synchronous generator system (including array cables) and the doubly-fed induction generator system.
Source: (IEA, 2021[91]).

StatLink https://stat.link/389tob

Much policy attention focuses on rare-earth elements, by virtue of their importance and the geographic concentration of their production and processing (Figure 2.12). While rare earths are abundant in the Earth's crust, minable concentrations are rarer than for most other mineral commodities (US Geological Survey, 2022[94]). Owing to their environmental impacts, many mines and refining facilities have closed in recent decades.[30] China accounted for around 60% of rare earths mined in 2021, a decline compared to recent years. However, the processing of critical minerals is typically more concentrated than their extraction, and China heavily dominates production at every stage of the supply chain downstream of mining in both electric-vehicle batteries and photovoltaics (IEA, 2022[95]; Schwellnus et al., forthcoming[96]; OECD, 2022[97]). This is an outcome of policies that have supported the growth of a vertically integrated domestic supply chain as a strategic industrial sector (Politi, 2022[98]). It reflects China's growing market share in major downstream industrial ecosystems, which consume 70-75% of the global supply of rare earths (Alves Dias et al., 2020[92]).[31]

Figure 2.12. Current production of many energy-transition minerals is more geographically concentrated than for oil or natural gas



Source: IEA, Share of top three producing countries in extraction of selected minerals and fossil fuels, 2019, IEA, Paris https://www.iea.org/data-and-statistics/charts/share-of-top-three-producing-countries-in-extraction-of-selected-minerals-and-fossil-fuels-2019.

StatLink https://stat.link/7izuv2

China's embargo on rare-earth exports to Japan in 2010-11 raised supply concerns, yet separation and refining of rare-earth oxides continue to be predominantly performed in China (Alves Dias et al., 2020[92]; Nakano, 2021[99]).[32] The main Chinese rare-earth mining and processing companies are state-owned and subsidised through both direct and indirect policy measures (Gauß et al., 2021[100]). Beyond rare-earth elements, Russia's war of aggression in Ukraine has raised further concerns about the supply of other critical minerals for green technology. For example, Russia accounts for one-quarter of worldwide palladium exports and, together with Ukraine, one-third of global nickel exports (OECD, 2022[18]).[33] Ukraine is also a major exporter of neon gas, a by-product of steel production used in semiconductor lithography (OECD, 2022[13]).

These concerns have encouraged investment in new sources of supply to enhance the diversity and resilience of clean energy supply chains. For example, several new projects have been launched outside China, and some 20 projects are currently under development in Australia, Canada and the United States (IEA, 2021[91]). However, long lead times to bring new mineral production online, as well as various environmental and social impacts, all raise concerns about the stability and sustainability of critical mineral supply.[34] No single country will be able to solve these issues alone. Strengthened international co-operation, combining open markets, strategic partnerships and a diversity of supply sources, will be essential to guarantee the security, resilience and sustainability of critical minerals (IEA, 2022[95]; OECD, 2022[97]). Along these lines, the United States and key partner countries have announced the establishment of the Minerals Security Partnership (MSP), an ambitious new initiative to bolster critical minerals supply chains, and to ensure that critical minerals are produced, processed, and recycled in a manner that supports the ability of countries to realise the full economic development benefit of their geological endowments (US Department of Commerce, 2022[85]). New supplies of critical minerals can also be unlocked through innovation in production and processing technologies (for example, emerging technologies like direct lithium extraction, or increased metal recovery from low-grade ores or waste streams), which would help reduce the need for new primary supplies. Technologies that lower energy or water use can also bring environmental and operational benefits (IEA, 2021[91]).

Supply vulnerabilities could also be reduced by switching to other green technologies or critical mineral substitutes, although these are generally less effective (US Geological Survey, 2022[94]). Innovation is therefore key to making green technologies less material-intensive, and their critical materials easier to recycle. While performance-competitive rare earth-free permanent magnets are still some way off, research is driving progress to reduce consumption of rare earths in the automotive industry and in wind turbine generators (Alves Dias et al., 2020[92]). For example, emerging sodium-ion technologies that rely on abundant and cheap minerals, and solid-state batteries could lead to a step improvement in performance. For solar photovoltaics, organic and non-silicon thin-film technologies promise higher efficiencies and lower manufacturing costs, although they remain at the prototype stage (IEA, 2022[95]).

As for recycling, rare earths are currently recovered in limited quantities from batteries, permanent magnets and fluorescent lamps (US Geological Survey, 2022[94]). Indeed, only 1% of rare-earth elements are currently recycled in Europe (a proportion that is likely similar globally), highlighting the need to greatly enhance recycling systems and infrastructure (Alves Dias et al., 2020[92]). This will likely require government support to incentivise recycling of end-of-life products, support collection and sorting activities, and fund R&D on new recycling technologies (IEA, 2021[91]).

This is a systemic challenge that calls for various sorts of co-operation, including cross-governmental and international. Along these lines, both the European Union and the United States have launched wide-ranging policy initiatives in recent years to address vulnerabilities in supply chains for critical minerals, as briefly described in Box 2.4.

Box 2.4. Recent EU and US initiatives to enhance supply-chain diversity in critical minerals

European Union

The European Commission developed the Action Plan on Critical Raw Materials and founded the European Raw Materials Alliance (ERMA) in 2020. The action plan leverages Horizon Europe, European Regional Development Funds, and national research and innovation programmes on waste processing, advanced materials and substitution. For example, around EUR 300 million was earmarked under Horizon Europe’s first work programme (2021-22) to fund raw materials-related research and innovation. Projects should concentrate on exploration, mining, processing, refining, recycling and substitution, as well as skill development, responsible mining practices, international co-operation with resource-rich nations, secondary-source mapping in the European Union and identifying investment needs (European Commission, 2021[11]). ERMA has been entrusted with identifying and addressing legislative bottlenecks, and related opportunities that would enable the emergence of alternative European and worldwide rare-earth supply chains. It also aims to promote a circular economy around rare-earth elements, by advancing recycling and substitution (Gauß et al., 2021[100]). The European Commission has also published a foresight study on critical materials for strategic technologies and sectors in the European Union (European Commission, 2020[101]), which identified supply risks in the stages of processed materials, components and assemblies.

United States

Building on earlier analysis of supply-chain vulnerabilities, the Biden Administration announced in October 2022 the American Battery Materials Initiative to align and utilise federal resources to expand the end-to-end battery supply chain. It aims to promote close collaboration with stakeholders, allies and partners to develop more sustainable, secure and resilient supply chains. It covers steps to steer research, grants and loans that support ecologically responsible essential-mineral extraction, processing and recycling. The initiative also incorporates diplomatic efforts to construct reliable and sustainable global supply chains. These include the creation of the Mineral Security Partnership, to catalyse investment from governments and the private sector in strategic opportunities that adhere to high environmental, social and governance standards across the entire value chain. The United States Geological Services has also been awarded more than USD 500 million from the Bipartisan Infrastructure Law to better map mineral resources, preserve historical geologic data and samples, and construct an energy and minerals research centre (The White House, 2022[102]).

Outlook

Thanks to its ascendancy in science and technology, China has contributed significantly to the world's stock of knowledge through its scientific research. It has also accelerated innovation in technology areas, particularly photovoltaics and electric-vehicle batteries, that are critical to sustainability transitions. However, as China is often seen as a systemic rival to liberal market economies, its rise also raises policy concerns that have deepened in recent years as relations have deteriorated. These include growing competition in critical technologies that are expected to underpin future economic competitiveness and national security, diverging values and interests that challenge the international post-Second World War rules-based order, and growing vulnerability from supply-chain interdependencies.

Technology lies at the core of these concerns, prompting technology leaders such as the European Union and the United States to promote technological sovereignty and strategic autonomy as strategic policy goals. Countries have adopted policies to restrict access to technologies (protection), invest in ambitious domestic industrial policies to bolster their economic competitiveness (promotion) and strengthen international technology alliances with like-minded countries (projection). The chapter has to some extent taken a symmetrical view to illustrate that China has many similar concerns regarding liberal market economies, and it is perhaps unsurprising to see certain parallels in the policy goals set and instruments used. Policy domains such as trade, foreign affairs, defence and industry are driving many of these policy developments, while research and innovation ministries and funding agencies have played a less central role. Some of these policy domains have considerable science and innovation activities of their own (e.g. defence and industry), others less so (e.g. foreign affairs).

The policy developments outlined in this chapter could have profound effects on STI policies, but these remain underexplored, particularly at an internationally comparative level. Taking first the restrictions imposed by protection measures – related to export controls, FDI screening, negative lists and research security – these will lead to a certain degree of decoupling between technology (and possibly science) ecosystems in China and liberal market economies. It remains difficult to predict how far this decoupling will go. While autarky is unlikely, the global economy could split into rival blocs that significantly reduce science and technology linkages compared to today. Assuming governments apply protection measures flexibly on a case-by-case basis according to specific threats, continuous co-ordination between STI policy and other policy domains – notably trade and investment, foreign affairs and national security, and environment and energy – will be essential, although existing links in most countries remain weak. Most R&D in technology-intensive economies is conducted in firms, where trade and investment restrictions will be felt most keenly. Firms may also face skill shortages in economies dependent on overseas talent if mobility is hindered because of visa restrictions or an unwelcoming environment. This issue applies especially to public science, where overseas PhD students and researchers make up a sizeable part of the workforce, particularly in the United States.

Promotion measures, in the shape of technology-fuelled industrial policies, look more positive for science and innovation activities at first glance. More resources could be available, especially given the large investments proposed, although what sorts of research and innovation will be funded is less clear. Many of these policies adopt whole-ecosystem perspectives, so investments could cover the full range of the innovation chain – including basic science – and support the costs of new research and technical infrastructures. Many policies are also mission-oriented, mobilising multiple ministries and stakeholders, and involve ambitious public-private partnerships, which could bolster industry-academic links. Furthermore, they often seek to accelerate sustainability transitions and promote greater societal inclusion (see Chapter 3), which should affect how, where – and by whom – research and innovation are prioritised and performed. A large domestic skill-development programme is important in this respect – especially if international mobility declines and fewer overseas STEM personnel are available – but such investments take several years to yield benefits. New EU and US industrial policies have taken care to signal the importance of developing international linkages with like-minded countries, which could spur new opportunities for international co-operation in science and innovation. At the same time, there exists a danger of these large public investments descending into a "subsidy race", with countries competing more for private investments than co-operating on shared-interest technology developments. Domestic STI ecosystems could be damaged irreparably if high-tech firms are attracted by generous subsidies offered elsewhere and uproot their operations.

Finally, projection measures, particularly in the form of technology standards and international technology alliances and partnerships, could provide platforms for diversifying and intensifying cross-country STI linkages. These policy efforts can be seen as part of a "recoupling" agenda that targets supply chains, science and technology collaboration, and STI capacity-building in a wide range of high-, middle- and low-income economies. As with the other types of policies, cross-governmental co-ordination will be important, including with overseas development policies. Projection measures provide opportunities for OECD countries to diffuse and consolidate core values that promote sustainability, inclusion, and responsible research and innovation on a more global scale. They could also spur much-needed investments in research and innovation capacity-building in low- and middle-income countries, both aiding their development objectives and contributing to solutions to global problems.

To some extent, the policies outlined in this chapter amount to "disruption by design", but they also carry the risk of unintended consequences. This might be said of any ambitious policy agenda, of course, but the stakes are high, and mistakes are likely to be costly. Different technology supply chains have different vulnerability risks, and the same applies to international science collaboration: different critical technologies have varying dual-use potential, 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. It also highlights the importance of a whole-of-government approach, given the range of policy areas involved.

At the same time, while strategic competition presents its own challenges, it can also offer opportunities. For example, international competition could be a major spur for technology-driven growth, and measures to reduce technology dependency vulnerabilities through new investments could enhance global resilience to future shocks. Furthermore, a "recoupling" agenda could potentially forge new research and innovation alliances that may enable new science and technology leaders to emerge.

Strategic autonomy policies could be highly disruptive to existing STI ecosystems, whether presenting new challenges or offering new opportunities. Their effects, intended or not, should be anticipated, and adaptation and mitigation measures put in place. Much uncertainty and ambiguity remains, however, calling for a future-scenario process that maps the "possibility space". Taking a systemic view, such a process should consider the range of possible disruptions and their upsides and downsides, as well as alternative adjustment pathways and mitigation options. These policy measures could be disruptive at multiple levels, including for innovative firms, public research-performing organisations (such as universities and government labs) and even individuals (such as scientists), whose research collaborations and mobility could be enhanced or curtailed. They could also strengthen or hinder prospects for international STI co-operation to address global problems. A key challenge for multilateralism will be to reconcile growing strategic competition with the need for global action to tackle grand challenges, like climate change. This challenge is further discussed in Chapter 3.

References

Allison, G. et al. (2021), "The Great Tech Rivalry: China vs the U.S.", Belfer Center for Science and International Affairs, Harvard Kennedy School, https://www.belfercenter.org/sites/default/files/GreatTechRivalry_ChinavsUS_211207.pdf (accessed on 6 March 2023). [55]

Alves Dias, P. et al. (2020), *The role of rare earth elements in wind energy and electric mobility*, Publications Office of the European Union, Luxembourg, https://publications.jrc.ec.europa.eu/repository/handle/JRC122671 (accessed on 6 March 2023). [92]

Araya, D. and M. Mavinkurve (2022), *Emerging Technologies, Game Changers and the Impact on National Security*, Centre for International Governance Innovation, https://www.cigionline.org/static/documents/NSS_Report9_SgEhTat.pdf (accessed on 6 March 2023). [12]

Arcesati, R., I. Hors and S. Schwaag Serger (2021), "Sharpening Europe's approach to engagement with China on science, technology and innovation", *MERICS workshop input paper*, MERICS, https://merics.org/sites/default/files/2021-12/211222_MERICS%20STI%20paper_final.pdf (accessed on 6 March 2023). [30]

Atkinson, R. (2020), *The Case for a National Industrial Strategy to Counter China's Technological Rise*, ITIF, https://www2.itif.org/2020-case-counter-national-industrial-strategy-china-technological-rise.pdf (accessed on 6 March 2023). [54]

Bauer, M. and F. Erixon (2020), *Europe's Quest for Technology Sovereignty: Opportunities and Pitfall*, European Centre for International Political Economy, Brussels, https://ecipe.org/wp-content/uploads/2020/05/ECI_20_OccPaper_02_2020_Technology_LY02.pdf (accessed on 6 March 2023). [62]

Bilgin, E. and A. Loh (2021), *Techno-nationalism: China's bid for global technological leadership,"*, https://blogs.lse.ac.uk/cff/2021/09/28/techno-nationalism-chinas-bid-for-global-technological-leadership/ (accessed on 6 March 2023). [37]

Blind, K. (2013), "The Impact of Standardization and Standards on Innovation", *Nesta Working Paper*, No. No. 13/15, Nesta, https://media.nesta.org.uk/documents/the_impact_of_standardization_and_standards_on_innovation.pdf (accessed on 6 March 2023). [68]

Brown, A., J. Gunter and M. Zenglein (2021), "Course correction: China's shifting approach to economic globalization", Mercator Institute for China Studies (Merics), Berlin, https://merics.org/en/report/course-correction-chinas-shifting-approach-economic-globalization (accessed on 6 March 2023). [38]

Center for Security and Emerging Technology (2021), *China's STI Operations: Monitoring Foreign Science and Technology Through Open Sources*, Center for Security and Emerging Technology, https://doi.org/10.51593/20200049. [34]

Chen, N. (2019), “Chinese Sciences Academy Provides 268 mln Dollars for BRI Projects”, https://english.cas.cn/newsroom/news/201904/t20190419_208623.shtml (accessed on 6 March 2023). [67]

China Power Team (2021), “Will the Dual Circulation Strategy Enable China to Compete in a Post-Pandemic World?”, China Power, https://chinapower.csis.org/china-covid-dual-circulation-economic-strategy (accessed on 6 March 2023). [33]

Council on Foreign Relations (2021), “China’s Belt and Road: Implications for the United States”, *Independent Task Force Report No. 79*, Council on Foreign Relations, New York, NY, United States, https://www.cfr.org/report/chinas-belt-and-road-implications-for-the-united-states/download/pdf/2021-04/TFR%20%2379_China%27s%20Belt%20and%20Road_Implications%20for%20the%20United%20States_FINAL.pdf (accessed on 6 March 2023). [63]

Crespi, F. et al. (2021), “European Technological Sovereignty: An Emerging Framework for Policy Strategy”, *Intereconomics*, Vol. 56/6, pp. 348-354, https://doi.org/10.1007/s10272-021-1013-6. [6]

Criscuolo, C. et al. (2022), “An industrial policy framework for OECD countries: Old debates, new perspectives”*, OECD Science, Technology and Industry Policy Papers*, No. 127, OECD Publishing, Paris, https://doi.org/10.1787/0002217c-en. [29]

Criscuolo, C. et al. (2022), “Are industrial policy instruments effective?: A review of the evidence in OECD countries”*, OECD Science, Technology and Industry Policy Papers*, No. 128, OECD Publishing, Paris, https://doi.org/10.1787/57b3dae2-en. [26]

Criscuolo, C., G. Lalanne and L. Díaz (2022), “Quantifying industrial strategies (QuIS): Measuring industrial policy expenditures”*, OECD Science, Technology and Industry Working Papers*, No. 2022/05, OECD Publishing, Paris, https://doi.org/10.1787/ae351abf-en. [112]

Deutsche Forschungsgemeinschaft (2022), “DFG Annual General Meeting 2022 in Freiburg: Focus on International Research Cooperation”, *Press Release No. 21*, https://www.dfg.de/en/service/press/press_releases/2022/press_release_no_21/index.html (accessed on 6 March 2023). [20]

DiPippo, G., I. Mazzocco and S. Kennedy (2022), *Red Ink: Estimating Chinese Industrial Policy Spending in Comparative Perspective*, https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/220523_DiPippo_Red_Ink.pdf?VersionId=LH8ILLKWz4o.bjrwNS7csuX_C04FyEre (accessed on 6 March 2023). [27]

Duchâtel, M. (2022), “Semiconductors in Europe: the return of industrial policy”*, Policy paper*, Institut Montaigne, Paris, https://www.institutmontaigne.org/ressources/pdfs/publications/europe-new-geopolitics-technology-1.pdf (accessed on 6 March 2023). [89]

Edler, J. et al. (2021), *Technology Sovereignty as an Emerging Frame for Innovation Policy – Defining Rationales, Ends and Means*, https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cci/innovation-systems-policy-analysis/2021/discussionpaper_70_2021.pdf (accessed on 6 March 2023). [5]

EEAS (2022), *A Strategic Compass for Security and Defence*, European Union, https://www.eeas.europa.eu/sites/default/files/documents/strategic_compass_en3_web.pdf (accessed on 6 March 2023). [48]

EPRS (2022), "The EU chips act: Securing Europe's supply of semiconductors", *European Parliamentary Research Service*, Vol. EU Legislation in Progress Briefing, https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733596/EPRS-Briefing-733596-EU-chips-act-V2-FINAL.pdf (accessed on 6 March 2023). [86]

European Chamber of Commerce in China and Mercator Institute for China Studies (2021), *Decoupling: Severed Ties and Patchwork Globalisation*. [23]

European Commission (2022), *A New Innovation Agenda*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2022) 332 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0332&from=EN (accessed on 6 March 2023). [43]

European Commission (2022), "European Chips Act: Factsheet", https://digital-strategy.ec.europa.eu/en/library/european-chips-act-factsheet (accessed on 6 March 2023). [87]

European Commission (2022), *European Chips Act: Staff Working document*, Commission Staff Working Document SWD(2022) 147 final, https://digital-strategy.ec.europa.eu/en/library/european-chips-act-staff-working-document (accessed on 6 March 2023). [82]

European Commission (2022), *Recovery and Resilience Scoreboard Thematic Analysis: Research and Innovation*. [42]

European Commission (2022), *Roadmap on critical technologies for security and defence*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2022) 61 final, https://ec.europa.eu/info/sites/default/files/com_2022_61_1_en_act_roadmap_security_and_defence.pdf (accessed on 6 March 2023). [50]

European Commission (2022), "State Aid: Commission approves up to €5.4 billion of public support by fifteen Member States for an Important Project of Common European Interest in the hydrogen technology value chain", https://ec.europa.eu/commission/presscorner/detail/en/ip_22_4544 (accessed on 8 March 2023). [46]

European Commission (2021), *Action Plan on synergies between civil, defence and space industries*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2021) 70 final, https://ec.europa.eu/info/sites/default/files/action_plan_on_synergies_en.pdf (accessed on 6 March 2023). [49]

European Commission (2021), "State aid: Commission adopts revised State aid rules on Important Projects of Common European Interest", https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6245 (accessed on 6 March 2023). [45]

European Commission (2021), *Strategic dependencies and capacities*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD:2021:352:FIN (accessed on 6 March 2023). [11]

European Commission (2021), *The landscape of Hybrid Threats: A Conceptual Model (Public Version)*, Publications Office, Joint Research Centre, https://publications.jrc.ec.europa.eu/repository/handle/JRC123305 (accessed on 6 March 2023). [47]

European Commission (2020), *A New Industrial Strategy for Europe*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2020) 102 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0102&from=EN (accessed on 6 March 2023). [41]

European Commission (2020), *Critical raw materials for strategic technologies and sectors in the EU – a foresight study*, Publications Office of the European Union, Luxembourg, https://doi.org/10.2873/58081. [101]

European Commission (2020), *Horizon 2020-funded security and defence R&D projects with dual-use potential: an overview (2014-2018)*, Joint Research Centre Publications Office, https://data.europa.eu/doi/10.2760/599783 (accessed on 6 March 2023). [51]

EU-US Trade and Technology Council (2022), *U.S.-EU Joint Statement*, https://www.whitehouse.gov/wp-content/uploads/2022/05/TTC-US-text-Final-May-14.pdf (accessed on 6 March 2023). [106]

EU-US Trade and Technology Council (2021), "EU-US Trade and Technology Council Inaugural Joint Statement"*, Council Inaugural Joint Statement, US-EU Summit*, EU-US Trade and Technology Council (TTC), Brussels, https://ec.europa.eu/commission/presscorner/detail/fr/statement_21_4951 (accessed on 6 March 2023). [72]

Finkbeiner, A. and R. Van Noorden (2022), "Will war in Ukraine mark a new era for European defence research?", *Nature*, Vol. 608/7923, pp. 466-467, https://doi.org/10.1038/d41586-022-02185-x. [52]

G7 (2022), *G7 Statement on Climate Club*, https://www.g7germany.de/resource/blob/974430/2057926/2a7cd9f10213a481924492942dd660a1/2022-06-28-g7-climate-club-data.pdf?download=1 (accessed on 5 March 2023). [80]

G7-Summit (2022), *Annex to the G7 Science Ministers` Communiqué 2022: Further Implementation and G7 Science Working Groups*, https://www.bmbf.de/SharedDocs/Downloads/de/2022/220613-g7-annex.pdf?__blob=publicationFile&v=4 (accessed on 24 February 2023). [79]

GAO (2021), "Science & Tech Spotlight: Deep-Sea Mining", No. GAO-22-105507, US Government Accounting Office, https://www.gao.gov/assets/gao-22-105507.pdf (accessed on 6 March 2023). [110]

García-Herrero, A. and N. Poitiers (2022), *Europe's promised semiconductor subsidies need to be better targeted*, https://www.bruegel.org/blog-post/europes-promised-semiconductor-subsidies-need-be-better-targeted (accessed on 6 March 2023). [108]

Gauß, R. et al. (2021), *Rare Earth Magnets and Motors: A European Call for Action*, a report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance, Berlin, https://eitrawmaterials.eu/wp-content/uploads/2021/09/ERMA-Action-Plan-2021-A-European-Call-for-Action.pdf (accessed on 6 March 2023). [100]

Goodman, M. and B. Robert (2021), "Toward a T12: Putting Allied Technology Cooperation into Practice", https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/211013_Goodman_Toward_T12.pdf?gPeOoAp9ER7mdhXQW7OWYxqga_s133l (accessed on 6 March 2023). [4]

Griffith, B. (2011), "Middle-Income Trap", in *Frontiers in Development Policy*, The World Bank, https://doi.org/10.1596/9780821387856_ch04. [111]

Grünberg, N. and V. Brussee (2021), "China's 14th Five-Year Plan – strengthening the domestic base to become a superpower", https://merics.org/en/short-analysis/chinas-14th-five-year-plan-strengthening-domestic-base-become-superpower (accessed on 6 March 2023). [35]

Guile, B. et al. (2022), "Democracies Must Coordinate Industrial Policies to Rebuild Economic Security", *Issues in Science and Technology*, No. accessed 30 August 2022, https://issues.org/coordinate-industrial-policies-democracies-economic-security-guile-tyson/ (accessed on 6 March 2023). [53]

Haramboure, A. et al. (forthcoming), *Vulnerabilities in the semiconductor supply chain: Preliminary results based on disaggregated Inter-Country Input-Output data*, http://file:///C:/Users/Fraccola_S/Downloads/CBS-WorldCafeVII_SemiconductorsOECD.pdf (accessed on 6 March 2023). [84]

Helwig, N., E. Sinkkonen and V. Sinkkonen (2021), *Strategic Autonomy and the Transformation of the EU: New Agendas for Security, Diplomacy, Trade and Technology*, FIIA, https://www.fiia.fi/wp-content/uploads/2021/04/fiia-report-67_niklas-helwig-et-al_strategic-autonomy-and-the-transformation-of-the-eu.pdf (accessed on 6 March 2023). [10]

Holland, M. (2020), "Reducing the health risks of the copper, rare earth and cobalt industries: Transition to a circular low-carbon economy", *OECD Green Growth Papers*, No. 2020/03, OECD Publishing, Paris, https://doi.org/10.1787/88ce1db4-en. [109]

Huang, Y. (2022), "The Health Silk Road: How China Adapts the Belt and Road Initiative to the COVID-19 Pandemic", *American Journal of Public Health*, Vol. 112/4, pp. 567-569, https://doi.org/10.2105/AJPH.2021.306647. [64]

IEA (2022), *Securing Clean Energy Technology Supply Chains*, OECD Publishing, Paris, https://doi.org/10.1787/be931bdc-en. [95]

IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, OECD Publishing, Paris, https://doi.org/10.1787/f262b91c-en. [91]

Joseph, J. et al. (2022), *Stumbling bear, soaring dragon: Russia, China and the geopolitics of global science*, Mossavar-Rahmani Center for Business and Government; Policy Institute at King's College London, https://nrs.harvard.edu/URN-3:HUL.INSTREPOS:37372501 (accessed on 6 March 2023). [19]

Kania, E. and L. Laskai (2021), *Myths and Realities of China's Military-Civil Fusion Strategy*, https://www.cnas.org/publications/reports/myths-and-realities-of-chinas-military-civil-fusion-strategy (accessed on 6 March 2023). [39]

Lewander, J. et al. (2021), *Strategic Autonomy – Views from the North*, Swedish Institute for European Policy Studies, https://www.sieps.se/globalassets/publikationer/2021/2021_1op.pdf (accessed on 6 March 2023). [40]

Liao, C. and T. Beal (2022), *The role of the G7 in mobilizing for a global recovery*, Royal Institute of International Affairs, https://doi.org/10.55317/9781784135355. [77]

Lin, J. (2017), "Industrial policies for avoiding the middle-income trap: a new structural economics perspective", *Journal of Chinese Economic and Business Studies*, Vol. 15/1, pp. 5-18, https://doi.org/10.1080/14765284.2017.1287539. [104]

March, C. and I. Schieferdecker (2021), "Technological Sovereignty as Ability, Not Autarky", https://www.cesifo.org/DocDL/cesifo1_wp9139.pdf (accessed on 6 March 2023). [7]

Matthews, D. (2022), "Researchers scramble to cut European dependence on Chinese rare earth magnets", *Science Business*, https://sciencebusiness.net/news/researchers-scramble-cut-european-dependence-chinese-rare-earth-magnets (accessed on 6 March 2023). [93]

MOST (China Ministry of Science and Technology) (2017), "China Science and Technology Newsletter", No. 10, 31 May 2027", *China Ministry of Science and Technology*, Vol. No. 10, http://un.china-mission.gov.cn/eng/chinaandun/201706/P020210831842639136200.pdf (accessed on 9 March 2023). [65]

Nakano, J. (2021), "The Geopolitics of Critical Minerals Supply Chains", Center for Strategic and International Studies, Washington, DC, https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/210311_Nakano_Critical_Minerals.pdf?DR03x5jIrwLnNjmPDD3SZjEkGEZFEcgt (accessed on 6 March 2023). [99]

National Academies of Sciences, Engineering, and Medicine (2022), *Protecting U.S. Technological Advantage*, National Academies Press, Washington, D.C., https://doi.org/10.17226/26647. [2]

National Science Board (2022), *Science and Engineering Indicators 2022: The State of U.S. Science and Engineering*, National Science Board, Alexandria, VA, United States, https://ncses.nsf.gov/pubs/nsb20221 (accessed on 6 March 2023). [15]

OECD (2023), "Education Database: Enrolment of international students by origin", *OECD Education Statistics* (database), https://doi.org/10.1787/d3abd071-en (accessed on 6 March 2023). [16]

OECD (2023), "STAN Bilateral trade database by industry and end-use category, ISIC Rev. 4", *STAN: OECD Structural Analysis Statistics* (database), https://doi.org/10.1787/data-00691-en (accessed on 6 March 2023). [17]

OECD (2022), *OECD Economic Outlook, Volume 2022 Issue 1*, OECD Publishing, Paris, https://doi.org/10.1787/62d0ca31-en. [13]

OECD (2022), *Security of Supply for Critical Raw Materials: Vulnerabilities and Areas for G7 Coordination*, G7, Schloss Elmau, Germany, https://www.bundesregierung.de/resource/blob/974430/2059152/913f41a5d52c8aa68b1bb0e03176879d/2022-07-01-security-of-supply-for-critical-raw-materials-data.pdf?download=1 (accessed on 9 March 2023). [97]

OECD (2022), “The supply of critical raw materials endangered by Russia’s war on Ukraine”, https://www.oecd.org/ukraine-hub/policy-responses/the-supply-of-critical-raw-materials-endangered-by-russia-s-war-on-ukraine-e01ac7be/ (accessed on 6 March 2023). [18]

OECD (2021), *Fostering Economic Resilience in a World of Open and Integrated Markets*, Report prepared for the 2021 UK presidency of the G7, https://www.oecd.org/newsroom/OECD-G7-Report-Fostering-Economic-Resilience-in-a-World-of-Open-and-Integrated-Markets.pdf (accessed on 6 March 2023). [21]

OECD (2019), “Measuring distortions in international markets: The semiconductor value chain”, *OECD Trade Policy Papers*, No. 234, OECD Publishing, Paris, https://doi.org/10.1787/8fe4491d-en. [83]

OECD (2017), “China and the next production revolution”, in *The Next Production Revolution: Implications for Governments and Business*, OECD Publishing, Paris, https://doi.org/10.1787/9789264271036-16-en. [31]

OECD (forthcoming), *Raw materials critical for the green transition: Production, international trade and export restrictions*, OECD, Paris, OECD Publishing, https://www.oecd-ilibrary.org/trade/oecd-trade-policy-working-papers_18166873 (accessed on 9 March 2023). [116]

Politi, A. (2022), *Rare Earth Elements and China*, NATO Defense College Foundation, Rome, https://www.natofoundation.org/food/rare-earth-elements-and-china/ (accessed on 6 March 2023). [98]

Rodrik, D. (2014), “Green industrial policy”, *Oxford Review of Economic Policy*, Vol. 30/3, pp. 469-491, https://doi.org/10.1093/oxrep/gru025. [24]

Sánchez Romero, L. (2021), “China’s ban on research monkey exports hits vaccine testing”, *European Animal Research Association*, https://www.eara.eu/post/china-ban-on-research-monkey-exports-hits-vaccine-testing (accessed on 6 March 2023). [103]

Schmidt, E. et al. (2022), *Mid-Decade Challenges to National Competitiveness*, Special competitive studies project, https://www.scsp.ai/wp-content/uploads/2022/09/SCSP-Mid-Decade-Challenges-to-National-Competitiveness.pdf (accessed on 6 March 2023). [9]

Schwellnus, C. et al. (forthcoming), *Global value chain dependencies under the magnifying glass*, OECD Publishing, Paris, https://doi.org/10.1787/23074957. [96]

Science and Technology Daily (2022), “Sci-tech Cooperation with 84 BRI Countries Set up”, http://www.stdaily.com/English/WorldNews/202203/8697175cb94f4f36a27f49a41233bc48.shtml (accessed on 7 March 2023). [66]

SCSP (2022), *Restoring the Sources of Techno-Economic Advantage*, Economy Interim Panel Report, https://www.scsp.ai/wp-content/uploads/2022/11/Economy-Panel-IPR-FINAL-Version.pdf (accessed on 6 March 2023). [56]

Semiconductor Industry Association (2021), *Taking Stock of China’s Semiconductor Industry*, Semiconductor Industry Association, Washington, DC,, https://www.semiconductors.org/taking-stock-of-chinas-semiconductor-industry (accessed on 6 March 2023). [107]

Shivakumar, S. (2022), *Securing Global Standards for Innovation and Growth*, Center for Strategic and International Studies, Washington, DC, https://www.csis.org/analysis/securing-global-standards-innovation-and-growth. (accessed on 6 March 2023). [70]

Soare, S. and F. Pothier (2021), "Leading edge: key drivers of defence innovation and the future of operational advantage", https://www.iiss.org/-/media/files/research-papers/2021/11/defence-innovation_oct-2021_s10.pdf?la=en&hash=557B195DFA53C7CC638B1551A59A21476D042DA9 (accessed on 6 March 2023). [8]

Szczepański, M. (2020), *Important projects of common European interest Boosting EU strategic value chains*, European Parliamentary Research Service, European Union, https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659341/EPRS_BRI(2020)659341_EN.pdf (accessed on 6 March 2023). [44]

Tagliapietra, S. and R. Veugelers (2020), *A green industrial policy for Europe*, Bruegel Blueprint Serie, No. 31, https://www.bruegel.org/sites/default/files/wp_attachments/Bruegel_Blueprint_31_Complete_151220.pdf (accessed on 6 March 2023). [28]

Tani, C. (2022), "Commission wants to plug 'information gap' between civilian and defence R&D", *Science Business*, https://sciencebusiness.net/news/commission-wants-plug-information-gap-between-civilian-and-defence-rd (accessed on 6 March 2023). [105]

Teer, J. and M. Bertolini (2022), *Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry*, https://hcss.nl/report/reaching-breaking-point-semiconductors-critical-raw-materials-great-power-rivalry/ (accessed on 7 March 2023). [114]

The State Administration for Market Regulation (2022), *National Standardisation Development Action Plan*, https://gkml.samr.gov.cn/nsjg/bzjss/202207/t20220708_348515.html (accessed on 7 March 2023). [113]

The White House (2022), "Fact Sheet: Biden-Harris Administration Driving U.S. Battery Manufacturing and Good-Paying Jobs", https://www.whitehouse.gov/briefing-room/statements-releases/2022/10/19/fact-sheet-biden-harris-administration-driving-u-s-battery-manufacturing-and-good-paying-jobs/ (accessed on 6 March 2023). [102]

The White House (2022), *Fact Sheet: CHIPS and Science Act Will Lower Costs, Create Jobs, Strengthen Supply Chains, and Counter China*, http://, https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/ (accessed on 6 March 2023). [57]

The White House (2022), *Fact Sheet: How the Inflation Reduction Act Will Help Small Businesses*, https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/12/fact-sheet-how-the-inflation-reduction-act-will-help-small-businesses (accessed on 6 March 2023). [59]

The White House (2022), "FACT SHEET: President Biden and G7 Leaders Formally Launch the Partnership for Global Infrastructure and Investment", https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/26/fact-sheet-president-biden-and-g7-leaders-formally-launch-the-partnership-for-global-infrastructure-and-investment/ (accessed on 6 March 2023). [76]

The White House (2022), “Fact Sheet: President Biden Announces the Americas Partnership for Economic Prosperity”, https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/08/fact-sheet-president-biden-announces-the-americas-partnership-for-economic-prosperity (accessed on 6 March 2023). [75]

The White House (2022), “Memorandum on the Partnership for Global Infrastructure and Investment”, https://www.whitehouse.gov/briefing-room/presidential-actions/2022/06/26/memorandum-on-the-partnership-for-global-infrastructure-and-investment/ (accessed on 6 March 2023). [78]

The White House (2022), *National Security Strategy*, https://www.whitehouse.gov/wp-content/uploads/2022/10/Biden-Harris-Administrations-National-Security-Strategy-10.2022.pdf (accessed on 6 March 2023). [1]

The White House (2022), *Remarks on Executing a Modern American Industrial Strategy by NEC Director Brian Deese*, https://www.whitehouse.gov/briefing-room/speeches-remarks/2022/10/13/remarks-on-executing-a-modern-american-industrial-strategy-by-nec-director-brian-deese/#:~:text=Here's%20what%20a%20modern%20American,spur%20private%20investment%20and%20innovation (accessed on 6 March 2023). [61]

The White House (2022), “Statement on Indo-Pacific Economic Framework for Prosperity”, https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/23/statement-on-indo-pacific-economic-framework-for-prosperity/ (accessed on 6 March 2023). [74]

The White House (2021), *Fact Sheet: The Bipartisan Infrastructure Investment and Jobs Act Creates Good-Paying Jobs and Supports Workers*, https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/03/fact-sheet-the-bipartisan-infrastructure-investment-and-jobs-act-creates-good-paying-jobs-and-supports-workers (accessed on 6 March 2023). [60]

The White House (2021), “Quad Principles on Technology Design, Development, Governance, and Use”, The White House, https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/24/quad-principles-on-technology-design-development-governance-and-use/ (accessed on 6 March 2023). [73]

US Department of Commerce (2022), *A Strategy for the CHIPS for America Fund*, US Department of Commerce, Washington, DC, https://www.nist.gov/system/files/documents/2022/09/13/CHIPS-for-America-Strategy%20%28Sept%206%2C%202022%29.pdf (accessed on 6 March 2023). [58]

US Department of Commerce (2022), “Commerce Implements New Export Controls on Advanced Computing and Semiconductor Manufacturing Items to the People’s Republic of China”, US Department of Commerce, Washington, DC,, https://www.bis.doc.gov/index.php/documents/about-bis/newsroom/press-releases/3158-2022-10-07-bis-press-release-advanced-computing-and-semiconductor-manufacturing-controls-final/file (accessed on 6 March 2023). [85]

US Department of State (2022), *Supply Chain Ministerial*, US Department of State, Washington, DC, https://www.state.gov/supply-chain-ministerial/ (accessed on 6 March 2023). [22]

US Geological Survey (2022), *Mineral commodity summaries 2022*, U.S. Department of the Interior, Reston, Va., United States, https://doi.org/10.3133/mcs2022. [94]

Valigra, L. (2022), “US CHIPS Act expected to create ‘productive competition’ with Europe”, *Science Business*, https://sciencebusiness.net/news/us-chips-act-expected-create-productive-competition-europe (accessed on 6 March 2023). [90]

Varas, A. (2021), *Strengthening the Global Semiconductor Value Chain*, https://www.semiconductors.org/wp-content/uploads/2021/05/BCG-x-SIA-Strengthening-the-Global-Semiconductor-Value-Chain-April-2021_1.pdf (accessed on 7 March 2023). [81]

Wagner, C. and X. Cai (2022), *Drop in China-USA international collaboration*, ISSI Newsletter, Vol.18/1, https://www.issi-society.org/media/1434/newsletter69.pdf (accessed on 6 March 2023). [14]

Warwick, K. (2013), “Beyond Industrial Policy: Emerging Issues and New Trends”*, OECD Science, Technology and Industry Policy Papers*, No. 2, OECD Publishing, Paris, https://doi.org/10.1787/5k4869clw0xp-en. [25]

Wigell, M. et al. (2022), *Europe Facing Geoeconomics : Assessing Finland’s and the EU’s Risks and Options in the Technological Rivalry*, http://urn.fi/URN:ISBN:978-952-383-205-3 (accessed on 6 March 2023). [3]

Wigell, M. et al. (2022), *Europe Facing Geoeconomics: Assessing Finland’s and the EU’s Risks and Options in the Technological Rivalry*, Report published by the Prime Minister’s Office, Helsinki, https://www.fiia.fi/wp-content/uploads/2022/02/europe-facing-geoeconomics.pdf (accessed on 6 March 2023). [71]

WTO (2022), *The Crisis in Ukraine: Implications of the war for global trade and development*, World Trade Organization (WTO), https://www.wto.org/english/res_e/publications_e/crisis_ukraine_e.htm (accessed on 9 March 2023). [115]

Wu, Y. (2022), “China Standards 2035 Strategy: Recent Developments and Implications for Foreign Companies”*, China Briefing*, Dezan Shira & Associates, https://www.china-briefing.com/news/china-standards-2035-strategy-recent-developments-and-their-implications-foreign-companies (accessed on 6 March 2023). [69]

Xinhua News Agency (2021), “The Chinese Communist Party Central Committee and the State Council Publish National Standardization Development Outline”*, Original CSET translation*, https://cset.georgetown.edu/publication/the-chinese-communist-party-central-committee-and-the-state-council-publish-the-national-standardization-development-outline (accessed on 6 March 2023). [36]

Zenglein, M. and A. Holzmann (2019), “Evolving Made in China 2025 China’s industrial policy in the quest for global tech leadership”*, MERICS Papers on China, No 8*, MERICS, https://merics.org/sites/default/files/2020-04/MPOC%20Made%20%20in%20China%202025.pdf (accessed on 6 March 2023). [32]

Zubașcu, F. (2022), “EU to launch €11B joint undertaking on advanced semiconductors”, *Science Business*, https://sciencebusiness.net/news/eu-launch-eu11b-joint-undertaking-advanced-semiconductors (accessed on 6 March 2023). [88]

Notes

[1] The chapter's focus on these technology leaders is a pragmatic one, reflecting time and space constraints. Further analysis should ideally include other existing technology leaders (e.g. Japan) and emerging ones (e.g. India).

[2] In the context of this chapter, "securitisation" refers to the reframing of regular policy issues, such as climate change, migration, and emerging technologies, into matters of "security".

[3] Griffith (2011[111]) defines a middle-income trap as "a situation whereby a middle-income country is failing to transition to a high-income economy due to rising costs and declining competitiveness."

[4] Data for the United States are for 2019.

[5] P*atents* protect technological inventions (i.e. products or processes providing new ways of doing something or new technological solutions to problems). *IP5 patent families* are patents filed in at least two offices worldwide, including one of the five largest intellectual property (IP)offices: the European Patent Office, the Japan Patent Office, the Korean Intellectual Property Office, the US Patent and Trademark Office, and the National Intellectual Property Administration of People's Republic of China.

[6] This selection of economies represents 43% of global imports of intermediate products from high and medium-high R&D-intensive activities in 2020 and 39% of such imports in 2000. However, it is unevenly distributed among those partners: 57% of Chinese imports are represented, while only 26% of the German imports and 38% for the United States are captured in 2020.

[7] Well-known export controls include those imposed by the United States on China with regards to semiconductors. Lesser-known examples include China's export ban on research monkeys, which has adversely affected biomedical research in several OECD countries (Sánchez Romero, 2021[103]).

[8] Described varyingly as a "slippery slope" (European Chamber of Commerce in China and Mercator Institute for China Studies, 2021[23]), "downward spiral" (Brown, Gunter and Zenglein, 2021[38]), and "chain reaction" (Wigell et al., 2022[3]), as China moves to pursue self-reliance, liberal market economies respond by restricting China's access to foreign technologies, further fuelling China's self-reliance campaign (Brown, Gunter and Zenglein, 2021[38]). The result is a decoupling into rival blocs.

[9] Decoupling of the global economy would have a very costly outcome for the world and for individual OECD members. According to WTO estimates, which are relatively modest, the disintegration of the global economy into two blocs would reduce global GDP by 5%. The cost will not be equal to all countries, with developing countries set to suffer the most. In a modest scenario, open markets that are geographically close to China, and large open markets such as E.U would lose 4%; Other large markets would lose only 1% (WTO, 2022[115]).

[10] This OECD has developed a new experimental methodology for reporting industrial policy expenditure in a comparable way across countries. It will gather harmonised data on industrial policy expenditures, their composition, and their mode of delivery. See (Criscuolo, Lalanne and Díaz, 2022[112]).

[11] According to (Lin, 2017[104]), the middle-income trap arises from a middle-income country's failure to achieve faster productivity growth through technological innovation and industrial upgrading when compared to high-income countries.

[12] Based on available data, (DiPippo, Mazzocco and Kennedy, 2022[27]) use nine categories of instruments to estimate China's industrial policy spending: direct subsidies to firms, R&D tax incentives, other tax incentives, government-financed business R&D, below-market credit to state-owned enterprises (SOEs), state investment funds (government guidance funds), below-market land sales to firms, implied credit advantage among SOEs for their large net payables balances and debt-equity swaps.

[13] The European Innovation Council, while a new initiative, is part of the wider Horizon Europe programme. See https://eic.ec.europa.eu/about-european-innovation-council_en.

[14] The EDF has adopted Horizon Europe tools, so that the two funds are becoming increasingly similar in how they are run, which opens opportunities for collaboration. Important differences remain, however, since EDF involves national ministries of defence in its projects. Projects and participating firms are also subject to a number of security requirements and a higher level of control and oversight of research (Tani, 2022[105]).

[15] https://beta.nsf.gov/tip/latest.

[16] (Chen, 2019[67]) states that by 2019, the Chinese Academy of Sciences had built 9 overseas science and education centres in BRI countries and trained nearly 5 000 people, including 1 500 with master's and doctoral degrees in science and engineering. Co-operation included more than 100 scientific and technological projects to support sustainable development in BRI countries, and collaboration with more than 100 high-tech enterprises and research institutions to establish the BRI Alliance to serve regional economic and social development goals.

[17] See the ANSO website (http://www.anso.org.cn) for more details.

[18] China recently followed up this strategy with two implementation documents: the National Standardisation Development Outline in 2021 (see (Xinhua News Agency, 2021[36]) and the National Standardisation Development Action Plan in (2022[113])).

[19] These include organisations like the International Telecommunication Union, the Institute of Electrical and Electronics Engineers, the International Organization for Standardization and the International Electrotechnical Commission.

[20] For example, Working Group 1 is charged with co-ordinating and co-operating on critical and emerging technology standards. In 2022, it established the "Strategic Standardisation Information" mechanism to take co-ordinated action if standardisation activities pose a challenge to EU-US strategic interests and values (EU-US Trade and Technology Council, 2022[106]).

[21] See the website of the Japanese Ministry of Foreign Affairs (https://www.mofa.go.jp/files/100347806.pdf).

[22] The member countries are Australia, Brunei Darussalam, India, Indonesia, Japan, Korea, Malaysia, New Zealand, Philippines, Singapore, Thailand, the United States and Vietnam.

[23] https://ec.europa.eu/info/strategy/priorities-2019-2024/stronger-europe-world/global-gateway_en.

[24] Further upstream, the supply chains for critical minerals/materials in chips is also global and dominated by countries like China and Russia (Teer and Bertolini, 2022[114]). Critical minerals are discussed in the sub-section that follows.

[25] Chip design is also quite concentrated, with US chip design companies outsourcing production but retaining their design activities.

[26] Chip design is the most R&D-intensive segment in the semiconductor supply chain (65% of total industry R&D), while fabrication is the most capital-intensive (64% of total industry capital expenditure) (European Commission, 2022[82]).

[27] According to analysis by the (Semiconductor Industry Association, 2021[107]), the Chinese government has long had an industrial policy to support its nascent chip industry, but these efforts accelerated in 2014 with the release of the National Guideline for the Promotion and Development of the IC Industry, which laid out ambitious targets for industry revenue, production capacity and technological advances in integrated circuits. In 2015, Made in China 2025 set aspirational goals for China to achieve 70% self-sufficiency in semiconductors by 2025. Central to China's semiconductor industrial policy is the National Integrated Circuits Industry Development Investment Fund, established in 2014 with USD 21 billion in state-backed financing and renewed in 2019 for a second round of state financing exceeding USD 35 billion. Around two-thirds of this funding has targeted front-end manufacturing, with the goal of increasing China's share of global semiconductor production. Other funds, including from regional governments (estimated at USD 25 billion), and other forms of intervention, including government grants, equity investments and low-interest loans (estimated at over USD 50 billion), further support China's semiconductor companies.

[28] This focus on promoting manufacturing is not without its critics. For example, (García-Herrero and Poitiers, 2022[108]) argue that the proposals in the European Commission's European Chips Act over-emphasise semiconductor production subsidies and do not focus enough on increasing value-added in research.

[29] Rare earths are a family of 17 elements comprising 15 elements in the lanthanides group (ranging from lanthanum to lutetium), plus scandium and yttrium.

[30] Substantial amounts of energy, as well as caustic and other hazardous substances, are used in the creation of refined rare-earth metal. Extraction also results in the release of other harmful compounds, such as the radioactive elements thorium and uranium, which are commonly found in mine tailings and other waste dumps (Holland, 2020[109]).

[31] According to (Nakano, 2021[99]), China's consumption of rare-earth minerals grew at an average annual rate of 7.5% between 2004 and 2014 while the rare-earth mineral consumption of the rest of the world decreased by 3.8%, raising China's share of global consumption from 43% to 70%.

[32] New OECD analysis suggests export restrictions may be playing a non-trivial role in international markets for critical raw materials, affecting availability and prices of these materials. OECD countries have been increasingly exposed to the use of export restrictions for critical raw materials. Such restrictions are also on the increase. For example, China increased the number of its restrictions by a factor of 9 over the period 2009-2020, making it the country with the largest number of restrictions in 2020 (OECD, forthcoming[116]).

[33] Palladium is a central component of vehicle catalytic converters that remove toxic emissions from exhaust fumes, while nickel is used in electric-vehicle batteries.

[34] For example, the ocean floor contains vast quantities of critical minerals. Growing demand is driving technology development for exploration and extraction from deep-sea mining. However, the long-term environmental effects from deep-sea mining are as yet unknown (GAO, 2021[110]).

3 Science, technology and Innovation Policy for Sustainability Transitions

The climate emergency requires nothing short of a total transformation of sociotechnical systems in areas such as energy, agrifood and mobility. STI has essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies to support them. They need to design policy portfolios that enable transformative innovation and new markets to emerge, challenge existing fossil-based systems, and create windows of opportunity for low-carbon technologies to break through. Larger investments and greater directionality in research and innovation activities are required, but should coincide with a reappraisal of STI systems and their supporting STI policies to ensure they are “fit-for-purpose” to contribute to sustainability transitions. For example, STI policies need to support new modes of partnership (e.g. between researchers, businesses, governments and citizens) and develop enabling resources (e.g. finance, skills and knowledge) conducive to tranformative change. They also need to balance supply and demand side interventions that target both production and consumption. The chapter outlines ten sub-domains of STI policy where reforms are needed and highlights significant gaps between R&D funding and net-zero ambitions.

Key messages

- To address the climate emergency requires nothing short of a total transformation of energy, agrifood, and mobility systems. Science, technology and innovation (STI) have essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies to meet these challenges.
- Governments may require altogether different STI policy frameworks and practices from those they commonly use today to help direct and accelerate the innovation cycle for low-carbon technologies. They should design policy mixes that enable transformative innovation and new markets to emerge, challenge existing fossil-based systems, and create windows of opportunity for low-carbon technologies to break through. Reforms concern all aspects of STI policy and governance, and the chapter sets out a checklist of STI policy sub-domains where these are needed.
- Significant levels of investment are needed across the entire innovation chain to meet the scale and pace of the net-zero transition. Governments should place greater emphasis on research, development and demonstration (RD&D), since achieving net-zero depends on technologies that are still far from market. Government incentives for low-carbon research and development (R&D), including public R&D grants, public procurement, and carbon pricing, should also pay greater attention to regime-changing radical innovations.
- Technological innovation is inherently uncertain, and technologies can often interact with one another in unexpected ways. Governments should diversify and pool their investments to search, develop and deploy a portfolio of technologies, while also continuously assessing potential trade-offs that may be created by these technologies.
- STI policies should encourage public-private partnerships and collaborative platforms operating at different stages of the low-carbon innovation chain to accelerate the pace of radical innovation. Wider society should also be actively engaged in STI processes and policies, since technological shifts need to coincide with transformations in behaviour, lifestyles and economic activity. Moreover, cross-government co-ordination will be essential, as policy efforts targeting RD&D and technology deployment are distributed across many different policy areas.
- International STI co-operation is also necessary, as global climate change requires collective action to meet net-zero targets. However, national research and innovation funding regimes can present barriers to international co-operation that governments need to address. It is also important for OECD member countries to co-operate on technological innovation with low- and middle-income countries, where the majority of growth in greenhouse gas emissions is expected to occur in the coming decades, but where scientific and technological capabilities for low-carbon innovation are underdeveloped.
- Gaps in the skills and capabilities of firms, governments and research actors need to be addressed to enact sustainability transitions rapidly. These gaps include both technological and “softer” capabilities related to new ways of working. Addressing these gaps requires a multi-agency approach that considers both supply- and demand-side perspectives, and also supports people of working age and communities in attaining new skills and opportunities as part of a just transition.
- Finally, the current knowledge and evidence base that supports policy decisions, such as evaluation and statistics, struggles to cope with the complexity and uncertainty of STI-enabled sustainability transitions. Governments need to invest in their “strategic intelligence” capabilities to monitor and evaluate sociotechnical transitions, and to formulate, design and implement effective STI policy agendas and measures.

Introduction

Sociotechnical systems in areas like energy, agrifood and mobility need to transform rapidly to become more sustainable and resilient, which will require simultaneous political, economic, behavioural, cultural and technological change, at multiple levels of governance (OECD, 2015[1]). STI has essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies to meet these challenges.

Along these lines, the *OECD Science, Technology and Innovation Outlook 2021* argued for reforms of STI policy that favour greater directionality in support of sustainability transitions. It also suggested that the disruptive COVID-19 moment offers a “window of opportunity” to enact reforms, particularly in the context of ambitious recovery packages and renewed commitments to address climate change (OECD, 2021[2]). Governments may require altogether different policy frameworks and practices from those they commonly use today. Reforms will require revisiting STI policy models, visions, targets and instruments with a view to adapting them or displacing them in favour of others (Schwaag Serger and Palmberg, 2022[3]). All aspects of STI policy and governance are involved, including research and innovation funding, human resources for science and technology, research and technology infrastructures, STI system co-ordination mechanisms, and evaluation and measurement.

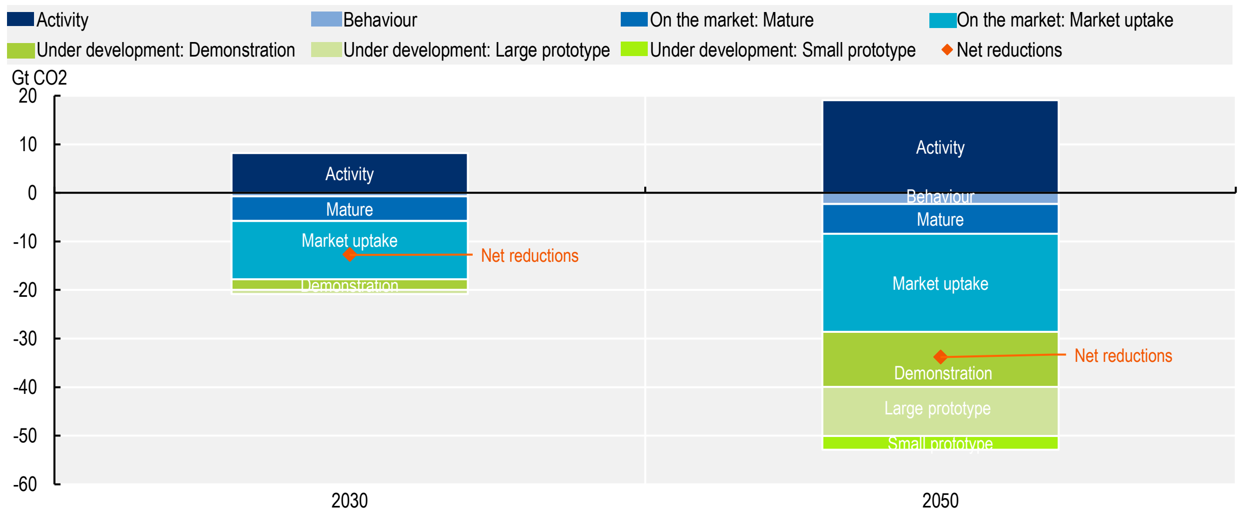
This chapter takes up the call for STI policy reforms and outlines those areas that need attention. It begins by outlining shifts in STI policy, including growing recognition of the need for greater directionality and a multilevel perspective on systems change. For STI to enable sustainability transitions, it needs to support new modes of partnership (e.g. between researchers, businesses, governments and citizens) and develop enabling resources (e.g. finance, skills and knowledge) conducive to tranformative change. It needs to balance supply and demand side interventions that target both production and consumption. The chapter outlines ten sub-domains of STI policy where reforms are needed. For example, it highlights important gaps between R&D funding and net-zero ambitions. A final section draws some lessons and presents a brief outlook on STI policy for sustainability transitions.

Towards a more directive and multilevel policy approach

The pace of low-carbon innovation needs to accelerate

Without a major acceleration in low-carbon innovation, reaching net-zero emissions by 2050 will be unachievable. For example, in the energy sector, achieving net-zero emissions by 2050 will require nothing short of the complete transformation of the global energy system. Instead of fossil fuels, two-thirds of total energy supply in 2050 will be from wind, solar, bioenergy, geothermal and hydro energy in the International Energy Agency’s (IEA) “Net-zero Emissions by 2050 Scenario” (NZE). Reaching this target requires rapid large-scale deployment of available technologies, such as wind and solar, as well as the development and widespread use of technologies that are far from mature today, such as green hydrogen. It also requires behavioural change.[1] Figure 3.1 shows that technologies that are available on the market today provide nearly all the emissions reductions required by 2030 in the NZE. However, by 2050, almost 50% of carbon dioxide (CO_2) emissions reductions in the NZE come from technologies currently at the demonstration or prototype stage, a share that is even higher in heavy industry (IEA, 2022[4]).

Figure 3.1. Global CO2 emissions changes by technology maturity category in the IEA's NZE



Source: IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050 (accessed on 15 December 2022)

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The urgency to achieve net-zero by 2050 points to the need to compress the innovation cycle for early-stage clean-energy technologies. In the IEA's NZE, most clean-energy technologies that have yet to be demonstrated at scale today would need to reach markets by 2030 at the latest. This is a much more rapid pace of development than has typically been achieved historically and places new demands on innovation systems, and by extension, on government policy. Innovation chains are fragile by nature, facing multiple "valleys of death" that can disrupt the flow of the "innovation pipeline". Many governments already try to deal with these, often playing wide-ranging roles in supporting innovation chains.

The sustainability challenge calls for greater directionality in policy making

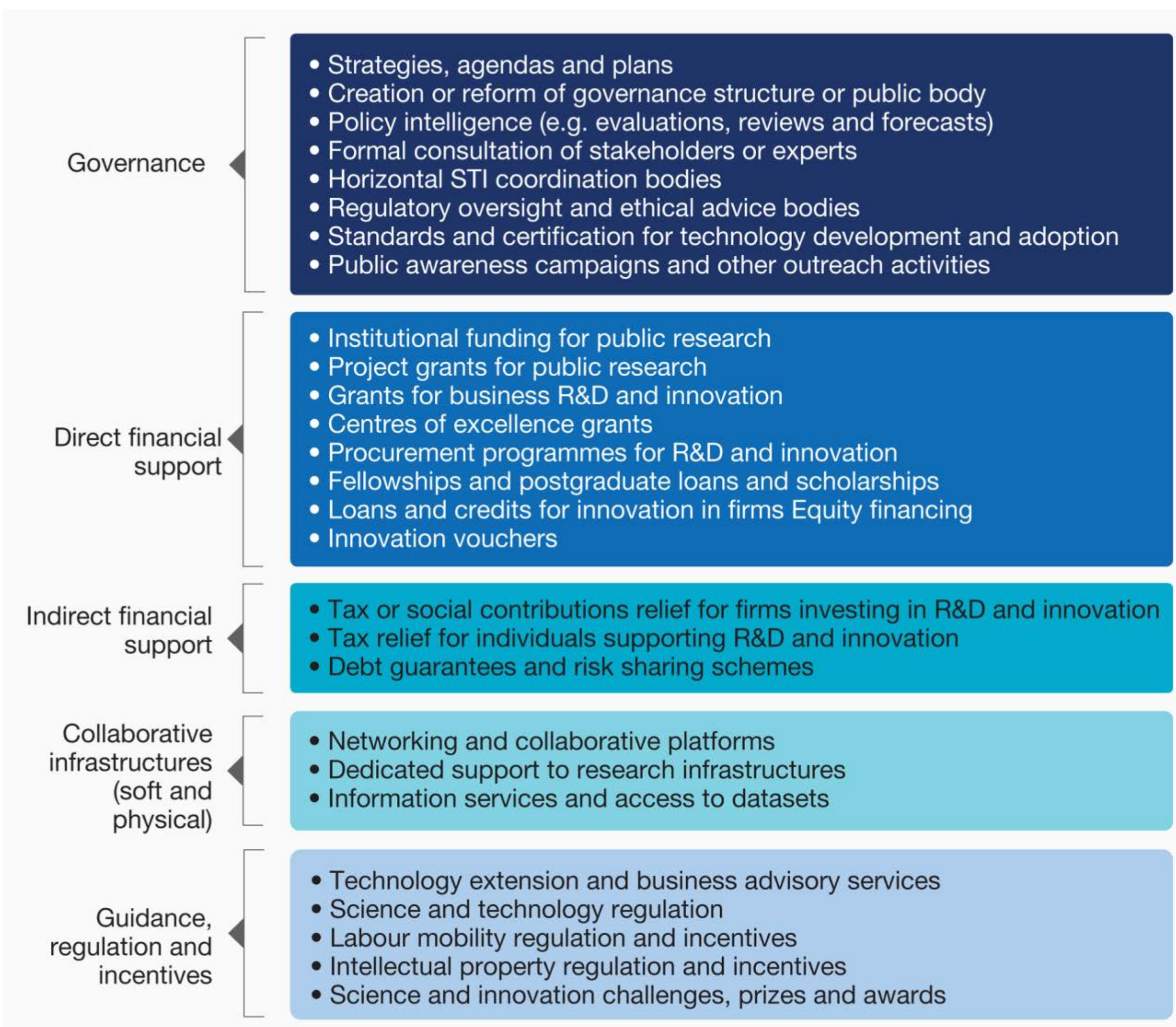
It is widely understood that sustainability transitions require a whole-system change, for example, in energy systems and agrifood systems. While research and innovation have critical roles to play in reconfiguring these systems, other factors are essential, including current social practices, institutions, infrastructures, and markets (Kern, 2012[5]). Sustainability transitions are therefore "sociotechical", insofar as technologies and societies co-evolve to meet the sustainability challenge. The breadth of change implies that firms, governments, public research actors and societies more broadly need to adapt. These actors have their own plans, strategies and agendas that shape the course of transitions. This creates complexity, uncertainty and ambiguity, so that the course of sociotechnical transitions remains impossible to predict and difficult to direct.

Shared goals and co-operation between different parts of the system can help reduce uncertainty and ambiguity, as multiple actors work towards common goals and solutions. An increasingly important focus of STI policy, therefore, is to help develop and articulate these common goals among diverse stakeholders. In this view, the traditional rationales for STI policy – fixing market failures and system failures – are joined by a further rationale – fixing directionality failures – which implies STI should support purposeful transitions (Weber and Rohracher, 2012[6]).

Directionality is implicit in all policy making by design, of course, but fixing directionality failures in STI systems presents a break from the recent orientation of STI policy, where, over the last couple of decades, the STI policy mix has become more horizontal and agnostic on the research and technologies it supports.[2] This is now challenged by the sustainability imperitive and the broader "securitisation" of STI policies discussed in Chapter 1, which are adding pressure on governments to make their STI policies more directive. Along these lines, governments are experimenting with new policy instruments, such as challenge-based funding and mission-oriented innovation policies (MOIPs) that bring together multiple actors, including firms and public-sector research organisations, to co-create and collaborate on pathways to net-zero (see Chapter 5).

Efforts like these can help "build up" and develop new structures, practices and technologies that contribute to sustainability transitions. Governments can use public policies to develop spaces for experimentation, notably through support for public R&D, but these spaces can extend to pilots, living labs, regulatory sandboxes (Attrey, Lesher and Lomax, 2020[7]) and other demonstrators that help develop alternative sustainable solutions, technologies, services, organisational processes and institutional practices. Public policies can also help scale up and anchor sustainable practices and solutions, including through subsidies or public procurement that promote low-carbon technology deployment. Figure 3.2 outlines an extended list of instruments commonly used to promote research and innovation activities; Box 3.1 highlights some of the most common STI policy instruments used to address net-zero.

Figure 3.2. List of policy instruments commonly used in STI policy



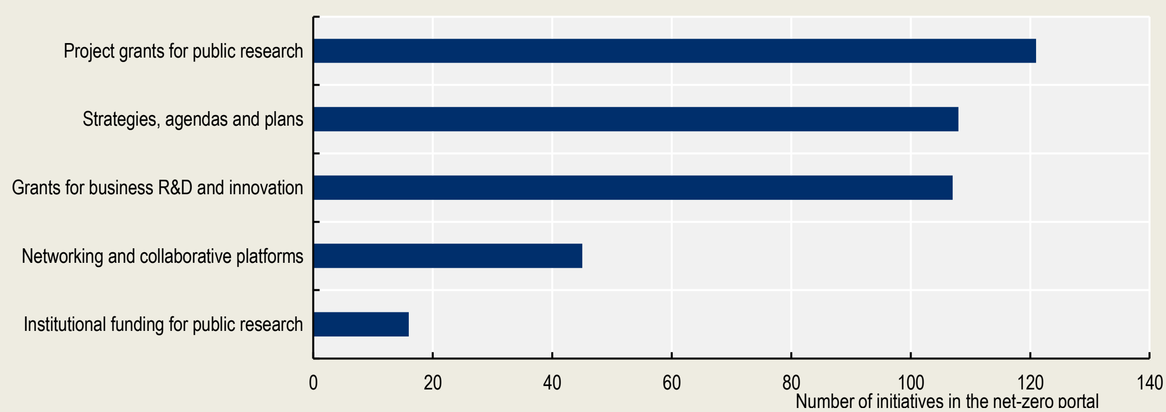
Source: EC-OECD STIP Compass, https://stip.oecd.org.

Box 3.1. “STI policies for net-zero” portal

To coincide with the 2021 United Nations Climate Change Conference (COP26), the OECD and the IEA joined forces in 2021 to launch the “STI policies for net-zero” portal as part of the EC-OECD STIP Compass infrastructure. The portal aims to support a better appreciation of the full landscape of STI policies targeting net-zero, which would benefit policy mix design, policy learning and, ultimately, policy coherence across governments. It provides information on hundreds of STI polices that explicitly support the transition to net-zero. The portal presents policy information in a series of interactive dashboards that provide both an overview of policy landscapes and options to obtain details on specific policy initiatives.

As of September 2022, the portal includes information on approximately 370 STI policy initiatives targeting net-zero in the energy sector. These policies come from 40 countries and the European Union, and involve around 180 government ministries and agencies. As Figure 3.3 shows, many of these initiatives use project grants for public research. Other commonly used instruments include national strategies, agendas and plans, grants for business R&D and innovation, and support for networking and collaborative platforms.

Figure 3.3. Top 5 STI policy instruments reported in “STI policies for net-zero” portal



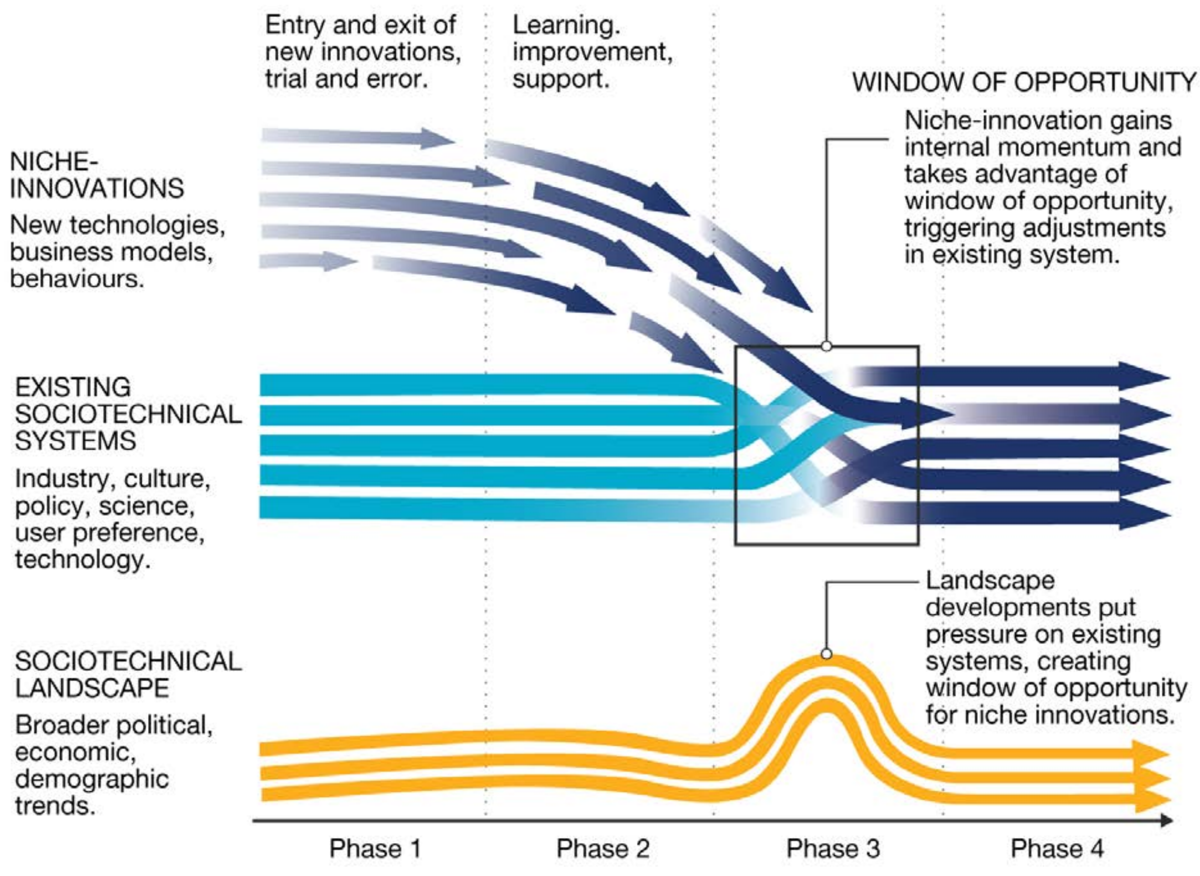
Source: EC-OECD (2021), STIP Compass: International Database on Science, Technology and Innovation Policy (STIP), September 2022 edition, https://stip.oecd.org/stip/net-zero-portal.

StatLink https://stat.link/tnj2zx

At the same time, sustainability transitions require the “breakdown” and discontinuation of unsustainable practices and structures, including the phase-out of polluting and high-carbon technologies (Kivimaa and Kern, 2016[8]). Without this breakdown, innovation experiments are often blocked from scaling up, since various lock-ins and path dependencies tend to preserve and protect incumbent fossil-based technologies and practices.[3] For example, other policies such as fossil-fuel subsidies support the stability of unsustainable sociotechnical systems and need to be phased out, but doing so is politically difficult. While governments need to reduce support to unsustainable and typically dominant technologies, they must also account for and mitigate the unintended social consequences that might result. For this reason, and to reduce the likelihood of resistance to transitions, transitional strategies need to incorporate adjustment measures, such as phased tightening of regulations, financial compensation, workforce retraining and regeneration programmes for disadvantaged regions (Geels et al., 2017[9]).

It is through the duality of these "buildup" and "breakdown" dynamics that sociotechnical transitions emerge.[4] In addition, the broader landscape of exogenous developments (e.g. slow-moving socio-economic trends) or shocks (e.g. elections, economic crises and wars) can trigger the destabilisation of the existing sociotechnical system and open up "windows of opportunity" for new low-carbon innovations to break through (Geels and Schot, 2007[10]). This "multilevel perspective", which is increasingly popular as a policy model for promoting sustainability transitions,[5] is summarised in Figure 3.4. Its key insight is that transitions occur through the alignment of mutually reinforcing processes within and between the three levels of build-up of "niche innovations", the breakdown of existing sociotechnical "regimes" and changes in the broader exogenous landscape. The resulting sociotechnical transitions go beyond the adoption of new technologies and include investment in new infrastructures, establishment of new markets, development of new social preferences, and support for people of working age and communities in attaining new skills and opportunities as part of a "just" transition (Geels et al., 2017[9]).

Figure 3.4. Promoting innovations to take advantage of windows of opportunity



Note: The multilevel perspective (MLP) sees system transitions as driven by interactions between three analytical levels: (i) the sociotechnical system itself, which is stabilised by lock-in mechanisms (such as sunk investments, core competencies, and institutional commitments) but experiences incremental improvements along path-dependent trajectories; (ii) niche innovations, which differ radically from the dominant existing system but are able to gain a foothold in particular geographical areas or market niches, or with the help of targeted policy support; and (iii) exogenous ("landscape") developments such as slow-changing trends (e.g. demographics and ideologies) or shocks (e.g. elections, economic crises and wars) that destabilise the system and facilitate the breakthrough of niche innovations. Instead of single drivers or a privileging of techno-economic factors, the MLP's key point is that transitions come about through the alignment of processes within and between these three levels.
Source: (Geels et al., 2017[9]).

Such alignments are difficult, if not impossible, to plan in a top-down manner, and transitions depend on multiple, often independent actions occurring at different levels that are galvanised by a shared common vision. These actions should be mutually supportive and create an "ambition loop" for technology development and deployment, initiating a positive feedback cycle in which policy reallocates finance towards low-carbon technologies, businesses innovate, technologies improve, and social support for the transition grows, enabling the next round of policies to move the transition forward (IEA, IRENA and UNFCCC, 2022[11]). This acceleration of sociotechnical transitions can be triggered by "positive tipping points" (Tàbara, 2021[12]; Sharpe and Lenton, 2021[13]) that reinforce feedbacks and virtuous cycles of subsequent transformative change (Box 3.2).[6] Public policies can enable positive tipping points, creating the spark for their initiation and the conditions for them to cascade through sociotechnical systems (SYSTEMIQ, 2023[14]).

Box 3.2. Enabling positive tipping points for sustainability transitions

Limiting global warming to well below 2 degrees Celsius (°C) requires rapid acceleration in sociotechnical transitions. There are plausible grounds for hope that tipping points can be activated to propagate rapid change through complex systems. This is because change in complex systems is often non-linear, and cause and effect do not have to be proportionate. A tipping point converts a small change in input to a large change in outcome, so that when a tipping point is crossed, highly disproportionate change can occur.

Positive feedback effects dominate the dynamics of a complex system at a tipping point, driving change upwards. In interconnected complex systems, the activation of one tipping point can sometimes raise the possibility of another at a greater scale. This is referred to as an "upward-scaling tipping cascade". Such cascades can induce rapid change on a broad scale, and several previous sociotechnical transitions began with disruptive technology innovations in niches that cascaded upwards through tipping points to society-wide transformation.[1] Any tipping point that gives a new technology a significant advantage, such as increased market share, easier access to finance or broader social acceptance, is likely to amplify its impact.[2]

Looking ahead, policy makers could activate tipping points and tipping cascades to meet climate-change targets. Policy may make a significant difference by investing in R&D for low-carbon technologies, diverting support from incumbents to disruptors, and reconfiguring markets and institutions. A more deliberate search for tipping points and tipping cascades could identify opportunities to accelerate decarbonisation, offering plausible grounds for hope that net-zero targets could still be met. Moreover, small groups of countries with sufficient political or economic clout in a given sector may be able to drive global change by co-operating on activating tipping cascades.

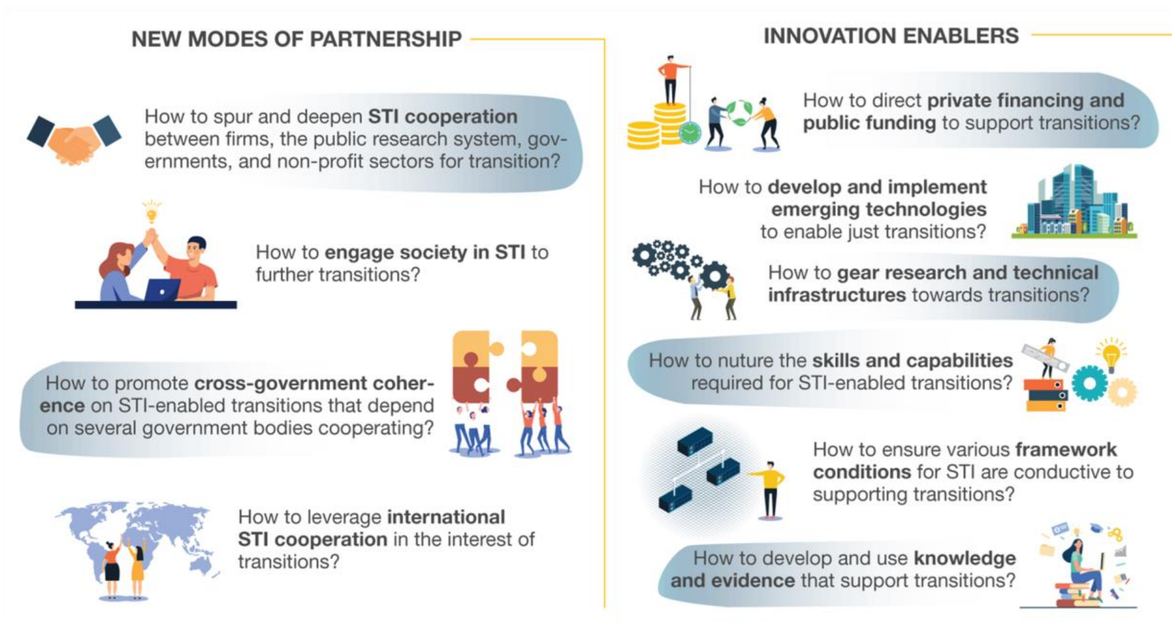
1. For example, citing (Sharpe and Lenton, 2021[13]), "the invention and refinement of the steam engine triggered a massive expansion of coal mining and the creation of a rail transport network, propelling the industrial revolution in England. At the start of the twentieth century, the transition from horse-drawn carriages to fossil-fuelled cars happened in just over a decade in US cities."
2. In a recent example, more than 50% of new vehicles now bought in Norway are electric, where progressive tax policies have made electric vehicles cheaper than petrol cars (Sharpe and Lenton, 2021[13]).
Source: (Sharpe and Lenton, 2021[13]).

Governments need to develop governance and institutional capacities to perform these buildup and breakdown tasks, exploit windows of opportunity in the broader sociotechnical landscape, search for opportunities to trigger tipping cascades and promote just transitions. These capacities are broad in scope and refer to the ways governments set directions and choose priorities; how they develop and maintain relationships with other actors in the innovation system, especially large R&D-performing firms; and how they learn, for example, through monitoring and evaluation. The crosscutting nature of sociotechnical transitions means these capacities should not be concentrated in a single ministry or agency, but widely distributed across government.

Promoting sustainability transitions in STI policy sub-domains

Sustainability transitions in sociotechnical systems like energy, food and transport depend on the development and deployment of enabling technologies. These, in turn, depend on well-functioning STI systems to generate relevant scientific knowledge and technologies at pace and at scale. Larger investments and greater directionality in research and innovation activities are needed, but these should coincide with a reappraisal of STI systems and their supporting STI policies to ensure they are “fit-for-purpose” to contribute to sustainability transitions. This reappraisal is perhaps best done at the level of policy “sub-domains” that constitute the broad STI policy mix. These are shown in Figure 3.5 and include various types of enabling resources (i.e. funding and finance, research and technical infrastructures, enabling technologies, skills and capabilities, various framework conditions and an evidence base to support decision-making) and a range of relationships in STI systems (i.e. between STI and society; between the public, private and non-profit sectors; across different parts of government; and at the international level). System thinking can help identify and understand critical linkages, synergies and trade-offs between these sub-domains that are frequently treated separately.

Figure 3.5. Key challenges for STI policy in promoting sustainability transitions



Source: OECD S&T Policy 2025 project website, https://www.oecd.org/sti/inno/stpolicy2025/, accessed on 15 November 2022.

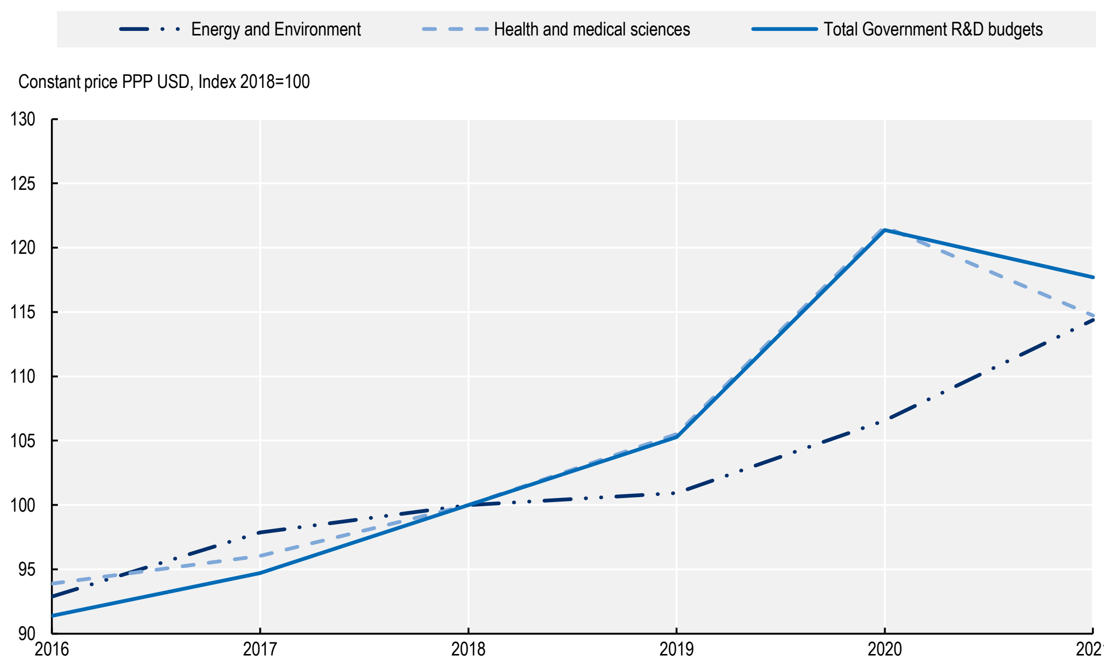
The sections that follow consider the prospects for transition-enabling reforms in these ten policy sub-domains. Given the systemic and multilevel aspects of sociotechnical systems, policy reforms will need to cut across these sub-domains, since many reform opportunities depend on progress in other sub-domains. Appreciating these interdependencies is essential and should empower policy makers to better recognise policy constraints and identify leverage points where they could act to unblock transition barriers.

STI funding and finance for sustainability transitions

Public research funding

While public investments in energy and environment R&D have increased in recent years (Figure 3.6), their growth will need to accelerate if technological developments are to keep pace with meeting net-zero targets. Sustainability transitions require transformational levels of investment over a long period, covering all parts of the innovation chain. The IEA estimates that the global public investment of its member countries on energy R&D and demonstration (RD&D) in 2021 was almost USD 23 billion (US dollars), most of which was targeted at low-carbon technologies. The annual increase of 5% was lower than the annual average of 7% from 2016 to 2020. Energy RD&D expenditure by the People's Republic of China (hereafter China) grew more than 2.5 times over 2015-21 (Figure 3.7), and China is estimated to be slightly ahead of the United States in public energy RD&D spending.[7] While these increases can be viewed positively, the levels of expenditures as a percentage of gross domestic product (GDP) are still less than half those of the late 1970s, when countries invested heavily in RD&D to deal with oil price shocks (Figure 3.8). The climate emergency is a larger challenge requiring arguably similar ambitious levels of investment.

Figure 3.6. Government R&D budget trends, 2016-21



Source: OECD R&D statistics, September 2022. See OECD MSTI Database, http://oe.cd/msti for most up-to-date OECD indicators.

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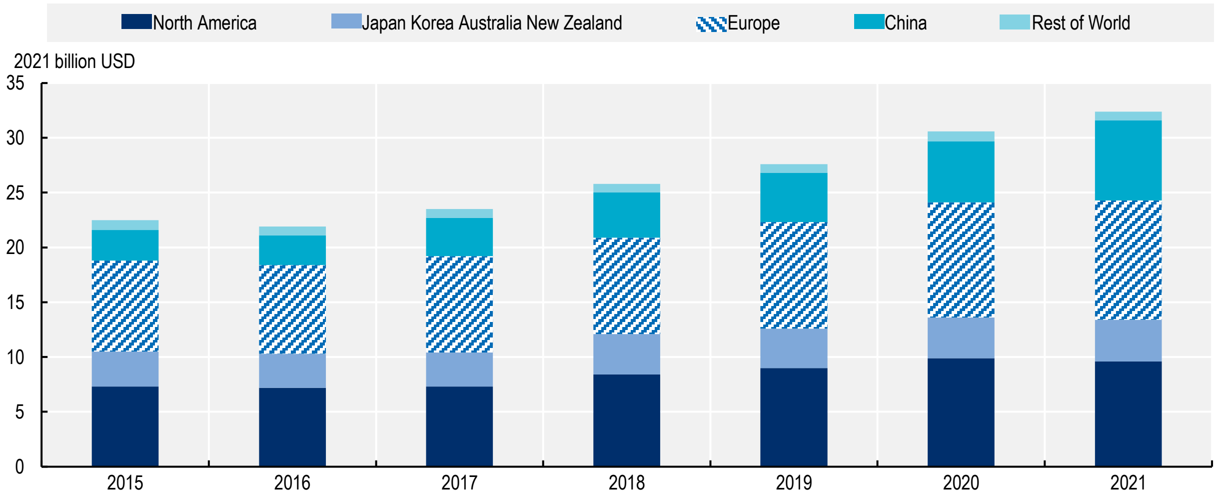
Figure 3.7. Key players in the global landscape

Global public low-carbon energy RD&D budget, 2015-21



Source: IEA, *Global public low-carbon energy RD&D budget, 2015-2021*, IEA, Paris, https://www.iea.org/data-and-statistics/charts/global-public-low-carbon-energy-rd-and-d-budget-2015-202, (accessed on 4 December 2022)

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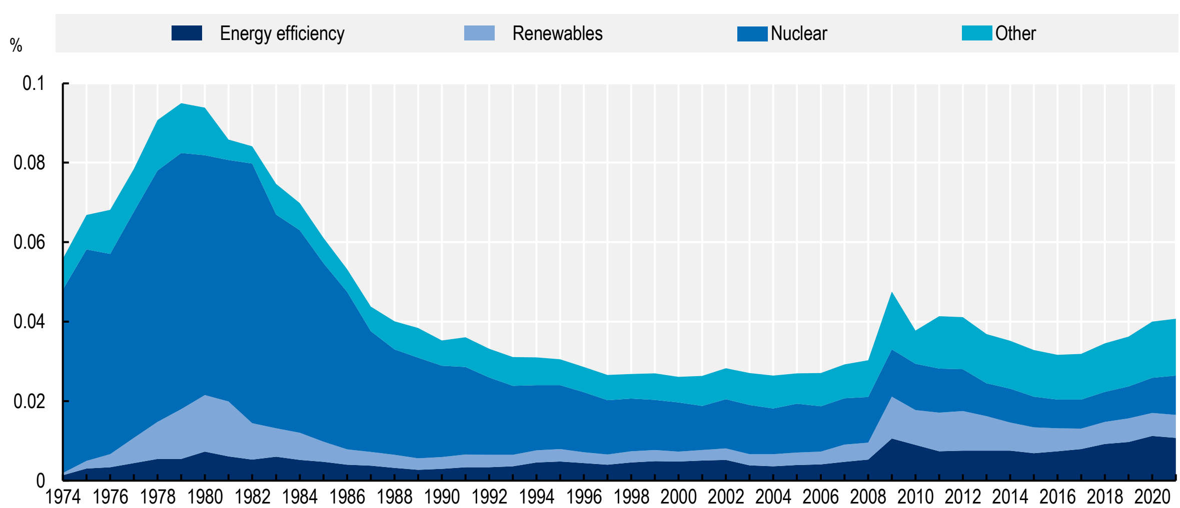
Figure 3.8. Low-carbon public RD&D expenditures in GDP across IEA member countries, 1974-2021

Percentage of GDP



Note: 2021 is estimated data. Data from 2016 for the United States are estimated. The "Others" category includes hydrogen and fuel cells, other power and storage technologies, and other crosscutting technologies and research. See https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2. IEA member countries are Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Lithuania, Luxembourg, Mexico, New Zealand, Norway, Poland, Slovak Republic, Spain, Sweden, Switzerland, the Netherlands, Türkiye, United Kingdom, United States.
Source: OECD calculations based on IEA, RD&D Budget, IEA Energy Technology RD&D Statistics (database), https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2, (IEA, 2023[15]) *and OECD National Accounts Statistics (database),* (OECD, 2023[16]) *(accessed on 17 February 2023).*

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As well as increasing levels of RD&D expenditures, governments need to consider the ways their investments are made and which parts of the innovation chain they target. Governments remain the main investors in fundamental discovery research, but this needs to be more solutions-focused and directed towards generating new knowledge and low-carbon technologies. This requires integrating expertise and insights from different disciplines and different sectors of society, as well as more inter- and transdisciplinary research (see Chapter 4). Such research is not currently mainstreamed and is poorly incentivised in academic research and assessment processes. While most countries are implementing policy initiatives to promote inter- and transdisciplinary research, and some pockets of excellence are emerging, these need to be urgently and substantially scaled up to support transitions to more sustainable socio-economic development pathways (OECD, 2020[17]).

A critical part of the climate innovation policy package is to close the funding gap for large-scale demonstration projects. The amount of funding needed is very significant, particularly in the industry sector.[8] The IEA estimates that at least USD 90 billion in public funding is needed globally by 2026 for demonstration projects in clean-energy technologies for these to be commercially ready by 2030 and help deliver net-zero emissions by the middle of the century (IEA, 2022[4]). Some progress is being made in this regard, with governments supporting major RD&D projects through their COVID-19 recovery packages (Box 3.3), as well as through a new generation of green industrial policies – including the US Inflation Reduction Act and Infrastructure Investment and Jobs Act, the EU Innovation Fund, Japan's Green Innovation Fund and China's 14th Five-Year Plan – with an increasing focus on heavy industry; hydrogen; carbon capture, utilisation and storage (CCUS); and other critical energy technologies (see Chapter 2). More specifically, the United States Government launched the Clean Energy Technologies Demonstration Challenge[9] in mid-2022 to meet the IEA's USD 90 billion target, an amount that was surpassed a few months later after several countries and the European Commission committed to making large contributions during the Global Clean Energy Action Forum in Pittsburgh in September 2022.[10]

Box 3.3. Will post-COVID-19 recovery packages accelerate low-carbon innovation?

The recovery packages adopted in the wake of the COVID-19 pandemic constitute a unique opportunity to accelerate the transition to a low-carbon economy. To assess the impact of recovery spending specifically on low-carbon technologies, the OECD is building the Low-carbon Technology Recovery Database (LTRD). The LTRD currently covers 14 countries within the project's scope of OECD, Group of Twenty (G20) and EU member countries. Combined, these countries represent 66% of global GDP and 53% of global annual CO_2 emissions. The final database, which will be released later in 2023, will include 52 countries.

According to the data gathered so far, a total of USD 1.2 trillion in funding for recovery packages has targeted low-carbon technologies. Half of the funding within the LTRD has been directed at the transportation sector and around one-third to energy generation, transmission or distribution. Around 85% of the measures target the deployment phase, and 15% the RD&D phase. Compared to the recovery packages following the 2007-08 Global Financial Crisis, the response to the COVID-19 crisis appears to have placed more emphasis on RD&D.

Among low-emission technologies that are still in the early stages of innovation and where significant investments in RD&D projects are necessary, hydrogen has been the main priority (especially in the United States, France and Germany), followed by CCUS and smart grids. Relatively small fractions of recovery packages are dedicated to nuclear innovation, zero-emission buildings and large-scale storage technologies.

The analysis shows that while recovery packages make a welcome contribution to closing the investment gap, they fall short of the substantial low-carbon technology investments requirements to be on track to meet the net-zero target. This overall shortfall, however, masks considerable heterogeneity across technologies. Low-carbon technology recovery funding contributes significantly to closing the investment gap for electric vehicles, CCUS and nuclear power; it is substantial for energy efficiency, clean-fuel supply (hydrogen), electricity network and renewables; but it is marginal in electric vehicle (EV) charging infrastructure and negligible in battery energy storage.

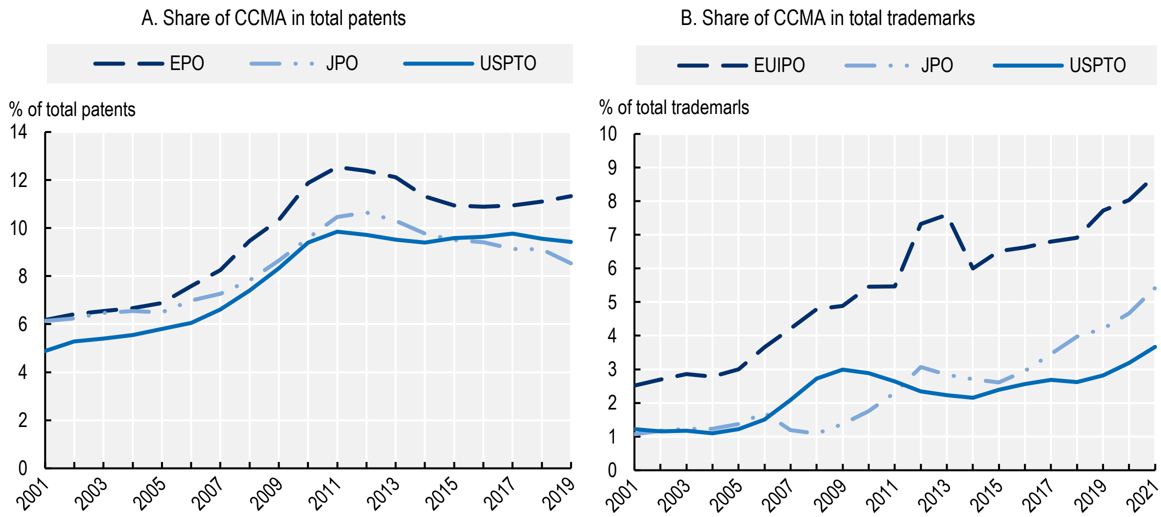
In short, while post-COVID stimulus packages have oriented investment towards sectors and technologies key for the low-carbon transition, they cannot by themselves close the investment gap as needed by 2030. They must now be accompanied by more ambitious complementary climate policies that would induce private investment and trigger the deeper structural changes made necessary by net-zero targets and the current fossil-fuel energy price crisis.

Note: These are preliminary findings of ongoing research on the impact of recovery packages announced in response to the COVID-19 pandemic on the development and diffusion of low-carbon technologies. The final results of this work are intended for publication later in 2023.
Source: (Aulie et al., 2022[18])

An important policy question is how much to spend on deployment of existing technologies compared to RD&D. The answer depends on the relative intensity of market failures associated with technology development, mainly knowledge spillovers at the RD&D stage and learning-by-doing at the diffusion stage. The relative importance of deployment support (market pull) vis-à-vis RD&D support (technology push) should increase with the movement from highly immature technologies towards technologies close to market competitiveness. Patent and trademark filing data can be used as one proxy among others to explore the relative effort assigned to RD&D and deployment (OECD, forthcoming[19]). Figure 3.9 shows that after a period of strong growth between 2006 and 2012, patenting in climate-related technologies has declined recently as a share of total patenting. This is mostly on account of higher growth in patenting in other technology areas, but also because of a sharp decline in climate-related technology patenting at the Japan Patent Office. Figure 3.9 also shows that, by contrast, the proportion of trademarks covering climate-related goods and services has grown markedly over the last two decades, a positive sign of success in technology diffusion and deployment. The patterns here need to be examined more closely and may differ markedly from one jurisdiction to another, but they suggest governments need to pay greater attention to RD&D if technologies currently at the research, development, demonstration or prototype stage are to make it to market by 2030.[11]

Figure 3.9. Patent filings and trademark registrations in climate-change mitigation and adaptation (CCMA) technologies

Percentage of total patents and trademarks



Note: Data refer to patents filed at the European Patent Office (EPO), the Japan Patent Office (JPO) and the United States Patent and Trademark Office (USPTO). Patents in climate change mitigation or adaptation (CCMA) are identified using the Y02 tag of the Cooperative Patent Classification (CPC). For trademarks, data refer to trademarks filed at the EU Intellectual Property Office (EUIPO), the JPO, and the USPTO. CCMA trademarks are identified using keyword searches in the goods and services description of the trademarks. For a definition of CCMA technologies, see (Aristodemou et al., 2022[20]).

Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, February 2023 (accessed on 9 February 2023).

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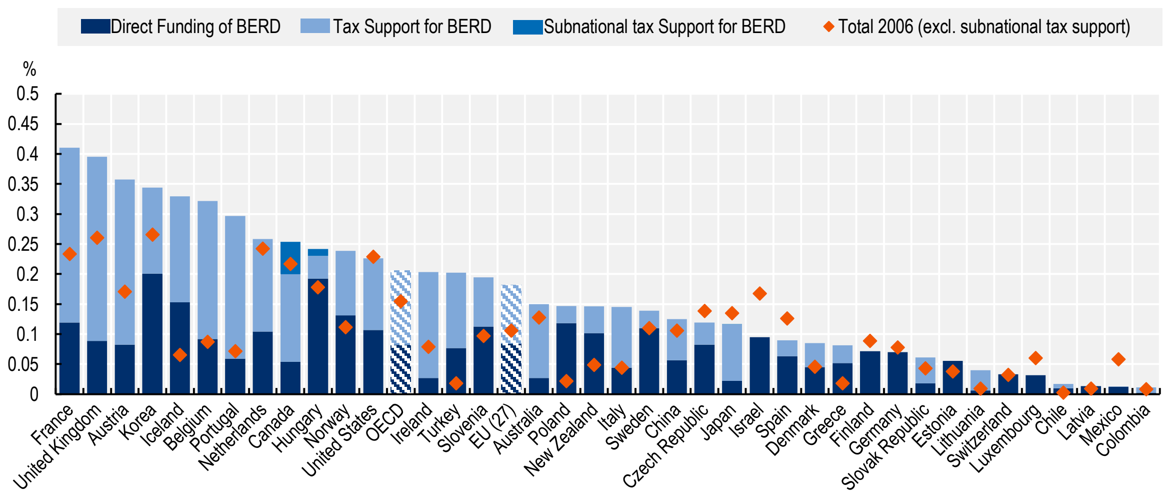
Public funding of business R&D and innovation

Businesses account for the largest share of expenditures on R&D in most OECD countries and are the main performers of innovation activities.[12] 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 3.10). There has been considerable change in the business R&D support policy mix over the last two decades, with a near-universal shift from direct support instruments to a greater reliance on R&D tax incentives. Across OECD countries, R&D tax incentives represented around 60% of total government support for business R&D in 2019, compared to 36% in 2006 (Figure 3.11).

Figure 3.10. Direct government funding and government tax support for business R&D

As a percentage of GDP, 2006 and 2020



Note: Data on subnational tax support not available for China, Spain United States. For general and country-specific notes on the estimates of government tax relief for R&D expenditures, please see http://www.oecd.org/sti/rd-tax-stats-gtard-ts-notes.pdf.
Source: OECD R&D Tax Incentives Database, http://oe.cd/rdtax, January 2023

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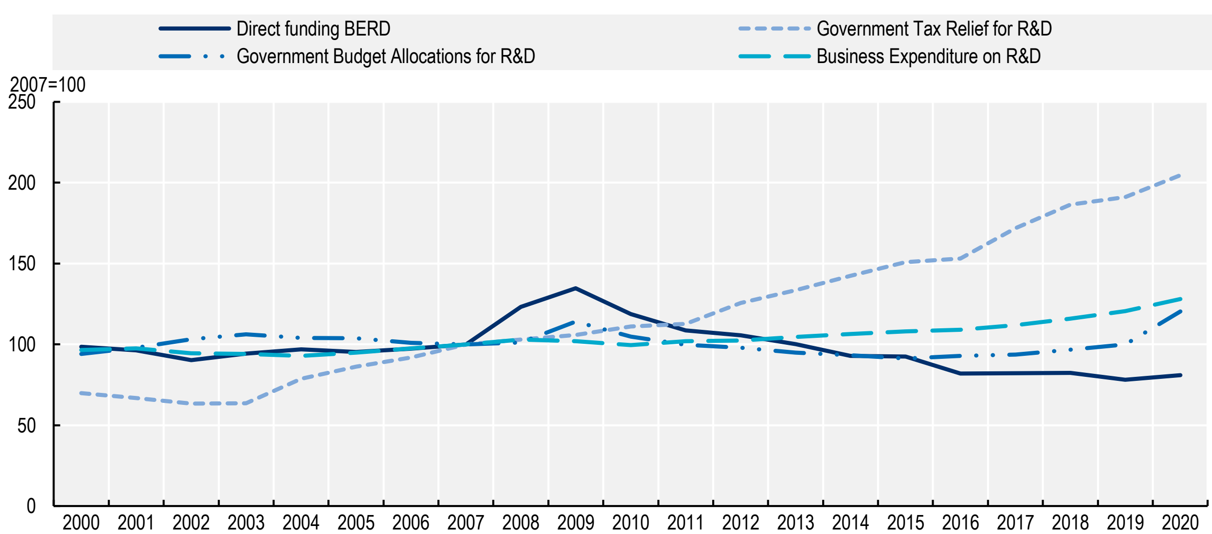
Figure 3.11. Continuing shift in government policy support mix for business R&D

Government funding of Business R&D in the OECD area, 2000-2020, normalised by GDP, 2007=100



Note: Estimates of total OECD direct funding of BERD cover OECD countries, except Costa Rica. Estimates of total OECD R&D tax support (central government level) cover all OECD countries. Direct support estimates include government R&D grants and public procurement of R&D services, but exclude loans and other financial instruments that are expected to be repaid in full. For general and country-specific notes on the estimates of government tax relief for R&D expenditures (GTARD), see http://www.oecd.org/sti/rd-tax-stats-gtard-ts-notes.pdf.
Source: OECD R&D Tax Incentives Database, http://oe.cd/rdtax, January 2023 and OECD R&D statistics, September 2022. See OECD MSTI Database, http://oe.cd/msti, for most up-to-date OECD indicators.

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After two decades of widespread deployment, there exists broad consensus that tax incentives are more suited, in principle, to encouraging R&D activities with near-market potential. By contrast, direct grants are more suitable for supporting longer-term, high-risk R&D, as well as 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 deal with key societal challenges like climate change points to the need for a more directive approach using direct measures (OECD, 2021[2]). Large parts of such innovation funding will likely be channelled through sectors, such as energy and transport, and STI policy will need to co-ordinate with other parts of government to bridge various "valleys of death" across innovation chains. This shift in policy emphasis coincides with the growing use of cross-government industrial policies, including MOIPs, which require governments to make explicit innovation policy choices, in conjunction with other actors (notably firms), on where to focus their limited resources. At the same time, governments need to reacquire at scale the skills and capabilities to operate the sorts of direct financing schemes the net-zero challenge calls for.

Private financing of R&D and innovation

Even with this mix of support, government financing is insufficient to fill the funding gaps that prevent innovations for sustainability reaching the market, and private financing must crowd in.[13] For example, venture capital is a key complement to government support for technology, financing pilots and demonstrations of innovative ideas and prospective technologies, which are often the output of government-funded R&D. Venture capital is also important for small companies to move beyond an initial niche market (OECD, forthcoming[19]). Yet investing in the green transition remains a challenge for private investors for several reasons: insufficient profitability compared to investments with similar risk profiles; difficulty assessing risks owing to information asymmetries between innovators and investors; and challenges in meeting "internal rate of return" requirements or "return on equity" thresholds. These imperfections in the market for capital limit the amount of private capital available for low-carbon RD&D.

The concept of "blended finance", which initially emerged as an innovative tool in the development community to crowd in private financing for sustainability projects in developing countries, is gaining traction in the STI policy field as a way to combine public and private finance across the innovation chain (OECD, 2022[21]; Miedzinski et al., 2020[22]). It works by combining risk-mitigation tools, such as first-loss mechanisms, with debt and equity funding to help firms cross multiple valleys of death at various stages of the innovation cycle. Each instrument has distinctive features in terms of where the capital source comes from, how the return to investment is to be realised, and how to mitigate the risk against the potential return. Blended finance can help scale up private investments in R&D and innovation to better meet sustainability challenges in both developed and developing countries, and has the potential to introduce greater directionality into STI finance.[14] In particular, it can be used to help increase the amount of funding directed to R&D and innovation for "public goods" such as clean air and water systems. These are areas where there are high social returns but weak incentives to invest in STI projects with high economic and technological risk.

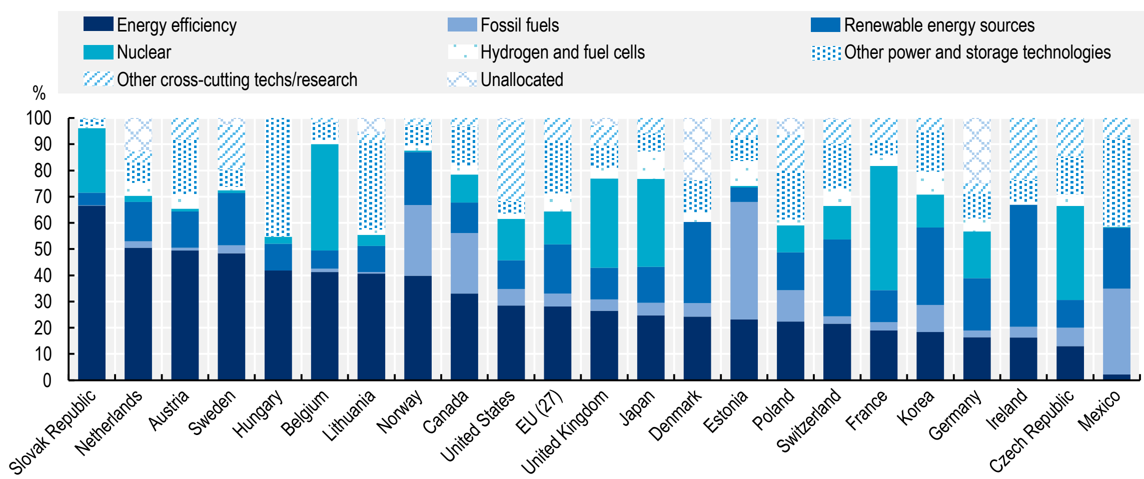
Enabling technologies for sustainability transitions

Recent years have seen widespread deployment of selected low-carbon energy technologies, notably photovoltaics, EV batteries and wind turbines.[15] This is thanks to sharp declines in their costs – for example, EV batteries and photovoltaics have both experienced cost reductions of 90% over the past decade. Costs reductions have been enabled by rapid technological progress, which has been driven by investments in R&D activities, generous subsidies (including feed-in tariffs), learning-by-doing and economies of scale. As a result, many sources of renewable energy are already cheaper than fossil fuels (OECD, forthcoming[19]).

Future technological development prospects are uncertain and often require major investments, particularly by the private sector. Governments are assuming more interventionist roles as they seek to compress the innovation cycle, which requires them to make technological choices. These choices are often informed by portfolio models that seek to "spread bets" on a diversity of technologies and to avoid technological lock-ins.[16] Nevertheless, countries vary in the priority they give to different technologies (Figure 3.12), reflecting in part historical technology commitments (e.g. as major fossil-fuel suppliers, Norway and Mexico devote sizeable proportions of their RD&D to this area, while nuclear technologies account for a large share of RD&D expenditures in France and other countries with large nuclear facilities). Hydrogen and fuel cells remain modest compared to other technology areas but are the fastest-growing area globally (Box 3.4).

Figure 3.12. Public RD&D budgets on renewable energy and other low-carbon technologies

As % of total public energy RD&D, by technology, 2020



Source: IEA, "RD&D Budget", *IEA Energy Technology RD&D Statistics* (database), https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2 (accessed on 21 December 2022).

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Box 3.4. The big push for hydrogen

Government support for the development of low-carbon hydrogen features in the recovery plans of several countries and is a key technology in net-zero emission scenarios by 2050. The potential of "green hydrogen" for decarbonisation has been the subject of particular policy focus recently and may serve as an example of the need for further innovation. Production of green hydrogen, i.e. hydrogen from water and renewable electricity through electrolysis, can contribute to reducing emissions through four channels. First, hydrogen is already a feedstock for a number of chemical products, and green hydrogen can make this production carbon-neutral. Second, hydrogen is a promising alternative to fossil fuels for high-temperature industrial processes in hard-to-abate sectors such as steel production. Third, hydrogen is necessary for the development of fuel-cell vehicles and can also, in specific circumstances, reduce emissions in the built environment by replacing natural gas. Finally, hydrogen can be used to store energy produced from intermittent sources, thereby supporting the supply of low-cost renewable electricity.

Most net-zero emission scenarios agree that hydrogen could play a pivotal role in decarbonisation at the 2050 horizon, particularly for agriculture and industrial applications, providing cheap and abundant renewable energy becomes available. However, in 2021, the production of green hydrogen was still about three times more expensive than grey hydrogen (made out of natural gas through steam reforming), even under the most favourable conditions. Major cost reductions – and the rapid deployment they would induce – are realistic in the next 10-20 years, but will crucially depend on massive improvements in the cost of electrolysers (through R&D and large-scale demonstration projects) and the availability of large volumes of cheap renewable electricity.

Against this backdrop, a number of countries have published national hydrogen strategies, which contain ambitious hydrogen production targets at the 2030 horizon. These targets are a significant improvement with respect to today's virtually non-existent green hydrogen production, but are still far from the necessary deployment at the 2050 horizon. Moreover, these targets mostly rely more on financial support for the deployment of new large electrolysers than on direct support for innovation. In this context, countries willing to support hydrogen should (i) ensure greater support for R&D in green hydrogen and demonstration projects; (ii) ensure a sufficient supply of renewable energy where possible, and encourage the creation of an international hydrogen market; (iii) establish clear carbon price trajectories to provide investors with the right incentives; (iv) reduce uncertainties for investors through regulatory action and standardisation; and (v) consider blue hydrogen (produced from natural gas with carbon capture) as an interim solution to facilitate the transition to green hydrogen.

Source: (Cammeraat, Dechezleprêtre and Lalanne, 2022[23]).

Alongside low-carbon and sector-specific technologies, net-zero will rest on innovation in other domains. The green and digital "twin transitions" offer the promise of leveraging digital technologies for sustainability transitions, with technologies like artificial intelligence (AI) and the Internet of Things (IoT) underpinning smart grids, for example (Box 3.5). Interactions between multiple innovations and sociotechnical systems is therefore an important consideration for STI policy makers, but there may also be trade-offs to manage. For example:

- AI-enabled products and services are creating significant efficiency gains, helping to manage energy systems and achieve the deep cuts in greenhouse gas emissions needed to meet net-zero targets. However, the computational needs of AI systems are growing, raising sustainability concerns. The physical infrastructure and hardware, together with software – collectively known as "AI compute" – require massive amounts of computational resources, which have their own environmental impacts (OECD, 2022[24]).
- The bioeconomy, generally defined as economic activities based primarily on biogenic instead of fossil resources, also offers potential solutions for finding sustainable materials and products. Several countries have introduced national bioeconomy strategies or programmes that aim to support the transition to a circular economy by developing materials that are easier to recycle and reuse (Box 3.6). However, the policy landscape remains complex because of potential sustainability trade-offs due to land and water use, and impacts on biodiversity (Philp and Winickoff, 2018[25]).

Box 3.5. Digitalisation and the green transition

The digital transformation could be a key enabler for reaching climate goals, thanks to technologies such as smart meters, sensors, AI, IoT and blockchain, and to digitally induced changes in business models and consumption.

In the energy sector, demand-side management can help balance the renewable-based electricity system. For example, AI can help forecast weather and electricity prices, mitigating intermittency problems in the system and increasing energy efficiency. Transmission and distribution system operators could use AI for real-time decision support (OECD, 2020[26]) (OECD, 2019[27]). Similarly, IoT devices could help buildings adapt in real time to weather conditions and prices, increasing energy efficiency (OECD, 2016[28]).

Smart mobility will change transport demand and efficiency: "smart" traffic lights can adapt to traffic flow, reducing air pollution and increasing energy efficiency of transport. Blockchain could help manage the distributed grid as it facilitates decentralised consumer-to-consumer selling of electricity and balancing supply with demand without needing a third party.

Industrial sectors will be reshaped through increased robotisation, smart manufacturing systems, additive manufacturing, IoT, smart appliances, sensors and AI, which can all improve energy and material efficiency. Digital solutions are equally important on the supply side, for example by accelerating low-carbon innovation with simulations and deep learning. Already, around 20% of patents protecting climate-change mitigation technologies have a digital component (Amoroso et al., 2021[29]).

The increased use of digital solutions can also change production patterns and trade, and bring production back to some countries ("reshoring") with better environmental performance. However, digital technologies consume large amounts of energy, implying higher direct energy demand and related carbon emissions, which warrant further efficiency improvements.

Source: (OECD, forthcoming[19]).

Box 3.6. Carbon management for net-zero: Bioeconomy and beyond

Net-zero carbon emissions can be achieved, in part, by a transition in how carbon is "managed", particularly the budget of carbon in the bioeconomy, carbon recycling and the creation of renewable energy required for various carbon pathways. But the frequently used term "decarbonisation" can be misleading as in some key economic sectors there is no alternative to carbon e.g., food and feed, chemicals, materials and cement. The more accurate term is "de-fossilisation" that implies leaving fossil reserves in the ground and exploiting other sources of carbon. This is the "renewable carbon" concept which entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere.

This resonates with the circular economy concept, an overarching objective of which is to close material loops to keep carbon circulating in the economy for as long as possible. This would break the pattern of "take-make-dispose" that has characterised the fossil era.

The renewable carbon concept largely supports the use of three sources of carbon as feedstocks, namely biomass, recycled solid carbon containing waste material or industry flue gases. Strengthening policies for reusing wastes as resources is a key action, since overly relying on biomass could have serious negative repercussions for biodiversity and food production. In the future, if the uncertainties around direct air capture (DAC) can be resolved, it may become more technically and economically feasible and be part of the solution.

In the meantime, bioproduction, if it can utilise industrial and domestic wastes as other feedstocks, offers promising opportunities, especially for CCU (Carbon Capture and Utilisation). CCU is effectively a value-adding proposition compared to CCS (Carbon Capture and Storage). Both will be necessary, but carbon capture will create a supply chain of pure and concentrated carbon also suited for CCU. Most CCU technologies are embryonic and there are many to choose from e.g., gas fermentation, biochar, advanced wood-based building materials, and chemical recycling of plastics. Recent OECD analysis demonstrates a need for hybrid technologies involving at least two different technologies.

This transition will need to be driven by public policy rather than the market as the feedstocks and energy sources are less efficient than the incumbent fossil sources. The policy types are many and can be arranged according to the innovation cycle. This calls for an holistic policy framework that highlights timing and sequencing for policy makers that aligns feedstock/technology push with market pulls for a more robust effect on the economic system.

Source: (OECD, forthcoming[30]).

These examples demonstrate that technologies can contribute to transitions, but can also generate negative externalities that STI policy should help anticipate and manage, for example, using some of the technology governance techniques outlined in Chapter 6. At the OECD, the Global Forum on Technology was launched in December 2022 to foster multi-stakeholder collaboration on digital and emerging technology policy (Box 3.7), and the 2021 Recommendation of the Council for Agile Regulatory Governance to Harness Innovation sets norms for rethinking governance and regulatory policy to better harness the societal impacts of innovation (OECD, 2021[31]).

Box 3.7. OECD Global Forum on Technology

International cooperation will be a cornerstone of effective emerging technology policy and governance, but the landscape of forums with a true multi-sectoral approach has been sparse. New forums for international cooperation on emerging technology policy are emerging. In December 2023, the OECD Digital Economy Ministerial meeting gave birth to a new OECD Global Forum on Technology that aims to provide a venue for regular in-depth dialogue to foresee and get ahead of long-term opportunities and risks presented by technology. It aims to facilitate multi-stakeholder and values-based discussions on specific technologies among OECD Members and partners, responding to gaps in existing fora.

Some of the other objectives include:

- Identifying and analysing specific technological developments where there are gaps in existing fora, where societal, economic, security, and sustainability impacts are likely to be significant, and where there are major potential implications for policy and regulatory frameworks.
- Exploring nascent approaches to policy challenges and opportunities posed by emerging technologies and business models.

Sharing of good practices for the governance of technologies to build trust among participants and foster common and coherent approaches based on mutual interests and democratic values.

Research and technical infrastructures

Various types of infrastructures are essential to research and technological innovation. Laboratories and research equipment are obvious examples, but other infrastructures include those supporting open science (e.g. digital repositories for research data) and open innovation (e.g. living labs, technology demonstrators and extension services). Many of these infrastructures – including large public research infrastructures (RIs) and technical infrastructures (TIs)[17] – require substantial initial outlays and must develop business models that distribute costs and benefits in fair and sustainable ways. Challenge-oriented transitions present them with new opportunities, for example, as sites of large demonstration and scale-up initiatives that are essential for sustainable transitions, but also difficulties in adapting to new constellations of actors and their research and innovation support needs.

Historically, structural siloes and bottlenecks have posed a significant challenge to effective collaboration between RIs and, more broadly, with potential users or partners operating in different disciplines and at different stages of the R&D pipeline, including TIs. This came to the fore during the COVID-19 response when established connectivity between system actors, such as those operating in basic, applied and industrial research was critical to accelerating the advancement of scientific solutions. The complexity of the crisis highlighted the value of cross-infrastructural workflows for projects that require the services of multiple RIs and TIs. It also emphasised their status as sites of collaboration between diverse and disparate partners, and as focal points for the development and dissemination of unique and cutting-edge research and data. Effective integration of crisis response capabilities into the mandates of RIs and TIs will require a shift from prioritising short-term financial efficiency to building strategic redundancies, resilience and long-term effectiveness. While this has a funding dimension, it also requires expertise, both for internal operations and for benefiting the broader STI system (Larrue, 2021[32]; OECD, forthcoming[19]).

Co-operation and partnerships within innovation ecosystems

Mobilising a diverse set of actors, including businesses, governments, the scientific community and citizens, to co-operate on transitions will be essential. Governments have a long tradition of promoting industry-academic links, using a mix of policy instruments, including funding, regulation, information services and governance arrangements, to spur and deepen relations. Governments increasingly use challenge-based funding and MOIPs to draw together diverse sets of actors into collaborative arrangements that target transitions (see Chapter 5). For mission-oriented collaborative platforms, the shift of national and international R&D programmes to more open and participatory models comes with a need for new governance processes for knowledge transfer, including alliance management, asset sharing, privacy, transparency, value creation and responsibility. Joint efforts between the public, private and non-profit sectors have encountered challenges to data sharing, ownership and value creation. Policies can help to share knowledge and resources, facilitate decision-making processes and align innovation with societal needs (OECD, 2021[2]).

As technology becomes more complex, innovation is increasingly shifting towards platform-based co-operation models. New institutional arrangements, such as collaborative platforms, are emerging to co-ordinate a diverse set of actors across the public and private sector, and create value by harnessing platform effects. They entail a technological architecture that allows their members to innovate rapidly, but also to collaborate with many external players who can use the platform for their own innovations. Many governments, along with partners in industry, start-ups and civil society, are developing experimental forms of these collaborative platforms to provide better linkages between research and innovation, and promote commercialisation. By bringing together experts from academia, industry and the philanthropic sector, collaborative platforms are often more flexible than national regulatory frameworks when it comes to setting technical standards for the application of technology and managing associated risks. Furthermore, government involvement in collaborative platforms can help de-risk investment in emerging technologies (OECD, 2021[2]).

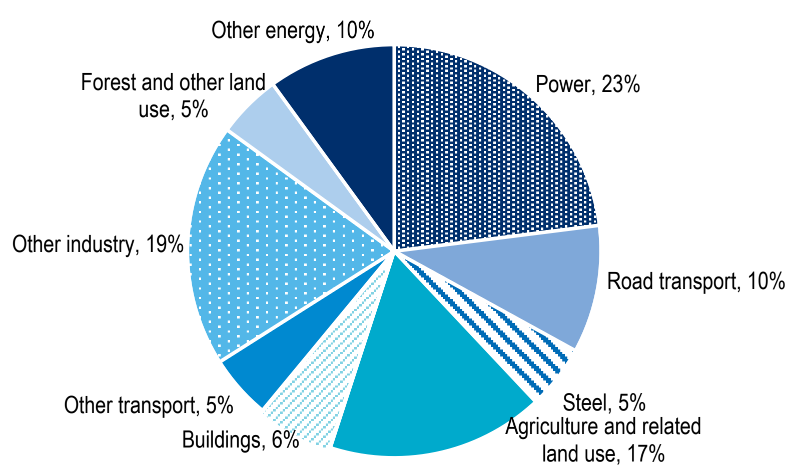
Finally, research funders in many countries are striving to promote transdisciplinary research (TDR), which can address complex problems beyond the reach of traditional science. TDR offers a practical way to address issues, such as sustainability transitions, that are highly contested and where stakes are high. It is a mode of research that integrates both academic researchers from unrelated disciplines – including natural sciences and social sciences and humanities – and non-academic participants to achieve a common goal involving the creation of new knowledge and theory. Given the scale and urgency of the human-environmental system challenges facing society, there is a strong argument that TDR needs to be scaled up singificantly and become a mainstream modus operandi for research. This would affect both the prioritisation of research areas and changes to funding processes, including funding criteria, peer review and evaluation (OECD, 2020[17]).

Cross-government co-ordination for transitions

Sociotechnical transitions are complex and uncertain, requiring multi-agency government responses. Cross-government linkages and policy coherence are therefore essential for transitions. However, like all large organisations, governments struggle with co-ordination challenges, which can lead to incoherence in the policy mix for transitions, and ultimately less policy effectiveness. This also applies to STI policies, and the mix of support measures governments offer might not adequately match the challenge at hand or the wider policy mix of regulation and incentives. Misalignments can be horizontal (between innovation policies and sectoral policies), vertical (between ministries and implementing agencies), or multilevel (between national and regional authorities).

Sustainability transitions cannot be achieved or even chiefly driven by STI policies, although they are certainly essential. A range of sectors contribute to greenhouse gas emissions (Figure 3.13), and sectoral policies in areas such as energy and agriculture are expected to do much of the heavy lifting. These sectors in many OECD countries have their own considerable STI activities and capabilities which, when taken together, can dwarf those under the direct responsibility of research ministries and their funding agencies. Government sectoral support covers the full range of innovation chain activities, from fundamental research to technology demonstration, diffusion and deployment. Governments also link achieving net-zero to growing industrial policy goals, where increasing the rate at which promising new technologies enter the energy system can potentially drive future economic growth. Energy security concerns also shape this policy agenda, for instance, through concepts like "strategic autonomy" (see Chapter 2). This wider framing therefore brings in other government policy domains, raising further co-ordination and coherence challenges.

Figure 3.13. Greenhouse gas emissions by sector, 2019



Source: (IPCC, 2022[33]).

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Domain specificities are therefore important considerations for STI policy when trying to promote and assemble configurations of actors to develop transition-enabling innovations. Sectoral STI activities operate with their own logics, institutions and policy practices that often differ from those of mainstream STI policy. This need not be problematic in itself, but it highlights the need for governance mechanisms that promote strategic alignment to deal with crosscutting issues like climate change. There are no “silver bullets”, and co-ordination failures are often caused by government budget structures, which tend to disincentivise co-operation and often promote competition between different parts of government. Various governance arrangements have emerged over the years to improve the overall coherence of STI policies, programmes and instruments across a range of government departments and agencies, as well as at different governance levels (e.g. regional, national, European Union). Among these are shared national visions, roadmaps and missions; new regulatory models that provide greater scope for experimentation; sectoral technology needs assessments; joint programming between research and innovation funding agencies; and strategic oversight by high-level cross-departmental committees. Beyond these “formal” mechanisms, informal arrangements and conditions (e.g. the circulation of civil servants) can also promote cross-governmental co-operation. Political leadership at the highest levels is also often a prerequisite for a directional approach that cuts across government.

In a similar vein, the recent turn to MOIPs attempts to bundle together a range of complementary public interventions to achieve ambitious goals for which more traditional fragmented STI policies have produced, at best, only mixed results. These specific ”co-ordinated packages” of research and innovation policy and regulatory measures can span different stages of the innovation cycle, from research to demonstration and market deployment; mix supply-push and demand-pull instruments; and cut across a range of policy fields with responsibilities for different thematic areas (Larrue, 2021[32]). Several countries are currently experimenting with different types of MOIPs to tackle all kinds of societal challenges, including net-zero, as outlined in Chapter 5.

Framework conditions for STI-enabled sustainability transitions

The roles science and technological innovation can play in sociotechnical transitions is shaped by a wide range of structural and institutional factors. For example:

- The disciplinary organisation of science and the autonomy of research-performing organisations, such as universities, all significantly shape the priorities and practices of public research and modulate the influence of public policy interventions.
- In technological innovation, the functioning of product and labour markets, the scope of regulation (including on carbon pricing, intellectual property, environmental protection, etc.), technical standards, firms’ business models and geography, among other factors, all influence the rate and direction of innovation. Low fossil-fuel energy prices also influence incentives for investment in low-carbon and energy efficiency innovation, with the trend in worldwide low-carbon patent intensity mapping closely to international oil price changes, i.e. the higher the oil price, the higher the patent intensity in low-carbon inventions.

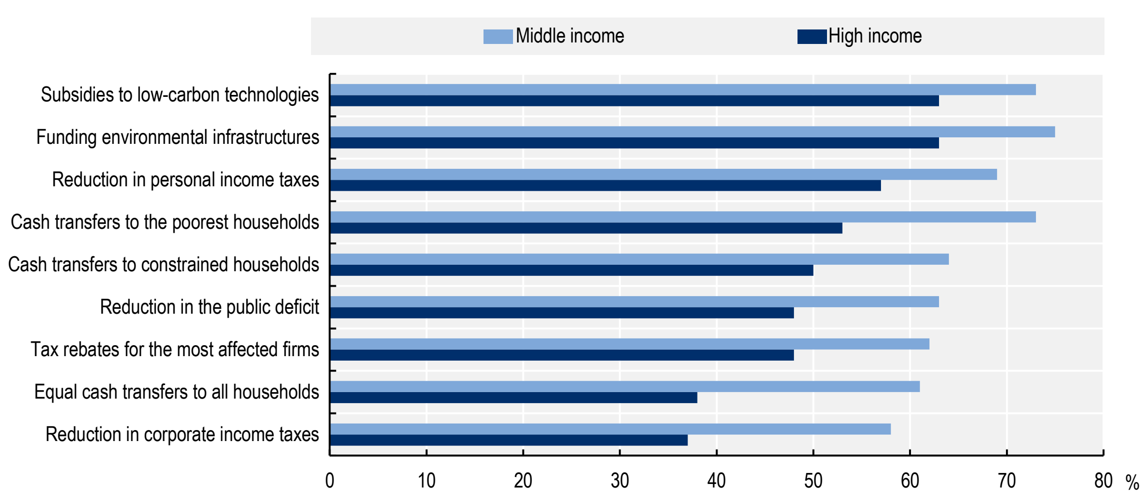
These framework conditions, which often have their origins outside of the immediate remit of STI policy, can either enable or hinder sociotechnical transitions. They are important leverage points for promoting transitions, but may also offer significant barriers and lock-in. This sub-section outlines three framework conditions that influence low-carbon innovation, namely business dynamism, standards and carbon pricing.

Lack of business dynamism may prevent low-carbon innovations from overtaking fossil fuel-based incumbents and secure market shares, even if they are more efficient. Start-ups are often the vehicle through which radical innovations enter the market, older incumbent firms often focusing on incremental changes to established technologies. Limits to competition can therefore slow down sustainability transitions. Concentration of market power can also be a challenge as long-term investors (e.g. asset-heavy banks, institutional investors) may favour incumbents because of perceived stable returns. Though alternative forms of financing (e.g. business angels and venture capital) can encourage greater risk-taking, they do not invest with a sufficiently long time horizon to drive transitions (OECD, forthcoming[19]).

Standards play key roles in shaping innovation trajectories, including in green technologies, where air quality and waste regulation (for example) have driven developments in clean technologies such as catalytic converters and incineration plants. Different types of standards can be used. For instance, a performance standard sets a uniform control target for firms, but does not dictate how this target is met. Technology-based standards specify the method, and sometimes the actual equipment, that firms must use to comply with a particular regulation, such as by requiring that a percentage of electricity be generated using renewable sources. In this way, standards help create demand for low-carbon innovations and induce technological change (OECD, forthcoming[19]); also see Chapter 2.

Because carbon pollution is unpriced by the market, there exist too few incentives for firms to develop or deploy technologies that can reduce carbon emissions. Carbon pricing is a way to make polluters pay for their greenhouse gas emissions, for example through a carbon tax or a cap-and-trade system. By making polluting emissions costly, carbon-pricing policies change the relative costs and benefits of competing technologies. This can lead to the development of new technologies and processes that are more energy-efficient and environmentally friendly. However, measures like carbon taxes are politically unpopular and are currently set at sub-optimal levels. STI policies can help reinforce the impacts of carbon prices by supporting innovations that lower the cost of green technologies, making them competitive with existing technologies. In this way, STI policies can partially substitute for low carbon prices, which supports the case for even stronger STI policies (OECD, forthcoming[19]). STI policies can also help create economic winners from the low-carbon transition, which can benefit the political acceptability of future climate policies. From a public acceptability point of view, STI climate policies also appear to be an attractive option. Recent research from a nationally representative population survey (Dechezleprêtre et al., 2022[34]) shows that subsidies for low-carbon technologies are systematically the most favoured climate policy compared to carbon pricing, bans or regulations (Figure 3.14).

Figure 3.14. Share of respondents who support climate-change policies (somewhat to strongly)



Note: Policy views are elicited on a five-point scale: “Strongly oppose,” “Somewhat oppose,” “Neither support nor oppose,” “Somewhat support” and “Strongly support.” The figure shows the share of respondents to answer: “Somewhat support” or “Strongly support.” High-income countries participating to the survey are Australia, Canada, Denmark, France, Germany, Italy, Japan, Poland, Korea, Spain, the United Kingdom and the United States. Middle-income countries participating are Brazil, China, India, Indonesia, Mexico, South Africa, Türkiye and Ukraine.
Source: (Dechezleprêtre et al., 2022[34]).

StatLink https://stat.link/yqblkj

Societal engagement and just transitions

An inclusive and people-centred transition is key to the world moving rapidly, collectively and consistently towards net-zero emissions by mid-century (OECD, 2021[35]). Widespread social acceptance is needed to create legitimacy and support for strong transition policies and improve resilience against political setbacks (Geels et al., 2017[9]). Achieving momentum to address green sociotechnical transitions will require public support of policies that rely on technical evidence, as well as public reasoning about the future of technology in society. Moreover, in a context of high complexity, engaging citizens in STI policy can tap diverse sources of ideas and information, as well as help identify the real needs and concerns of different social groups, including those that are under-represented in science, innovation and respective policy spaces. This can promote more legitimate policy decisions that better respond to citizens' needs, and take into account their broader socio-economic impacts and ethical implications (see Chapter 6).

These are important considerations for a ”just” transition, whose goal is to ensure that the costs and benefits of transitioning to a more sustainable future are shared fairly, and that no one is left behind (OECD, 2021[35]).[18] This can include measures such as providing support for people of working age who may be displaced by the low-carbon transition, investing in education and training to help people adapt to new industries, and ensuring that marginalised communities have a voice in the transition process.[19] For example, the European Commission has launched the Just Transition Mechanism, which mobilises around EUR 55 billion (euros) over 2021-27 to alleviate the socio-economic impact of the transition in the most affected regions. The IEA has established the Global Commission on People-Centred Clean Energy Transitions, which has unveiled 12 key recommendations designed to help citizens to benefit from the opportunities and navigate the disruptions created by clean-energy transitions.[20]

Finally, communicating scientific uncertainties to society and being transparent about conflicting or dissenting scientific views will continue to be a major challenge, and scientific mis- and dis-information risk undermining the critical role that scientific knowledge and new technologies have to play in any transformation to sustainable development. Governments, scientists and technologists need to draw lessons from the COVID-19 experience to formulate strategies and implement measures that combat mis- and dis-information, for example on the existence of climate change and the need for mitigation and adaptation measures (see Chapter 4).

Strategic intelligence for sustainability transitions

Transitions call for systemic and transformative STI policies that must act at pace under conditions of uncertainty. They also call for different sorts of knowledge and evidence bases to inform STI policy design, implementation, coherence and evaluation. Relevant methods include strategic foresight and technology assessment, modelling and simulations, systems and pathways mapping, monitoring and evaluation, and quantitative indicators development, all of which can be collectively referred to as ”strategic intelligence”. Whether existing strategic intelligence provision and use are well suited to the high ambition of transition policy agendas is doubtful. Transformative STI policies demand knowledge and evidence to support direction-setting, experimentation and learning in contexts that are systemic, transdisciplinary, complex and uncertain. These demands may require new or significantly adapted knowledge institutions and infrastructures, as well as new skills and organisational capabilities – essentially a transition in the production and use of strategic intelligence itself. A specific challenge for countries is to make sense of the range of data available, and in particular to combine and synthesise knowledge and evidence from different sources that have different formats and have been produced for different purposes.[21] With this in mind, several countries are in the process of developing crosscutting strategic intelligence infrastructures for STI policies to meet the transitions challenge.

Future-oriented technology analysis

Many national research ministries and funding agencies have used strategic foresight in recent decades to help them set research priorities, organise new configurations of actors, and become more agile as organisations in times of uncertainty. The "twin transitions" challenge has seen heightened interest in foresight practices, as signified for example by the European Commission recently appointing a commissioner for foresight, publishing an annual strategic foresight report since 2020 and organising a foresight network of ministers for the future from EU Member States.[22] Both long-term trends and drivers, as well as disruptive events like the COVID-19 pandemic, mean existing assumptions may no longer hold and the near-future may look considerably different from the recent past. Policy tools, such as strategic foresight, can help shed light on possible futures. They can also indirectly reduce uncertainty by promoting collective action around widely shared future visions, for example, on sustainability transitions (Cagnin, Amanatidou and Keenan, 2012[36]).

Technology assessment (TA) is an evidence-based, interactive process to bring to light the societal, economic, environmental and legal aspects and consequences of new and emerging science and technologies. It aims to inform public opinion, help direct R&D, and act as a source of strategic intelligence to shape policies that both promote and govern new and emerging technologies. TA is conducted for a variety of sometimes overlapping reasons. It is deployed to anticipate the potential impacts of new and emerging technologies, to avoid surprise and allow for risk and uncertainty management. It is also used to guide innovation and technology development towards societal goals, by informing and shaping agenda-setting and bringing to light key values and norms in the relationship between technology and society (OECD, forthcoming[19]). Chapter 6 discusses TA in the context of technology governance.

Monitoring, evaluation and statistical indicators[23]

The emergence of transformative STI policies brings new challenges for monitoring and evaluation, since current STI indicators and traditional evaluation approaches are unable to grasp the complexity of the underlying transitions of sociotechnical systems. Methods that can capture system-level effects and allow for reflexive learning and formative evaluation are needed (Janssen, 2019[37]), as are approaches that can account for policy interactions, the engagement of multiple stakeholders, and co-ordination among different domains and levels (Haddad et al., 2022[38]). Since policies set priorities for transformative change, evaluation should also capture whether the direction of innovation and change responds to societal needs.

Sociotechnical transitions are deep and wide-ranging, and many aspects are not well served by existing metrics. One key challenge for building evidence is the limited capacity to bring together data on innovation inputs with data about material flows that matter for sustainability transitions. While progressively advancing at a general level, the data-linking agenda is not moving as fast as required by the severity of the policy challenge and needs to go beyond the domain of economic statistics. This requires more effective policy co-ordination and regulation to ensure there are safe spaces in which data that may be deemed confidential can be safely processed and analysed to its full potential.[24] Several national statistical organisations are rising to the challenge, but the innovation perspective is still seen as residual.

The challenge straddles multiple disciplines and actors. This is therefore a shared agenda with other policy and statistical domains that requires breaching silo mentalities while preserving some degree of specialisation. The green transition challenge requires measurement and analysis to carefully account for the distinct nature of micro-level indicators, as well as indicators about the emergent properties of innovation at the local, regional, national and global systems, and their transformation. STI measurement and policy analysis should also equip itself with the necessary tools to depict and manage uncertainty.

As policy makers use indicators as incentives to steer the green transition, a major challenge for both policy and measurement is the tendency for generalised "greenwashing" of activity, which risks diluting the informational content of such indicators. Policy makers need to work with indicator experts to put in place robust, hard-to-cheat systems, approaching the challenge strategically. The larger the (economic, environmental, reputational) stakes, the larger the risk that biased information will displace high-quality data and analysis.

International co-operation

International co-ordinated action can accelerate innovation, enhance economies of scale, strengthen incentives for investment and foster a level playing field where needed. Sharing experiences between countries and industries can reduce individual risks and accelerate progress towards viable low-carbon solutions. Measures and commitments to deployment can accelerate economies of scale and the corresponding cost reductions (IEA, IRENA and UNFCCC, 2022[11]). Given the global scale and scope of challenges like climate change, there is a growing sense that more needs to be done at the multilateral level to promote technological development, deployment and diffusion. The United Nations negotiations on climate change have established a strong consensus for action, and a large number of countries have committed to significant individual actions through their nationally determined contributions (NDCs). A great many initiatives for practical global engagement are already operating and involve governments, businesses, international and multilateral organisations, civil society organisations, and investors. The number and diversity of collaborative international initiatives has grown remarkably over recent years, and many of these have already made important contributions to the progress in low-carbon transitions (IEA, IRENA and UNFCCC, 2022[11]).

Several recent international initiatives have been launched. They include “Mission Innovation”, a global initiative launched alongside the Paris Agreement in 2015 that aims to catalyse action and investment in RD&D to make clean energy affordable, attractive and accessible to all countries in the next decade. Mission Innovation brings together governments,[25] public authorities, firms, investors and academia to work together on public-private action and investment through sector-specific ”missions” that accelerate clean-energy innovation in critical areas.[26] Another initiative, launched during COP26 in 2021, is the “Breakthrough Agenda”, which involves 45 countries[27] that are committed to working together to accelerate innovation and deployment of clean technologies, and making them accessible and affordable for all by 2030. The agenda is designed to help trigger tipping points (see Box 3.2) and stimulate international collaboration involving both the public and private sectors. It focuses on five key emitting sectors of the economy – power, road transport, steel, hydrogen and agriculture (IEA, IRENA and UNFCCC, 2022[11]). More recent initiatives include the proposed Group of Seven (G7) Climate Club (G7, 2022[39]), which aims to provide an intergovernmental forum to to promote ambitious climate policy around the world, and the OECD’s Inclusive Forum on Carbon Mitigation Approaches, which aims to facilitate multilateral dialogue on climate-change mitigation policies (OECD, 2022[21]).

Wide access to clean technologies will require considerable technology diffusion, particularly to low- and middle-income countries that are expected to account for the vast majority of the increase in global carbon emissions until 2050. This is a complex issue requiring multiple interventions. A key determinant of international diffusion is the domestic level of technological development, or technological capabilities, in recipient countries. The latest IPCC report (IPCC, 2022[33]) discusses the main challenges and possible solutions at some length, and highlights emerging ideas for international co-operation on innovation. These include promoting developing-country participation in technology programmes, climate-related innovation system builders and the creation of universities in developing countries that play the role of central hubs for capacity-building, as well as encouraging sectoral agreements and international emission standards. The United Nations Framework Convention on Climate Change (UNFCCC) set up the Technology Mechanism in 2010 to facilitate support to developing countries on climate technology development and transfer. This includes financial mechanisms and capacity-building, and technical support to help countries implement their NDCs. The UNFCCC recently published guidance on stimulating the uptake of technologies in support of NDC implementation and its new work programme until 2027 for accelerating climate action through technology development and transfer (UNFCCC, 2021[40]). However, it remains grossly underfunded in view of its ambitious mandate (OECD, forthcoming[19]).

Skills and capabilities

Transitions call for wide-ranging changes – from lifestyles to the ways scientific research is carried out – involving many different types of actors, including research organisations, industry, government, entrepreneurs and civil society. Yet many individuals and organisations lack what might be considered transition-enabling skills[28] and capabilities (including dynamic capabilities that enable organisations to adapt to changing conditions). For example:

1. Research-funding and research-performing bodies need to adapt their disciplinary management processes and training to promote TDR, which has implications for their organisational capabilities and their employees' skill sets. For example, peer-review and programme development and management processes need to be adapted to take into account the specificities of TDR. Some research-performing organisations have already gone as far as articulating their missions and reorganising their faculty and departmental structures around societal challenges, while others have invested in inter-disciplinary and/or multi-stakeholder platforms. Yet others have adjusted their teaching and training activities to promote TDR. Still, much more needs to be done to foster TDR (OECD, 2020[17]).
2. In the public sector, the sorts of capabilities needed to promote sustainability transitions go beyond the skills of civil servants (important as these are) to also encompass organisational capacities and routines. These are not easy to develop quickly, nor can successful organisational capacities and routines be simply replicated, given their embeddedness in organisational histories and cultures. There has also been a certain degree of "hollowing out" of state capacities in many OECD countries over the last few decades, which means governments may need to rebuild the organisational capabilities necessary to carry out transition tasks (OECD, 2021[2]). This is at a time when many governments are looking to reduce their expenditures and reduce the size of their administrations.
3. In firms, a lack of skills and capabilities reduces their choices to invest in innovation. New technologies require new skills and business models to enable their development and diffusion, and the deployment of new infrastructure. A successful green transition is likely to entail, for example, upgrading skill sets in industries experiencing only minor adjustments; gearing up educational institutions and firms to provide the new skills for new occupations and sectors that will emerge from the green economy; and retraining and realigning skills in sectors that will decline as a result (OECD, forthcoming[19]).

Addressing new skills and capabilities requirements in the STI system brings together a number of policy areas, including the labour market, education and STI. On the one hand, it requires understanding the supply side of skills and capabilities, including labour-market dynamics and the performane of education systems. On the other hand, it requires an appreciation of changing demand as societal priorities increasingly aim to boost sustainability and other key technological developments. Policies for future skill and capability development in STI systems also need to target a broader range of societal, demographic and economic groups to avoid perpetuating inequalities and promote a just transition. For example, the engagement of younger generations in climate policy-making and action is increasingly seen as key to meeting net-zero targets. Education systems need to equip youngsters with the skills and competences that would help them adopt environmentally sustainable behaviours, including science skills (Borgonovi et al., 2022[41]). In the workplace, new types of jobs are being created while many existing jobs are changing with the adoption of cleaner technologies and greener work processes. At the same time, some sectors will face jobs losses, as societies move away from polluting activities. Work-based learning – and vocational education and training more generally – can provide opportunities for adults to up- and reskill for a greener labour market. These opportunities should be explored from a systemic perspective that incorporates innovation and industrial policy agendas (Cedefop, 2022[42]).

Outlook

Sustainability transitions will depend on science and technology for their success, but will also present challenges for research and innovation activities – and, by extension, for the STI policies that support them. This chapter has highlighted the need to compress the innovation cycle, which implies rapid changes in multiple systems simultaneously. This calls for greater directionality in STI systems, including in STI policies, which can help articulate shared visions that mobilise a wide range of actors. However, sociotechnical systems are complex and adaptive, and difficult to direct in a top-down manner. A systemic, multilevel perspective can help design policy mixes that simultaneously create windows of opportunity, build up innovative technologies and markets, and break down existing fossil-based sociotechnical systems.

To operationalise these insights in concrete terms, the chapter has outlined a simple framework that considers transition reforms from the perspective of ten different but interlinked STI policy sub-domains. Funding and finance are the first of these, where transformational levels of investment across the innovation chain, including low-carbon technology diffusion and deployment, are needed to meet the scale and pace of the net-zero transition. Moreover, the balance of funding support for public and private R&D should shift to become more directive and solutions-oriented than today's policy mix. A related policy mix consideration concerns which technology areas to target. Technological innovation is an uncertain activity, and technologies often interact with one another in unpredictable ways. Ideally, countries would spread their investments to develop domestic absorptive capacities for a range of technologies, but this is difficult for countries with smaller STI systems, who would benefit from co-operation with other countries to pool their efforts. Furthermore, technologies can create negative externalities, and potential trade-offs need to be assessed continually (see Chapter 6).

More directed and solution-oriented R&D and innovation imply strengthening co-operation and partnerships in STI systems, including between scientific disciplines and between technology areas, as well as between actors and activities at different stages of the innovation chain. This can help direct and accelerate the pace of technological change, strengthening innovation chain linkages through the co-design and co-production of science, technology and institutions, including markets. Wider society also needs to be actively engaged in these processes. Public RIs and TIs can be useful focal points for assembling constellations of innovation system actors, providing large-scale facilities for RD&D. However, to perform this role effectively, they need to acquire new skills and capabilities, and receive more long-term strategic funding.

While STI policy can enable sustainability transitions, other policy areas will likely take the lead – notably those responsible for the largest greenhouse gas emissions, such as energy, transport and agricultural policy. These have their own sizeable RD&D and deployment activities, together with supporting policy systems with which STI policy needs to interface. These policy areas also determine many of the framework conditions that shape technological development paths, including competition policies that encourage new innovative firms to challenge incumbents, standards that help create demand for low-carbon innovations and carbon pricing that incentivise firms to adopt clean technologies. Governments continue to experiment with new approaches to improve cross-governmental co-ordination, including MOIPs (as described in Chapter 5), but this is a long-standing challenge with no quick and easy solutions.

The global scale and scope of climate change mean that international co-operation is essential to meet net-zero targets. International STI co-operation can take many different forms, and its benefits can be wide-ranging. However, it faces several barriers, not least that the vast majority of public R&D funding is allotted within national boundaries, and international alignment between national calls and programmes in notoriously difficult to achieve. Many low- and middle-income countries also need to enhance their scientific and technological capabilities to absorb low-carbon innovations. The growing securitisation of STI policies and rising geopolitical tensions could also impede future international co-operation (see Chapter 1).

The systemic scale and scope of the sustainability transition, and uncertainties over its future course, call for a transformation of the knowledge and evidence base on which policy decisions will need to be made. Future-oriented technology analysis, including strategic foresight and TA, can enhance governments' anticipatory capacity and provide collective spaces where societal values and technological developments can be considered together. Monitoring and evaluating the contribution of policy interventions will be essential, not least to change course if necessary. There are, however, significant knowledge gaps on how to monitor and evaluate sociotechnical transitions, a challenge that extends to the lack of appropriate statistical indicators. There is potential here for governments to make greater use of data-linking and national statistical offices are carrying out experiments along these lines, but much more needs to be done and at a faster pace.

Finally, the need for new skills and capabilities cuts across all STI policy sub-domains. Many gaps exist within government itself, which is called upon to perform more active roles than in the recent past, working closely with business, researchers and citizens, and across government to advance sustainability transitions. Similar capabilities gaps exist in the business and research worlds. A further policy concern is supporting people of working age and communities in attaining new skills and opportunities as part of a just transition.

The policy goals and practices pursued in these STI policy sub-domains should reflect the kinds of sustainability transitions wanted. Transitions should be just and have democratic legitimacy. They should embody different forms of inclusivity in STI, for example, with respect to differences in geography, socio-economic status, gender and ethnicity. While it is beyond the scope of this chapter to articulate a definitive set of key values to which STI activities should adhere in support of sustainability transitions, the following aspirations may provide some guidance:

- *Sustainability*: ensure STI policies support sustainability in multiple dimensions (i.e. economic, social and environmental) by promoting equality, supporting ecosystem recovery and resilience, and promoting system change, without compromising the ability of future generations to meet their own needs
- *Diversity*: promote resilience by supporting a range of research and technology areas involving a range of actors working on different challenges, beyond the realm of traditional STI actors
- *Inclusivity*: support broad participation in science and innovation and sharing of resources that contribute to transparency, trust and collaboration, while targeting the development of solutions that provide equal access and opportunities for society and promote social justice
- *Agility*: encourage the ability to move quickly and timely in tackling societal challenges like net-zero, supporting the acceleration of change through experimentation and adaptation of research, innovation and governance systems
- *Ethics*: nurture norms and principles that foster progress towards sustainability, promote justice and fairness, and account for the trade-offs emerging among multiple system dimensions by proposing actions that are consistent with the "greater good" and "what's right".

Ultimately, science and technological innovation should offer hope and mobilise human creativity and ingenuity to tackle the most pressing contemporary challenges, including the race to net-zero. Aspirations like these should underlie policy practice and serve as a compass to guide policy reforms enabling just sustainability transitions.

Along these lines, the OECD has embarked on a new project, "S&T Policy 2025: Enabling Transitions through Science, Technology and Innovation",[29] to help governments further articulate the need for reform and transitions, and reformulate their STI policy agendas accordingly. One of the project's main goals is to develop an overarching guiding vision and policy framework that helps STI policy makers rethink, redesign and implement a new portfolio of STI policies that drive sustainability transitions. The project uses the simple policy sub-domain framework outlined in this chapter to formulate practical policy guidance on specific key challenges.

References

Aghion, P. (2019), "Path dependence, innovation and the economics of climate change", in *Handbook on Green Growth*, Edward Elgar Publishing, https://doi.org/10.4337/9781788110686.00011. [49]

Amoroso, S. et al. (2021), *World Corporate Top R&D Investors: Paving the way for climate neutrality*, A joint JRC and OECD report, Publication Office of the European Union., https://op.europa.eu/en/publication-detail/-/publication/910ccf7b-4c16-11ec-91ac-01aa75ed71a1/language-en (accessed on 26 February 2023). [29]

Aristodemou, L. et al. (2022), *Commercialisation and Diffusion of Climate Change Mitigation and Adaption (CCMA) Goods and Services: Identification and analysis of (eco-) green trademarks using a natural language processing (NLP) approach and a climate change vocabulary (CCV)*, https://www.researchgate.net/publication/363573426_Commercialisation_and_Diffusion_of_Climate_Change_Mitigation_and_Adaption_CCMA_Goods_and_Services_Identification_and_analysis_of_eco-_green_trademarks_using_a_natural_language_processing_NLP_approach_ (accessed on 5 March 2023). [20]

Attrey, A., M. Lesher and C. Lomax (2020), "The role of sandboxes in promoting flexibility and innovation in the digital age", *OECD Going Digital Toolkit Notes*, No. 2, OECD Publishing, Paris, https://doi.org/10.1787/cdf5ed45-en. [7]

Aulie, F. et al. (2022), *Will post-COVID-19 recovery packages accelerate low-carbon innovation?*, https://www.oecd.org/greengrowth/2022GGGSD-IssueNote2-Will-post-COVID-19-recovery-packages-accelerate-low-carbon-innovation.pdf (accessed on 26 February 2023). [18]

Borgonovi, F. et al. (2022), "Young people's environmental sustainability competence: Emotional, cognitive, behavioural, and attitudinal dimensions in EU and OECD countries", *OECD Social, Employment and Migration Working Papers*, No. 274, OECD Publishing, Paris, https://doi.org/10.1787/1097a78c-en. [41]

Cagnin, C., E. Amanatidou and M. Keenan (2012), "Orienting European innovation systems towards grand challenges and the roles that FTA can play", *Science and Public Policy*, Vol. 39/2, pp. 140-152, https://doi.org/10.1093/scipol/scs014. [36]

Cammeraat, E., A. Dechezleprêtre and G. Lalanne (2022), "Innovation and industrial policies for green hydrogen", *OECD Science, Technology and Industry Policy Papers*, No. 125, OECD Publishing, Paris, https://doi.org/10.1787/f0bb5d8c-en. [23]

Cedefop (2022), *Work-based learning and the green transition*, http://data.europa.eu/doi/10.2801/69991 (accessed on 5 March 2023). [42]

Dechezleprêtre, A. et al. (2022), “Fighting climate change: International attitudes toward climate policies”, *OECD Economics Department Working Papers*, No. 1714, OECD Publishing, Paris, https://doi.org/10.1787/3406f29a-en. [34]

EEA (2019), *Sustainability transitions: policy and practice*, European Environment Agency , Copenhagen, https://op.europa.eu/en/publication-detail/-/publication/da060542-d8f7-11e9-9c4e-01aa75ed71a1/language-en (accessed on 5 March 2023). [46]

G7 (2022), *G7 Statement on Climate Club*, https://www.g7germany.de/resource/blob/974430/2057926/2a7cd9f10213a481924492942dd660a1/2022-06-28-g7-climate-club-data.pdf?download=1 (accessed on 5 March 2023). [39]

Geels, F. (2020), “Transformative innovation and socio-technical transitions to address grand challenges”, Alliance Manchester Business School University of Manchester, https://euagenda.eu/upload/publications/transformative-innovation-and-socio-technical-transitions-to-address-grand-challenges.pdf (accessed on 5 March 2023). [47]

Geels, F. and J. Schot (2007), “Typology of sociotechnical transition pathways”, *Research Policy*, Vol. 36/3, pp. 399-417, https://doi.org/10.1016/j.respol.2007.01.003. [10]

Geels, F. et al. (2017), “Sociotechnical transitions for deep decarbonization”, *Science*, Vol. 357/6357, pp. 1242-1244, https://doi.org/10.1126/science.aao3760. [9]

Haddad, C. et al. (2022), “Transformative innovation policy: A systematic review”, *Environmental Innovation and Societal Transitions*, Vol. 43, pp. 14-40, https://doi.org/10.1016/j.eist.2022.03.002. [38]

IEA (2023), “RD&D Budget”, *IEA Energy Technology RD&D Statistics* (database), https://doi.org/10.1787/data-00488-en (accessed on 7 March 2023). [15]

IEA (2022), *Net Zero by 2050: The need for net zero demonstration projects*, https://iea.blob.core.windows.net/assets/76426d5e-0c9c-4f9f-809f-feca6bde702e/Theneedfornetzerodemonstrationprojects.pdf (accessed on 26 February 2023). [4]

IEA (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector*, OECD Publishing, Paris, https://doi.org/10.1787/c8328405-en. [43]

IEA, IRENA and UNFCCC (2022), *The Breakthrough Agenda Report 2022: Accelerating Sector Transitions Through Stronger International Collaboration*, https://www.iea.org/reports/breakthrough-agenda-report-2022 (accessed on 26 February 2023). [11]

IPCC (2022), *Climate Change 2022: Mitigation of Climate Change*, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf (accessed on 5 March 2023). [33]

Janssen, M. (2019), “What bangs for your buck? Assessing the design and impact of Dutch transformative policy”, *Technological Forecasting and Social Change*, Vol. 138, pp. 78-94, https://doi.org/10.1016/j.techfore.2018.08.011. [37]

Kern, F. (2012), “Using the multi-level perspective on socio-technical transitions to assess innovation policy”, *Technological Forecasting and Social Change*, Vol. 79/2, pp. 298-310, https://doi.org/10.1016/j.techfore.2011.07.004. [5]

Kivimaa, P. and F. Kern (2016), “Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions”, *Research Policy*, Vol. 45/1, pp. 205-217, https://doi.org/10.1016/j.respol.2015.09.008. [8]

Larrue, P. (2021), “The design and implementation of mission-oriented innovation policies: A new systemic policy approach to address societal challenges”, *OECD Science, Technology and Industry Policy Papers*, No. 100, OECD Publishing, Paris, https://doi.org/10.1787/3f6c76a4-en. [32]

Miedzinski, M. et al. (2020), *International STI collaboration and investment for Sustainable Development Goals. Science, Technology and Innovation (STI) for SDGs Roadmaps*, https://www.researchgate.net/publication/345978505_International_STI_collaboration_and_investment_for_Sustainable_Development_Goals_Science_Technology_and_Innovation_STI_for_SDGs_Roadmaps (accessed on 26 February 2023). [22]

OECD (2023), “Aggregate National Accounts, SNA 2008 (or SNA 1993): Gross domestic product”, *OECD National Accounts Statistics* (database), https://doi.org/10.1787/data-00001-en (accessed on 7 March 2023). [16]

OECD (2022), *Climate Tipping Points: Insights for Effective Policy Action*, OECD Publishing, Paris, https://doi.org/10.1787/abc5a69e-en. [48]

OECD (2022), *Inclusive Forum on Carbon Mitigation Approaches*, https://www.oecd.org/climate-change/inclusive-forum-on-carbon-mitigation-approaches/ (accessed on 26 February 2023). [21]

OECD (2022), “Measuring the environmental impacts of artificial intelligence compute and applications: The AI footprint”, *OECD Digital Economy Papers*, No. 341, OECD Publishing, Paris, https://doi.org/10.1787/7babf571-en. [24]

OECD (2021), *OECD Science, Technology and Innovation Outlook 2021: Times of Crisis and Opportunity*, OECD Publishing, Paris, https://doi.org/10.1787/75f79015-en. [2]

OECD (2021), *Recommendation of the Council for Agile Regulatory Governance to Harness Innovation*, https://legalinstruments.oecd.org/en/instruments/OECD-LEGAL-0464 (accessed on 5 March 2023). [31]

OECD (2021), “The inequalities-environment nexus: Towards a people-centred green transition”, *OECD Green Growth Papers*, No. 2021/01, OECD Publishing, Paris, https://doi.org/10.1787/ca9d8479-en. [35]

OECD (2020), “Addressing societal challenges using transdisciplinary research”, *OECD Science, Technology and Industry Policy Papers*, No. 88, OECD Publishing, Paris, https://doi.org/10.1787/0ca0ca45-en. [17]

OECD (2020), *The Digitalisation of Science, Technology and Innovation: Key Developments and Policies*, OECD Publishing, Paris, https://doi.org/10.1787/b9e4a2c0-en. [26]

OECD (2019), *Artificial Intelligence in Society*, OECD Publishing, Paris, https://doi.org/10.1787/eedfee77-en. [27]

OECD (2016), “The Internet of Things: Seizing the Benefits and Addressing the Challenges”, *OECD Digital Economy Papers*, No. 252, OECD Publishing, Paris, https://doi.org/10.1787/5jlwvzz8td0n-en. [28]

OECD (2015), “Book review”, *Environmental Innovation and Societal Transitions*, Vol. 22, pp. 90-91, https://doi.org/10.1016/j.eist.2016.05.001. [1]

OECD (2015), *SYSTEM INNOVATION: SYNTHESIS REPORT*, https://archiwum.pte.pl/pliki/2/1/OECD%20System.pdf (accessed on 5 March 2023). [45]

OECD (forthcoming), *Carbon Management for Net Zero: Bioeconomy and Beyond*, OECD Publishing, Paris. [30]

OECD (forthcoming), *Driving low-carbon innovations for climate neutrality*. [19]

Palavicino, C., C. Matti and J. Witte (2022), *Motion handbook. Developing a transformative theory of change*, https://transitionshub.climate-kic.org/publications/motion-handbook-developing-a-transformative-theory-of-change/ (accessed on 5 March 2023). [50]

Philp, J. and D. Winickoff (2018), “Realising the circular bioeconomy”*, OECD Science, Technology and Industry Policy Papers*, No. 60, OECD Publishing, Paris, https://doi.org/10.1787/31bb2345-en. [25]

Schwaag Serger, S. and C. Palmberg (2022), “Towards transformative policy in Finland and Sweden: some viewpoints from practice”, in *Smart Policies for Societies in Transition*, Edward Elgar Publishing, https://doi.org/10.4337/9781788970815.00012. [3]

Sharpe, S. and T. Lenton (2021), “Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope”, *Climate Policy*, Vol. 21/4, pp. 421-433, https://doi.org/10.1080/14693062.2020.1870097. [13]

Silvestrin, G., G. Diercks and C. Matti (2022), *X-curve: A sense-making tool to foster collective narratives on system change*, https://drift.eur.nl/app/uploads/2022/02/X-Curve-booklet-DRIFT-EIT-Climate-KIC-2022.pdf (accessed on 5 March 2023). [44]

SYSTEMIQ (2023), “The Breakthrough Effect: how tipping points can accelerate net zero”, https://www.systemiq.earth/breakthrough-effect/ (accessed on 5 March 2023). [14]

Tàbara, J. (2021), *Enabling positive tipping points towards global sustainability in uncertain times*, https://council.science/current/blog/enabling-positive-tipping-points-towards-global-sustainability-in-uncertain-times/ (accessed on 26 February 2023). [12]

UNFCCC (2021), *Technology and nationally determined contributions: Stimulating the Uptake of Technologies in Support of Nationally Determined Contribution Implementation*, https://unfccc.int/ttclear/tec/techandndc.html (accessed on 5 March 2023). [40]

Weber, K. and H. Rohracher (2012), “Legitimizing research, technology and innovation policies for transformative change”, *Research Policy*, Vol. 41/6, pp. 1037-1047, https://doi.org/10.1016/j.respol.2011.10.015. [6]

Notes

[1] In the NZE, behavioural change refers to changes in ongoing or repeated behaviour on the part of consumers which impact energy service demand or the energy intensity of an energy-related activity. Three main types of behavioural change included in the NZE: (1) reducing excessive or wasteful energy use; (2) transport mode switching; and (3) materials efficiency gains. Three-quarters of the emissions reductions from behavioural changes in the NZE are achieved through targeted government policies supported by infrastructure development, e.g. a shift to rail travel supported by high-speed railways. The remainder come from adopting voluntary changes in energy saving habits, mainly in homes. Even in this case, public awareness campaigns can help shape day-to-day choices about how consumers use energy (IEA, 2021[43]).

[2] As stated in the previous sentence, directionality is implicit in all policy by design, and horizontal and agnostic policy support favours incremental rather than radical innovation, development rather than R&D, and mature rather than breakthrough technologies.

[3] (Aghion, 2019[49]) identify five determinants of path dependence: knowledge spillovers (as innovations build upon prior innovations in cumulative ways), network effects (when the attractiveness of a technology depends upon networks of other users or suppliers), switching costs (the cost of switching to a different technology, e.g. due to the need for different infrastructure and overcome incumbent interests), positive feedbacks (when technologies benefit from scale) and complementarities (when technologies have complementary roles, such as renewables and storage) (OECD, forthcoming[19]).

[4] These have been presented as "the X-curve" of sustainability transitions. See, for example, (Silvestrin, Diercks and Matti, 2022[44]), (Palavicino, Matti and Witte, 2022[50])

[5] For example, see (OECD, 2015[45]), (EEA, 2019[46]), (Geels, 2020[47]) and (IEA, IRENA and UNFCCC, 2022[11]).

[6] The concept of "positive tipping points" has emerged from scholars working on climate system tipping points. For a recent review of the latter, see (OECD, 2022[48]).

[7] https://www.iea.org/reports/clean-energy-technology-innovation.

[8] For example, a single 100 MW electrolyser for green hydrogen production costs EUR 50-75 million; in the case of CCS, demonstration projects currently cost around USD 1 billion, take five years or more to build and have a market value of around one-tenth of their cost (OECD, forthcoming[19]).

[9] https://www.energy.gov/ia/clean-energy-technologies-demonstration-challenge.

[10] For example, through its Horizon Europe, Innovation Fund and InvestEU measures, the European Commission will contribute over EUR 28 billion to the Clean Energy Technologies Demonstration Challenge by 2027 to advance clean energy innovation and deployment, mainly in hard-to-abate sectors.

[11] Re-balancing green technology policies towards more RD&D support also has to be considered from an industrial policy perspective. Some countries have specialised in the manufacturing of green goods, with the emergence of the Chinese solar PV industry in the recent decade as a prime example of this trend. However, while RD&D support policies by nature target domestic firms only, deployment subsidies benefit domestic and foreign firms alike. Indeed, the Chinese solar PV industry was built on the back of renewable energy subsidies in the United States, Europe and other regions (e.g. Australia). In line with recent industrial policy objectives (see Chapter 2), governments could design deployment support policies against a clear understanding of the domestic supply-side (firms, talents, infrastructure) so that they benefit both consumers and the domestic economy (OECD, forthcoming[19]).

[12] Business R&D is mostly "D"-oriented, i.e. it focuses on development, and less oriented to "R", i.e. research. This is even more so when incentivised by R&D tax incentives.

[13] Philanthropy – for example, the Bezos Earth Fund and Bill Gates' Breakthrough Energy initiative – is playing a growing role in promoting and funding technological innovation for net-zero. Breakthrough Energy, for example, has several initiatives – including Breakthrough Energy Ventures, Breakthrough Energy Catalysts, and Breakthrough Energy Fellows – that support research and innovation activities across the innovation chain.

[14] At the same time, recent changes in corporate governance and the emergence of environmental, social and governance (ESG) criteria, as well financial or fiscal signals such as carbon pricing and taxation, have helped stimulate interest among private investors in financing longer-term investments. Blended finance in this context represents only one part of a broader financing framework for sustainability.

[15] The IEA maintains the ETP Clean Energy Technology Guide, an interactive framework that contains information on over 500 individual technology designs and components across the whole energy system that contribute to achieving the goal of net-zero emissions. For each technology, the guide includes information on the level of maturity and a compilation of development and deployment plans, as well as cost and performance improvement targets and leading players in the field. See https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide.

[16] When framing their choices, governments use various labels (and underlying concepts) to describe technologies, such as "key", "emerging", "enabling", "converging", "general purpose" and "niche". They also refer to technology-readiness levels to indicate a technology's maturity, invoking the innovation cycle model. These descriptors have consequences for the types of policy interventions governments pursue.

[17] TIs in the public sector are often located in a type of public research institute known as "research and technology organisations".

[18] The impacts of environmental degradation are concentrated among vulnerable groups and households. Yet the benefits and costs of mitigating environmental policies are likely to be unevenly distributed across households. For example, while carbon pricing is a central component of green policies, affordability concerns need to be taken into account as higher energy costs may put greater burden on low-income households and compromise their well-being. Moreover, higher taxes on road transport fuels may affect rural residents more than urban dwellers, since the former tend to rely more on private cars and have limited access to viable public transport alternatives. Green policies can also have important distributional implications for jobs at the sectoral or regional levels. For example, employment levels in carbon-intensive heavy industries and fossil fuels extractive activities are expected to fall, which can have gender and regional implications (OECD, 2021[35]).

[19] An integrated, systemic policy approach is needed to ensure reforms are both green and people-centred. These should include (i) mitigation of the possible regressive impact of pricing environmental externalities for vulnerable households, e.g. through well-designed revenue recycling schemes; (ii) investment in human capital, e.g. through active labour market policies, well-targeted income support measures, and upgrading skills to facilitate labour reallocation; and (iii) sectoral and place-based policies that address systemic inequalities, e.g. through policies that facilitate social dialogue, social capital investments, social protection, and skills and education investments to ease structural adjustment of local economies (OECD, 2021[35]).

[20] The Global Commission on People-Centred Clean Energy Transitions made 12 recommendations in four broad areas. *I. Decent jobs and worker protection*: 1. design transitions to maximise the creation of decent jobs; 2. develop tailored government support for communities and workers as well as a focus on

skills and training; and 3. use social dialogue, robust stakeholder engagement and policy co-ordination to deliver better outcomes. *II. Social and economic development*: 4. ensure that policies enhance social and economic development, and improve quality of life for all; 5. prioritise universal clean energy access and the elimination of energy poverty; and 6. maintain and enhance energy security, affordability and resilience. *III. Equity, social inclusion and fairness*: 7. incorporate gender, equality and social inclusion considerations in all policies; 8. ensure fair distribution of clean energy benefits and avoid the risk of disproportionate negative impacts on vulnerable populations; and 9. integrate the voices of younger generations in decision making. *IV. People as active participants*: 10. involve the public through participation and communication; 11. use insights from behavioural science to design effective behaviour change policies; and 12. enhance impact through international collaboration and exchange of best practice.

[21] Citing (Geels et al., 2017[9]) "Policy-oriented research on deep decarbonization requires complementing model-based analysis with sociotechnical research. Whereas the former analyzes technically feasible least-cost pathways, the latter addresses innovation processes, business strategies, social acceptance, cultural discourses, and political struggles, which are difficult to model but crucial in real-world transitions. Although full integration of both approaches is not possible, bridging strategies may enable iterative interactions in which models provide techno-economic checks of qualitative narratives, while sociotechnical approaches provide wider feasibility checks on model outcomes. Such analyses may underpin the development and implementation of policy strategies that are both cost-effective and socio-politically feasible."

[22] For further information, see https://ec.europa.eu/info/strategy/strategic-planning/strategic-foresight_en.

[23] The text on statistical indicators in this section is based on discussions during an S&T Policy 2025 policy dialogue, "Policies for data and evidence on STI in a world in transition", organised by the OECD Committee for Scientific and Technological Policy (CSTP) and the OECD Working Party of National Experts on Science and Technology Indicators (NESTI) on 15 September 2022. https://www.oecd.org/sti/inno/stpolicy2025.

[24] The OECD NESTI leads the OECD's statistical work on STI, contributing to the development of indicators and quantitative analyses needed to meet the requirements and priorities of the CSTP. In 2021, NESTI established the OECD Expert Group on the Management and Analysis of R&D and Innovation Administrative Data (MARIAD) to facilitate and support its work on international collaboration in the statistical processing and analysis of administrative data relevant to the study of STI systems and government policies. The central focus for MARIAD's objectives and scope of activity is the domain of administrative microdata for public support and funding of R&D and innovation. One of its key aims is to facilitate the exchange of best practices in the management of administrative data on R&D and innovation, a field of considerable complexity and under constant evolution.

[25] Mission Innovation has 22 member countries, plus the European Commission: Australia, Austria, Brazil, Canada, Chile, China, Denmark, Finland, France, Germany, India, Italy, Japan, Morocco, the Netherlands, Norway, Korea, Saudi Arabia, Sweden, the United Arab Emirates, the United Kingdom, and the United States.

[26] See the "Mission Innovation" website for further information: http://mission-innovation.net/.

[27] As of 1 September 2022, the Breakthrough Agenda signatories are: Australia, Azerbaijan, Belgium, Cabo Verde, Canada, Chile, China, Denmark, Egypt, the European Union, France, Germany, Guinea Bissau, Holy See, India, Ireland, Israel, Italy, Japan, Kenya, Latvia, Lithuania, Luxembourg, Malta, Mauritania, Morocco, Namibia, the Netherlands, New Zealand, Nigeria, North Macedonia, Norway, Panama, Poland, Portugal, Senegal, Serbia, Slovakia, Korea, Spain, Sweden, Türkiye, the United Arab Emirates, the United States and the United Kingdom.

[28] There are many definitions of "skills for the green transition", and most share that they refer to a broad set of technical and transversal skills that will be driven by, or contribute to, the green transition. A working group of the Inter-Agency Group on Technical and Vocational Education and Training, which includes the OECD, recently arrived at the following definition: '"Skills for the green transition" include skills and competences but also knowledge, abilities, values and attitudes needed to live, work and act in resource-efficient and sustainable economies and societies. They are: (1) technical: required to adapt or implement standards, processes, services, products and technologies to protect ecosystems and biodiversity, and to reduce energy, materials and water consumption. Technical skills can be occupation-specific or cross-sectoral; and (2) transversal: linked to sustainable thinking and acting, relevant to work (in all economic sectors and occupations) and life. Alternatively referred to as "sustainability competences", "life skills", "soft skills" or "core skills".' (Cedefop, 2022[42]).

[29] See the S&T Policy 2025 website: https://www.oecd.org/sti/inno/stpolicy2025/.

4 Mobilising science in times of crisis: Lessons learned from COVID-19

Science played an essential role in generating the knowledge and technologies needed to respond to the COVID-19 crisis. The pandemic offers lessons that can position science to respond more effectively to future crises. For instance, much can be learned from successful co-operation between various actors during the pandemic, but reinforcing these relationships over the longer term may require significant change to academic culture, structures, incentives and rewards. Many of the required changes – including in research performance assessment, public engagement, and transdisciplinary research – are already underway but have not yet been adopted at the necessary scale and speed because of embedded inertia in science systems. More radical change is necessary to spur science to engage with other societal stakeholders to produce the broader range of outputs and solutions that are urgently required to deal with complex global challenges and crises.

Key messages

- The COVID-19 pandemic has been a complex and cascading global crisis, with science playing an essential role in generating the knowledge and technologies to enable effective policy responses. Ensuring the necessary scientific capacity is a critical consideration for governments in preparing for and responding to other ongoing and future crises, including the climate emergency.
- The scientific response to a complex crisis depends on the mobilisation of existing knowledge and resources across a broad range of disciplines. This requires long-term commitment and sustainable support for research infrastructures (RIs) and basic research across the breadth of science.
- The pandemic has illustrated both the potential and challenges in using big data and digital tools for crisis management. It has positively accelerated access to research data and scientific information and at the same time revealed the limits of current open science approaches. It is important that this progress continues after the pandemic, and that inclusion (in terms of both data coverage and access) becomes embedded in open science policies.
- The traditional distinction between policy for science and science for policy weakens during a crisis, when science becomes easily politicised. Nevertheless, maintaining the independence and autonomy of scientific research and advice is critical to ensure public trust.
- It is a primary responsibility of the scientific community to ensure the rigour and completeness of the scientific research and communications that inform policy and decision-making during crises. This requires integrating insights and knowledge across many different disciplines, and open discussion of knowledge gaps and uncertainties.
- Ultimately, the effectiveness of the scientific response to a crisis depends on the relationships between science and other sectors of society, including politicians and policy makers, business and industry and, most importantly, the public. Establishing resilient and trusted relationships across these sectors is essential.
- Although public trust in scientific institutions has increased overall during the pandemic, it is fragile and needs to be nurtured. Scientists must play an active role in responsibly communicating scientific evidence to the public and engaging citizens in transdisciplinary initiatives. Training, support and new incentives will be required to achieve this.
- A global pandemic requires a global response. International scientific co-ordination and co-operation structures and mechanisms were severely tested by the pandemic, and showed their limitations. Many countries and populations could not access the benefits of science for a variety of reasons. Ensuring equity and inclusion is not the sole responsibility of science but it is in the mutual interest of all countries to enable a global and inclusive scientific response to crises.

Introduction

Science underpinned the fight against the COVID-19 pandemic from the outset. It was expected to provide both the tools (e.g. diagnostics, vaccines and therapeutics) and knowledge (e.g. understanding of viral infectivity, epidemiological monitoring and behavioural insights) that policy makers could use to effectively respond to and manage the crisis. The scientific response had to be rapid and encompass many different scientific domains and sources of evidence. The response also had to be rigorous, yet the evidence base for various interventions was severely limited and even basic questions (such as how the virus was spread) could not be fully answered during the first few months of the pandemic. The pandemic did not wait for science, and what had originally been framed as a largely biomedical/public health crisis soon expanded across all sectors of economies. It was quickly apparent that openness and accountability would be important to establish and maintain the necessary public trust in science and associated policies.

Science was in the spotlight more than ever before and endowed with huge expectations, and yet the pandemic dramatically disrupted normal scientific practice itself. As in other economic sectors, many scientists had to adapt rapidly to a new virtual and working environment for extended periods. International travel and meetings, which are critical mechanisms for scientific exchange, were largely replaced by video calls and virtual conferences (Buchanan et al., 2021[1]). Physical access to experimental resources and facilities was replaced by remote access. Doctoral and early-career researchers were particularly affected: as laboratory investigations and fieldwork were disrupted, they were forced to adopt digital tools to maintain essential contact with colleagues, mentors and peers. As in other areas of the economy, women scientists were harshly affected, as they often had to balance the double burden of care duties and professional responsibilities while working from home (OECD, 2021[2]) (OECD, 2021[3]).

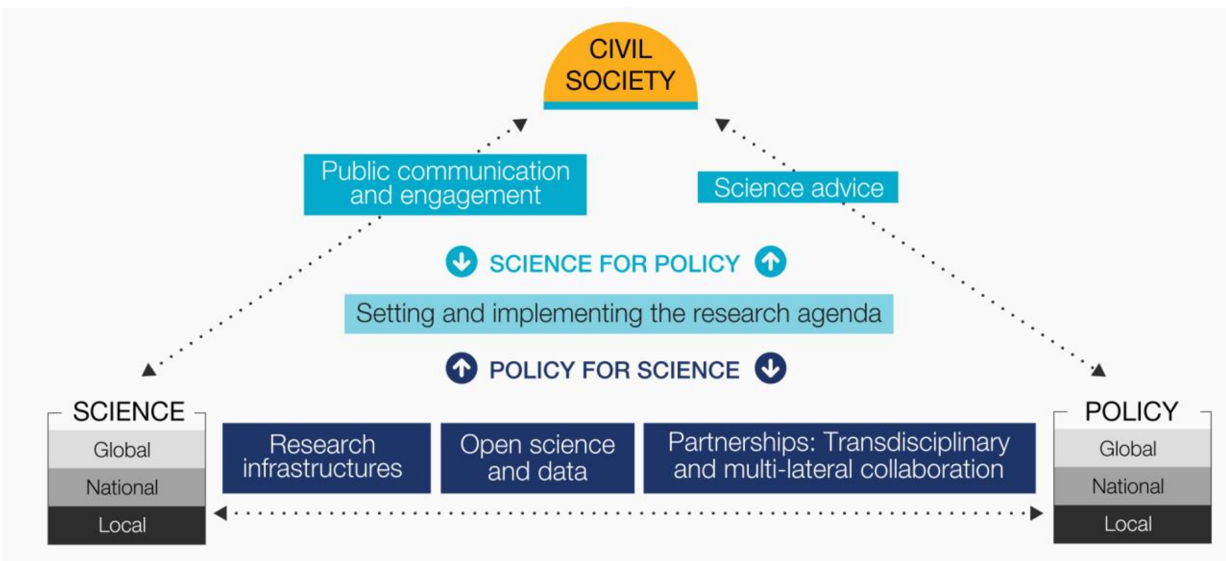
Given the rapidly changing, high-pressure context, this chapter analyses how science performed in response to the pandemic. It draws out lessons that can position science to respond more effectively to crises – including those that are already with us (such as climate change or biodiversity loss), those that we can reasonably foresee (such as the next infectious disease pandemic) and those that we cannot predict, but which will surely arrive. Previous OECD work (OECD, 2018[4]) has investigated the different roles of science in terms of the so-called "crisis management cycle", i.e. preparedness, response, and recovery / feedback. Science is embedded across the whole of this cycle, and in each phase, it interacts with other stakeholders outside the public science system, including policy makers, the private sector, and civil society. Such interplay is critical to mounting effective responses to crises. It is important in relation to COVID-19 and crisis response more broadly to consider not only how the science ecosystem responded but also – and perhaps more saliently – to evaluate the efficacy of the interactions and relationships with other sectors and actors.

Rather than simply producing excellent research, science has had to engage rapidly with other sectors on a major scale to develop "fit-for-purpose" technological tools and evidence to enable effective policy responses to the crisis. Science policymakers have implemented a number of different initiatives in order to achieve this. At the same time, they have had to pay careful attention to ensure the continued functioning of the broader science system and balance urgent versus long-term needs and expectations. While the resources for science have increased in some countries – specifically to support the pandemic response – this increase has not reflected the scale of additional demands. Hence, the scientific response has been highly dependent on what already existed, and actions by science policy makers have been largely concentrated on re-focusing, adapting, accelerating, enabling and scaling-up existing activities and processes.

The OECD has compiled a detailed description of science, technology and innovation (STI) policy initiatives taken by different countries during the first six months of the pandemic. An updated catalogue can be found on the Science, Technology and Innovation Policy (STIP) Compass COVID-19 Watch portal[1] (see also Chapter 1). This chapter analyses the challenges faced by countries in implementing these policy initiatives. It delves into what policies worked well (or less well) – and why – and discusses the policy implications for the future. This analysis focuses on two main areas:

1. **Policy for science**, i.e. the policies adopted to facilitate the necessary research for addressing the pandemic. The chapter focuses on three broad topics that have been particularly important in the science response to the pandemic, namely: (i) access to data and scientific information; (ii) mobilisation of RIs; and (iii) development of transdisciplinary research and multinational partnerships.
2. **Science for policy**, i.e. the policies adopted to ensure that research agendas reflected policy needs, and that research evidence effectively informed policy and decision-making (including by citizens). The chapter focuses on three critical areas for attention, namely: (i) ensuring that research addresses policy needs; (ii) the operation of science advisory systems; and (iii) public communication and engagement.

Figure 4.1. Policy for science and science for policy



Note: Science policy influences the development of science through support for science system assets – RIs, data, and science-industry collaborations – and science has a role in facilitating broader policy development through enabling activities – research agenda setting, public communication and engagement, and provision of science advice during crises. However, there are interplays between these areas, with science assets contributing to the ability of science to inform policy development and enabling activities influencing science policy choices and the direction of science.

These two main areas map onto what might normally be considered as core business for science – i.e. research and knowledge generation – and what may be referred to as “third-mission” activities, which generally receive less attention and are less valued within academia. Although this division is commonplace, COVID-19 – where science has been put squarely at centre stage – has clearly illustrated the continuous interaction between science for policy and policy for science, and the importance of considering them together and allocating them equal attention during crises (see Figure 4.1). This has required a major shift in thinking from science policy makers and research providers. For example, individual scientific excellence as measured by publication outputs needed to be balanced against urgent policy needs, rapid sharing of data and information, and public communication and engagement. As science ministries, agencies and institutions now begin to evaluate their response to the crisis, it will be important to adopt criteria and indicators that reflect the full range of demands on science.

Over the past two years, the OECD has organised a series of international workshops on "lessons learned from COVID-19", exploring each of the six topics listed above.[2] Building on earlier OECD work in each of these areas, the workshops included case presentations and panel discussions. Their aim was to identify actions that science policy makers could take to better mobilise science in response to crises. As the COVID-19 pandemic was the primary focus of these discussions, some of the issues identified were specific to pandemics. Strikingly, however, many of these issues could readily be extrapolated to overall crisis preparedness. This chapter focuses on these more generic areas for policy action.

Policy for science

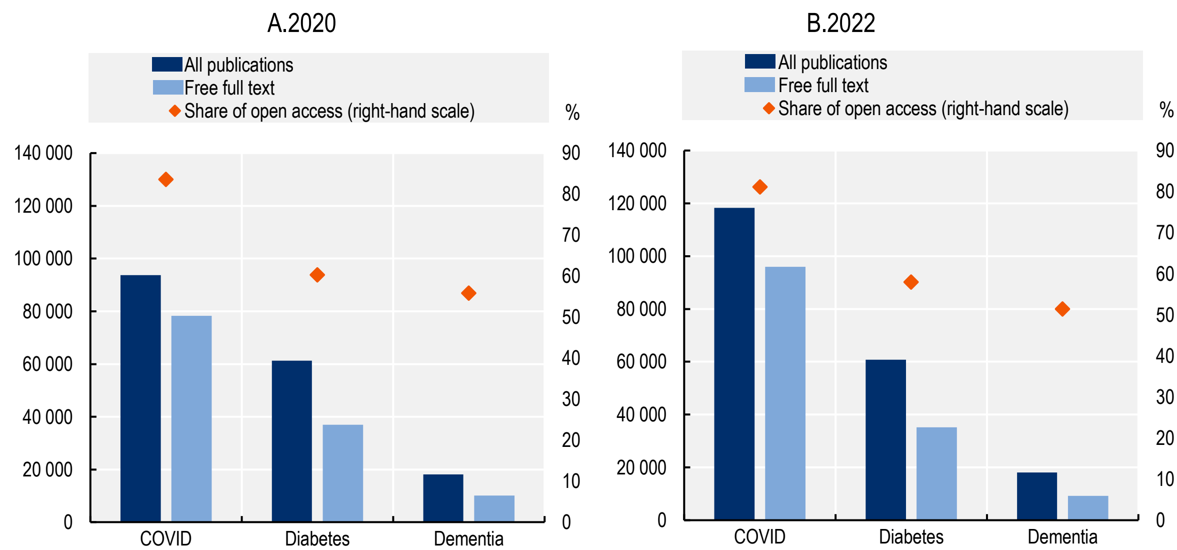
Open science and data

Prior to the pandemic, science policy makers in many countries had already begun to implement policies to promote the three main pillars of open science, i.e. open access to scientific publications, increased access to research data and public engagement (OECD, 2015[5]) (Dai, Shin and Smith, 2018[6]). At the very onset of the pandemic, it became clear that access to scientific information and data would be critical for all countries, and this was an early target for science policy initiatives. In January 2020, the open sharing of the original SARS-Cov-2 virus sequence by an international consortium led by Yong-Zhen Zhang of the Shanghai School of Public Health was the starting point for scientists across the world to begin work on diagnostic tests, vaccines and therapeutics (Wu et al., 2020[7]). Meta-analyses of literature from previous infectious disease pandemics, combined with the development and sharing of epidemiological models and scenarios, enabled evidence-based policy making. Effective public engagement was important not only to collect data and information, but also to inform researchers and policy makers about the real-life effects of the pandemic. As the pandemic progressed, it also became clear that access and sharing within the scientific community was not sufficient and that the public wanted access to the scientific data and information that were informing policies. Indeed, the pandemic significantly shifted the emphasis on openness and transparency, while at the same time raising new ethical considerations around the collection and use of personal data and information.

Several national and international organisations took initiatives early on to promote open access to COVID-19 related scientific publications and this has had a major impact on the accessibility of most of this information. Figure 4.2 shows that the proportion of open access publications on COVID-19 is significantly higher than for other medical conditions, e.g. dementia and diabetes. There has also been a significant increase in scientific publications related to COVID-19 between 2020 and 2022. In a landmark initiative facilitated by the National Institutes of Health in the United States, a group of major science journal publishers made relevant articles available in formats and under licence terms that facilitated text mining and secondary analysis.[3] Similar open-access collections of published scientific literature were developed in other countries and scientific domains. One example is the COVID-19 LOVE (Living Overview of Evidence) initiative, launched in Chile as an open repository and classification platform that uses systematic methods and automation technologies to connect users to a comprehensive collection of published COVID-19 evidence for decision-making (Verdugo-Paiva et al., 2022[8]) (see also Figure 4.5). Some of these initiatives integrated pre-prints in their collections. Indeed, the growth in openly accessible pre-prints was one of the characteristics of scientific information dissemination during the pandemic (Fraser et al., 2021[9]). This was a response to the demand for rapid and timely access to new scientific research information and in that regard, it can be considered a success. Scientific research published in pre-prints helped inform policies. However, in the absence of prior peer review, the rigour of the research was not always assured, and the media and public made little distinction between preliminary research results published in pre-prints and peer-reviewed articles in scientific journals.

Figure 4.2. Open access of COVID-19, diabetes and dementia publications, 2020 and 2022

Total and free full text Pubmed publications



Note: Publications include the following types of peer-reviewed articles: Books and Documents, Clinical Trials, Meta-Analysis, Randomized Controlled Trials, Reviews and Systematic Reviews[4].
Source: OECD calculations based on US National Institutes of Health PubMed data, https://pubmed.ncbi.nlm.nih.gov (accessed 2 December 2022).

StatLink https://stat.link/lta0je

Ensuring scientific integrity was sometimes a challenge, jeopardising public trust

A number of unsubstantiated, poorly designed or fraudulent scientific results were communicated via pre-prints, undermining science and in some cases promoting conspiracy theories and populist political positions. At the same time, it was not only pre-prints that were used as vehicles for dissemination of false and fraudulent results – one of the most notorious cases was a publication in the prestigious medical journal *The Lancet*, for which the purported international patient data set did not exist (Baker, Van Noorden and Maxmen, 2020[10]). This publication added to the confusion and controversy around the use of hydroxychloroquine as a therapy for COVID-19. Ensuring scientific integrity, and the quality and rigour of scientific publications and other information outputs in a crisis when there is increased emphasis on timeliness and openness, is a critical challenge for the scientific community. Mandating that the data underpinning a pre-print or publication are made openly available – or, in cases where these data are sensitive, ensuring that they are peer-reviewed – are important safeguards that should be widely implemented. If this issue is not adequately addressed, then public trust in science can rapidly dissipate.

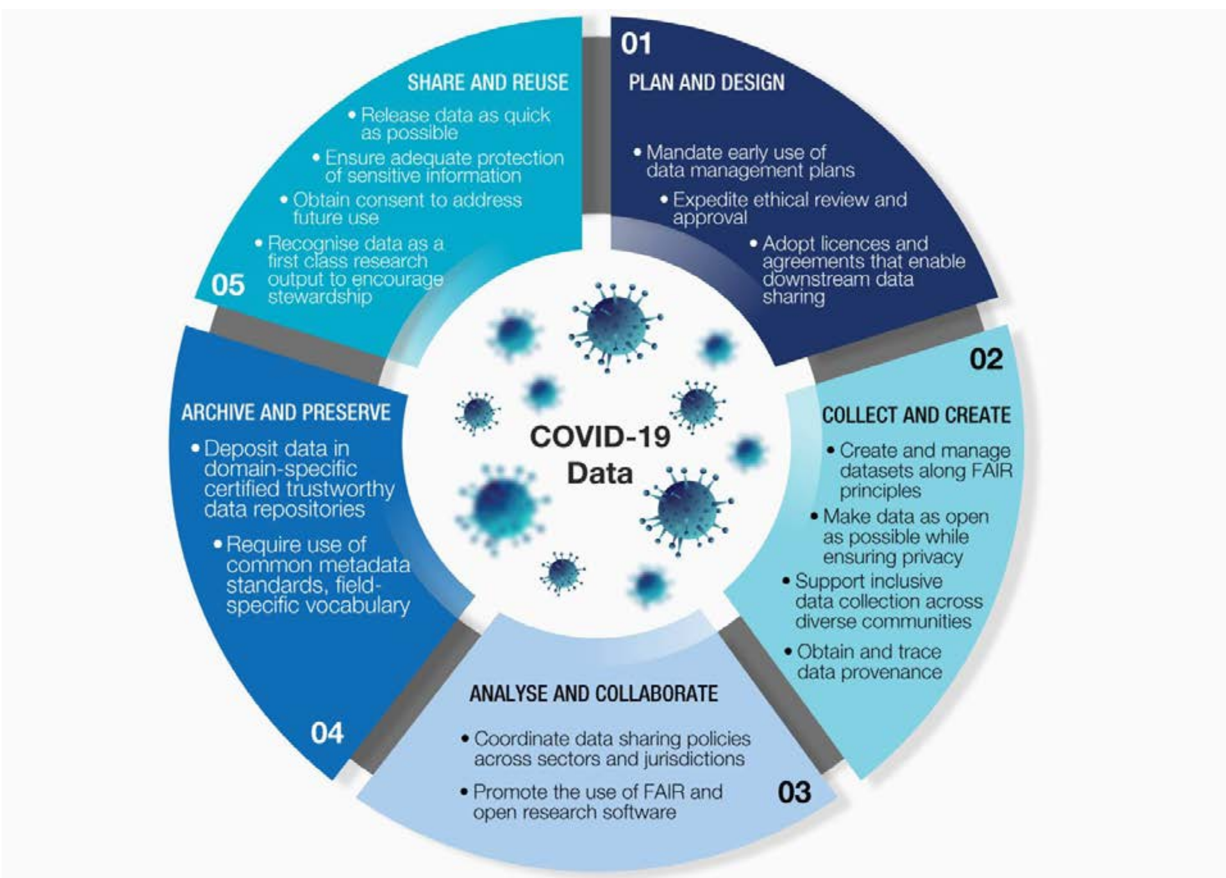
Scientific domains varied in making their research data open

Many different types of scientific or research data are relevant to the COVID-19 pandemic, and should ideally be findable, accessible, interoperable and re-useable (FAIR) (Research Data Alliance, 2020[11]). While the specific details may differ, the requirement for FAIR data across many scientific domains is characteristic of any complex or cascading crisis. When such a crisis is international, operating across different jurisdictions or borders further complicates efforts to make data FAIR. This is even more the case when much of the data of interest are personal or otherwise sensitive, as was the case for COVID-19. The pandemic was a stress-test for all research domains to assess where they are up to in making their data FAIR. In this regard, the infrastructures, processes, standards, and trusted relationships for managing and sharing data that had been established prior to the pandemic, proved to be critical. Those fields, such as genetics, which had made significant investments in FAIR data prior to the pandemic were able to build rapidly on this. Other fields, such as clinical research or social sciences, with a narrower data-sharing culture were generally ill-prepared for the demands of a complex crisis like COVID-19.

The revised OECD Recommendation concerning Access to Research Data from Public Funding was adopted in January 2021 and identifies the generic areas to be addressed in making research data FAIR (OECD, 2021[12]). At a more operational level, the RDA-COVID-19 WG Recommendations and Guidelines for Data Sharing, which were developed bottom-up by the inter

national research community, were published six months into the pandemic and provided detailed advice for specific research domains (Research Data Alliance, 2020[11]). Different actions (see Figure 4.3) are required at different stages of the research data life cycle to make data FAIR, and many of these can be supported and incentivised by judicious policy interventions. Different areas of research will require varying levels of support and incentives to implement these actions and make their data FAIR.

Figure 4.3. The Covid-19 research data life cycle and policy levers



Note: Policy actions are necessary across the different steps of the research data life cycle to ensure enhanced access to COVID-19 research data.
Source: developed by the OECD and the Research Data Alliance.

Trusted data repositories are needed to deal with privacy concerns

While the research community has the primary responsibility for providing access to the data (and the associated software) it collects or generates, much of the data used for research during the pandemic came from other sources and were not primarily designed for research. This is particularly the case in social sciences, which use data from multiple sources – including administrative data from the public sector and social media data, which are controlled by the private sector (OECD, 2016[13]). Much of these data are personal and, even when anonymised, are subject to specific regulatory and ethical considerations. Clinical and health services data, which are important for epidemiological modelling and many other areas of pandemic research, are subject to similar considerations, and need to be managed and shared accordingly (OECD, 2020[14]).

Much of the value of population data depends on their being disaggregated, e.g. by gender, social status or ethnicity. Such granular information can be critical for crisis management and – as with COVID-19 – targeting policy interventions and communication strategies (OECD, 2020[15]), (OECD, 2021[16]). However, this is precluded in many jurisdictions because of privacy concerns. It is important to support trusted data repositories, located in academic centres or other public-sector organisations such as national statistical agencies or medical institutions, in ensuring FAIR, ethically correct, legally compliant and timely access to sensitive or personal data, and to enable their "safe" usage by accredited academic researchers. The science community needs to be involved, together with other relevant stakeholders, in defining the policies and processes governing access to different types of administrative data. Dialogues and agreements should also be established with commercial-sector data holders and citizens to determine which data should be made available to scientists (and under what conditions), both routinely and in times of crisis (OECD, 2016[13]).

Recommendations:

1. Accelerate efforts towards open access to publications, provision of FAIR data and safe sharing of sensitive data, building on the momentum provided by the pandemic and supporting and consolidating ongoing initiatives in each of these areas.
2. Prioritise the collection of quantitative and qualitative data and robust evidence for use in designing public health and social measures (PHSMs). In particular, "baseline data" on the effectiveness of commonly deployed measures are required, which will often require international collaboration.
3. Ensure inclusion across countries and population groups in data collection. Many of the groups that are most vulnerable during crises are absent or under-represented in the administrative and research datasets that are commonly used to inform policy. Online collection represents a particular challenge for those who are not "digitally connected".
4. Support and incentivise efforts to share and integrate administrative, research and commercial data that are relevant to crisis management. Some of these data will be sensitive, and provisions and protocols should be put in place to enable safe and timely access in emergency situations.
5. Accelerate the adoption of new technology and processes to deal with real-time collection of big data for policy and decision-making. A combination of human expertise, workflows and technologies (apps, algorithms, high-performance computers, etc) is required to extract the maximum benefit from the massive – and increasing – amounts of data that are available to inform both crisis management and routine policy development.

Research infrastructures

RIs provide shared experimental facilities and resources for the scientific community. There exist many different types of RI which operate at different scales, from local/regional to global, and play a critical role in facilitating research in most scientific domains. The primary mission of all RIs is to enable excellent science, requiring long-term strategic investment. In this regard, they overlap with some public research institutes, as well as research and technology organisations that also provide research services – although typically focusing more on the needs of specific economic sectors and supporting applied research and innovation. The distinction between these groups, which differs across countries, is not critical to this chapter, which uses the term “research infrastructure” generically. RIs provide the scaffolding for scientific research. Because of their service function, unique expertise and established links with multiple users – and often multiple countries – they are a critical scientific resource in responding to crises.

Bio/health RIs played a central service provision and co-ordination role

RIs from the biomedical, clinical and life sciences (bio/health) were at the centre of the science response from the very outset of the pandemic. In many countries, dedicated public health institutes played a central co-ordination role, working closely with academic researchers to develop the necessary data, information and tools to inform policy decisions. For instance, the Norwegian National Institute for Public Health, the Robert Koch Institute in Germany, and to a lesser extent the Centers for Disease Control and Prevention in the United States performed this function at the axis between policy, science and the public, placing them in a sometimes exposed and vulnerable position (see section on science advice). Other bio/health RIs played a critical role in the early development and testing of diagnostics and therapies, working closely with scientists from academia and industry. Many also played an essential role in providing the FAIR data and analytical services that have underpinned efforts by the research community to understand the pandemic and support policy makers.

Networking and co-operation among bio/health RIs proved particularly valuable. As the scientific questions raised during the crisis were often complex, researchers often required services and data from multiple RIs. Close liaison between RIs enabled the development of common cross-infrastructural workflows that could be readily integrated in regular operations (e.g. linking chemical screening, structural biology and data analytics). Trusted relations and collaborations established before the crisis were important as they enabled partners to align different administrative requirements rapidly and streamline their normal processes. Existing links sometimes consolidated into more concrete alliances that further facilitated access to connected data and services. Notable examples include the Alliance of Medical Research Infrastructures,[5] the Analytical Research Infrastructures of Europe,[6] and the Collaborating Network of Networks for Evaluating COVID-19 and Therapeutic Strategies in the United States.[7] Capacity-building and training was a particularly important charge for many RIs. In some instances, RIs or alliances of RIs provided direct support to public health systems, boosting existing diagnostic capacity to manage samples, developing high-throughput screening, and training health service staff on diagnostic testing and biosafety.[8]

Many clinical RIs, including dedicated clinical trial centres, played an important role in developing and testing new diagnostics and therapies.[9] However, clinical trials were one area in which the response from the scientific community was “mixed” (see Chapter 1). There was a particular challenge in ensuring adequate patient sample sizes to produce reliable and reproducible results.[10] This was compounded by a lack of trial registrations and, in many instances, limited access to the trial data even after results were published (Besançon et al., 2021[17]). Overall, a large number of underpowered clinical studies and trials were performed in many countries (OECD, 2020[18]). Many of these could not be reproduced and generated little useful information. At the same time there are a number of exemplary initiatives, where clinical RIs and other academic and private-sector actors worked together internationally, adopting common protocols and processes to recruit large patient numbers and generate rigorous results in record time.[11] In areas where such networks did not exist, most notably with regard to testing the efficacy of PHSMs, the evidence base for policy has been severely lacking. It is important that the clinical and public health research community learn from the experience during COVID-19 and establish the necessary infrastructures, networks and protocols to support rigorous evaluation studies.

RIs from other research domains also played important roles

The mobilisation of RIs during the crisis was not restricted to bio/health RIs. At the beginning of 2020, physics RIs, which provide access to specialist equipment and services, developed fast-tracked access for COVID-19-related projects. This was largely the case for synchrotron facilities, which can be used to explore the structure and interactions of molecules, including viral proteins and potential drugs. High-performance computing (HPC) was another area of major mobilisation. HPC has played a critical role in data analysis and modelling for multiple aspects of COVID-19 research, from exploring viral replication mechanisms to drug design, and from understanding transmission to developing large-scale epidemiological models (Nature Computational Science, 2021[19]). Large RIs (such as CERN) with HPC systems and know-how made their resources available for COVID-19 research, and federated HPC networks were established to provide easy access to both public and private facilities.[12] As the pandemic progressed, RIs in the social sciences and humanities were also mobilised in a number of countries to conduct social surveys, analysing attitudes towards and the potential impacts of the PHSMs that were being implemented in response to the pandemic.[13]

With the exception of Europe, there was a lack of international co-ordination

Although RIs are often used by international communities of researchers, the COVID-19 crisis highlighted a lack of international co-ordination. Despite increased networking between RIs, those links were mostly restricted to the national or regional level (Europe was an exception in this regard, with RI strategies and co-operation mechanisms having been developed at the European level for some years). The lack of international co-ordination hindered the sharing of data (particularly in clinical and social domains where countries have different ethical and regulatory standards) and the full mobilisation of other complementary assets. Furthermore, the uneven distribution of RI capacities at the global level prevented access to resources and data in many parts of the world, contributing to the disconnect between needs and solutions. Thus, effective global action on crises will require science stakeholders to address a lack of engagement with, and funding for, low- and middle-income countries (LMICs). This applies not only to future pandemics, but also to ongoing and future crises related to environmental change and natural disasters.

The notable exception with regard to cross-border co-ordination was Europe, where the European Commission (EC) framework programmes have promoted European research co-operation for many years. This investment paid off in mobilising science across national borders (Veron and Di Ciommo, 2020[20]). European RIs, such as ELIXIR and BBMRI-ERIC, provided access to data, materials, facilities and services across countries. In addition, many European research projects were re-oriented to address COVID-19, and new projects were rapidly initiated using well-tested cross-national funding mechanisms. The pandemic gave extra impetus to the European Open Science Cloud, moving it from an attractive but ambitious concept for the science community to an essential requirement for the evidence-based management of complex long-term crises. Many EC-funded activities provided an anchor point for scientists from outside the European Union to co-operate with multiple European countries. In some cases (e.g. for genomic data), European co-operative activities have provided a basis for intercontinental collaboration.[14]

Recommendations

1. Consider RIs as strategic assets with a major role to play in crisis preparedness and response. This means integrating RIs into crisis preparedness and response strategies, and ensuring that this role is included in the missions of individual RIs (and incentivised accordingly).
2. Recognise RIs as unique resources for training and capacity-building and support them in building and maintaining the capacities required to respond to ongoing and future crises. This entails ensuring sustainable career paths for the professional staff required to keep an RI operating effectively and supporting their role in upskilling other personnel in preparation for emergencies.
3. Provide long-term strategic investment to RIs, focusing on resilience as well as efficiency. While maximising efficiency and operating to maximum capacity may be understandable targets during

times of calm, having some spare capacity and immediate access to deployable resources is critical to ensure a timely response to crises.

4. Facilitate networking across RI ecosystems and partnership-building between different stakeholders. RIs demonstrated during the pandemic that they can play a critical intermediary or brokering role across disciplines and sectors. This function should be emphasised and supported during their normal operations.
5. Recognise the unique role that RIs play in international co-operation, including through the provision of data and analysis, and make the necessary long-term investment in building trusted cross-border relationships.

Partnerships: Transdisciplinary and multi-lateral collaboration

Given the scale and complexity of the pandemic and the urgent need for information and tools to effectively respond, it has been critical that scientists from different disciplines, sectors and countries are able to combine their resources and expertise. In practice, this has translated into a variety of co-creation (Kreiling and Paunov, 2021[21]) and transdisciplinary (OECD, 2020[22]) initiatives, some of which are focused around RIs (see previous section) or collaborative platforms, and all of which are characterised by the involvement of multiple different actors.

Vaccine development drew heavily on public-private partnerships

Promoting knowledge transfer and public-private partnerships (PPPs) between academic research and industry has long been a focus of STI policy. The main challenges to this objective are well-known: different aims and incentives, different approaches to openness and different approaches to intellectual property rights. In fields such as biotechnology and biomedicine, these challenges have been a focus of policy attention for several decades and – providing commercial interest and a potentially viable market can be identified – PPPs are relatively easy to establish and often flourish. Many such “classical” PPPs played a role in the response to COVID-19, most notably vaccine development. In addition, more recent experimentation with novel open science-industry-academia partnerships, in which multiple companies and academic institutions share expertise in pre-competitive research, provided a basis for the establishment of similar arrangements in response to COVID-19 (Gold, 2021[23]).

The early days of the pandemic were characterised by a considerable lack of clarity on the potential commercial returns from diagnostics, vaccine and antiviral therapeutics, and there was strong demand from many LMICs and international organisations to ensure equitable access at reasonable prices. Ensuring affordable access was an important motivation for some academic institutions, as witness the role of Oxford University in developing a ‘low cost’ vaccine with AstraZeneca, or Baylor College of Medicine, Texas with its patent-free CORBEVAX vaccine (OECD, 2021[12]). This was less the case for several other vaccines, including the mRNA[15] vaccines that were developed by biotech companies in partnership with the pharmaceutical industry, albeit on the back of long-term public investment in academic research (Dolgin, 2021[24]). The commercial return for several of these vaccines was assured by prior procurement commitments from individual countries in return for preferential provision, with equitable worldwide access a secondary consideration (OECD, 2021[2]). Despite efforts by the World Health Organization (WHO), COVID-19 Vaccines Global Access (COVAX) and other organisations, many countries are still deprived of equitable access to vaccines (see also Chapter 1 for an overview of the current status of COVID-19 vaccine development).

There has been less success in developing new therapeutics

With several effective vaccines developed using different technologies, and tested and rolled out in record time, the vaccine story is nevertheless an excellent demonstration of what can be done when academia and industry combine resources. The process of developing antiviral therapies has been less positive: moving promising compounds from the laboratory to the bedside continues to be a challenge owing in part to issues around ownership and appropriation of commercial returns.[16] These challenges mirror those that prevail in the development of antibiotics and there are lessons that can be learned from this field, such as the use of novel market guarantee and procurement mechanisms, and new not-for-profit business models that might be more broadly applicable for the provision of essential medicines during crises and beyond (Lobanovska and Pilla, 2017[25]), (OECD, 2021[3]).

Many new partnerships were transdisciplinary

The response to COVID-19 was characterised by the creation of new partnerships and networks that engaged actors beyond academia and industry in developing solutions for a diverse range of practical challenges.[17] Many of these joint activities were truly transdisciplinary – integrating knowledge and perspectives from different science disciplines and different sectors (business, the public sector and civil society). Establishing trust between different actors has proved to be the critical factor in getting such arrangements to function effectively. Not surprisingly, many of them relied on existing relationships, and involved institutions and organisations that were well respected in their respective sectors.[18] Funding such transdisciplinary activities was a challenge in many countries as they do not fit neatly with traditional research-funding schemes, which tend to focus on specific research domains and recognised public research providers such as universities or public research institutes. In some cases, existing in-house institutional funds were used, or (as in Ireland) "one-stop-shop" emergency research-funding mechanisms were established to enable multiple actors to apply for joint projects.[19]

Citizen science was also an important part of the pandemic response

Citizen science – defined in this context as the engagement of citizens in research activities – contributed in important ways to many aspects of the pandemic response. Much of the data used to understand the pandemic "belonged" to individuals. Some of the data were not just donated but also collected by citizens, for example by using apps that were themselves sometimes developed by citizen scientists.[23] Digital tools were also used to organise a number of "hackathons" – crowdsourcing events open to multiple actors (including citizens) that focused on applied research or solutions to specific challenges (Paunov and Planes-Satorra, 2021[26]). Nevertheless, recognising citizens as true partners in research raises sensitive issues about scientific expertise and power relations between experts and lay persons. The identification and professional recognition of "long COVID" is illustrative in this regard (see section on public communication and engagement). There is still some way to go before academia recognises the full value of citizen science and embraces citizens not just as data collectors, but also as purveyors of expertise and knowledge in co-designing and co-producing research.

Disciplinary silos hindered co-operation between science, technology, engineering and mathematics (STEM), and social sciences and humanities (SSH)

Just as the pandemic shed light on the power relations between experts/scientists and citizens, it also highlighted the differences between science disciplines, most notably STEM and SSH. There has been criticism of the focus on numbers, numerical models and indicators in assessing and communicating the pandemic's progression, to the detriment of more qualitative research insights that could help explain infection patterns (Bardosh et al., 2020[27]) (see section on science advice). Pandemic modelling largely ignores important insights from behavioural research that do not easily fit into conventional statistical models.[20] Part of the challenge is that quantitative and qualitative data from SSH are often not openly available. Where they are available, they are frequently not well described or structured and, in the absence of common standards, are difficult to integrate with data from other sources. Where SSH and STEM have worked effectively together, such as in transdisciplinary research projects and some science advisory systems, this has generated valuable new insights for fighting the pandemic in a more holistic manner.

Disciplinary silos within research institutions and funding agencies have hampered the inter- and transdisciplinary research that has been required during the pandemic and will be necessary to address complex societal challenges in the future (OECD, 2020[18]).

A globally inclusive response to the pandemic has remained elusive

The pandemic has been truly global in nature. It has been clear from the outset that no single country will be safe until all countries are safe. Intergovernmental bodies, most notably WHO, and related international scientific networks, such as GLOPID-R, have tried hard to co-ordinate the global research effort. International RIs, networks and collaborations that existed prior to COVID-19 have been mobilised to support pandemic monitoring, identify research needs, and establish global research priorities and agendas. While researchers from all over the world have collaborated with each other regardless of their countries' geopolitical and ideological differences (see Chapter 2), the strategic global co-ordination of research has not been immune to such differences. The WHO research agenda for COVID-19 was established early in the pandemic, following consultation with leading experts from many countries (WHO, 2020[28]). It undoubtedly influenced many national research agendas, although this influence has not always been fully acknowledged. However, co-ordinated action to implement the global agenda was lacking, with governments competing rather than co-operating. It became a matter of national pride for the largest economies to have the best data sets and epidemiological models, produce their own vaccines, or lead their own clinical trials.[21] In the meantime, LMICs – which wanted to co-operate but struggled to compete – were largely left behind (or sometimes invited to host clinical studies led by other countries). The lack of political will to adopt a more global and inclusive approach to managing the pandemic was accentuated by a dearth of mechanisms allowing national research funders to truly co-operate and collaborate. While scientists do collaborate internationally, public research funding rarely crosses borders. There exist very few global RIs and, although international co-operation around data management and access is common in some scientific domains, it is not the norm in many fields.

Recommendations

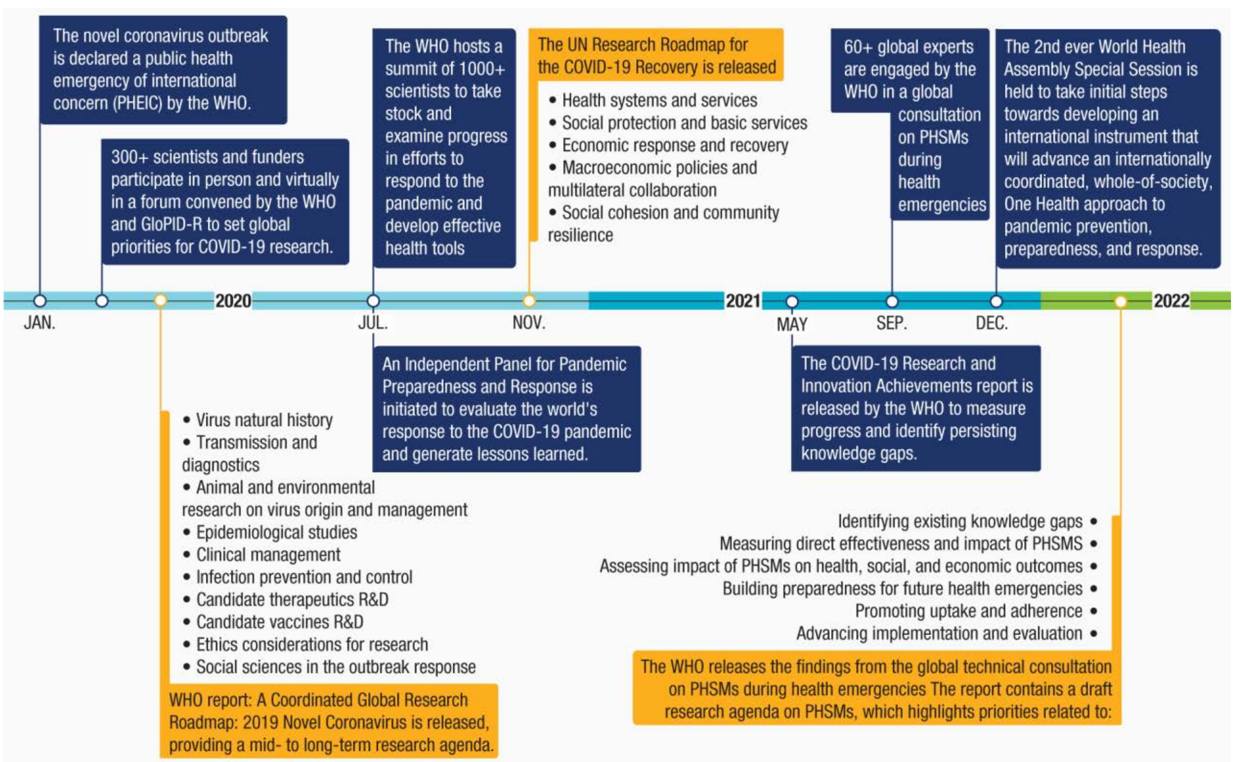
1. Promote collaboration across disciplines and countries. Major global challenges cannot be fully addressed by a single scientific domain or country; shared RIs and digital technologies provide powerful tools to make effective links.
2. Adopt and promote a sociotechnical framing for solutions-focused research that addresses grand societal challenges and complex crises, recognising these cannot be adequately addressed by technology alone.
3. Recognise that citizen engagement and trust in science is critical to effective crisis response; promote citizen science and transdisciplinary research that addresses citizens' "lived experiences".
4. Establish international funding mechanisms, trusted relationships and scientific networks *now* that can respond to existing and future crises. It is important to build on what already exists, avoiding excessive duplication while recognising that a degree of redundancy can increase the overall resilience of a global system.
5. Address barriers to co-operation across disciplines and sectors, i.e. academia, government, the private sector and civil society. Much can be learned from successful co-operation efforts during the pandemic, but sustaining these over the longer term may require significant changes to academic culture, structures, incentives and rewards.

Science for policy (and decision-making)

Setting and implementing the research agenda

As discussed in the previous section, the international science community was engaged from the very early stages with WHO in setting a global research agenda to track the course of the pandemic and develop universally applicable interventions, such as diagnostics and vaccines (Figure 4.4). However, implementing this agenda proved challenging. Even within Europe, most COVID-19-related research was supported and performed at the national level, either to further basic understanding of COVID-19 or address national priorities and policy needs.

Figure 4.4. Setting global research priorities during the COVID-19 pandemic



Note: The initiatives are illustrative and are not a fully comprehensive representation of all established international initiatives mobilised to set global research priorities during the COVID-19 pandemic response. Events outlined in orange represent times when formal priorities were released in reports. Summarised priorities are listed.
Source: Adapted by the authors from the timeline of the WHO's COVID-19 response (WHO, 2022[29]).

The biomedical community set the agenda early on

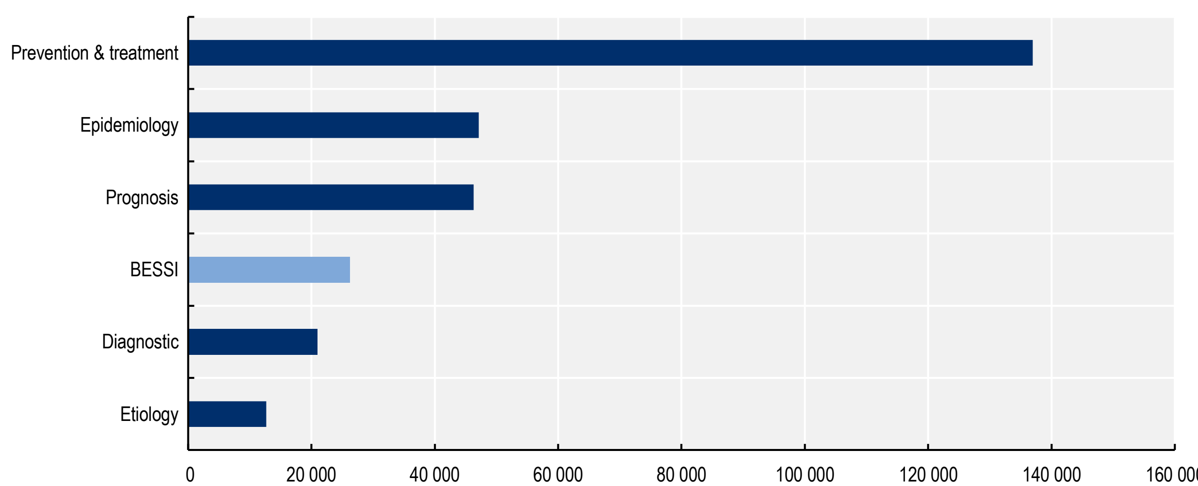
At the beginning, the pandemic was widely perceived as a mainly biomedical challenge, so that in most countries, the biomedical community and its relevant research-funding institutions took the lead in establishing a national research agenda. At this incipient stage, the challenge was to understand the disease and the likely progression of the pandemic, and to support the rapid development of diagnostic and therapeutic tools. Crisis managers and policy makers across government needed scientific information to understand what was happening, and what the options for mitigation were. To a large extent, the research community was left to develop its own research agenda and in so doing, to estimate future policy requirements based on past experience.

In early 2020, most OECD member countries rapidly implemented a variety of emergency funding measures to expand existing biomedical research and support new research to address COVID-19 (Paunov and Planes-Satorra, 2021[26]), (OECD, 2021[16]). As the pandemic developed and more scientific information became available, knowledge gaps were identified and specific policy questions formulated, albeit still mainly focusing on biomedical issues. A number of basic questions, such as how the infectious agent was spread, were only adequately answered several months into the pandemic, and some of the initial assumptions, based on past pandemics, were probably given too much weight. Although the academic community held active discussions on some of these issues, rigorous studies were surprisingly slow to be implemented. In contrast, basic knowledge and understanding of the Sars-CoV-2 virus expanded enormously, leading to the rapid development of diagnostic tools, followed in record time by vaccines.

Public health and social measures came into the picture later

Once the extent of the pandemic became clear and the necessary data collection systems and epidemiological models were in place to generate reasonably reliable scenarios for its future course, the main policy questions and evidence gaps related to PHSMs. The expertise required to address these measures transcended biomedical research. In most countries, research on PHSMs barely featured in the initial emergency research-funding priorities that had been largely established by the biomedical research community; the response to COVID-19 from the social science research community was less of a priority and less co-ordinated, with a plethora of small-scale projects being funded and critical knowledge gaps remaining largely unaddressed. Thus, it was only in September 2021 that a rigorous study on the effectiveness of face masks in preventing the spread of COVID-19 was published (Abaluck et al., 2022[30]). While the effectiveness of measures such as lockdowns, school closures and "social bubbles" are context-specific and very much predicated on behaviour and compliance, the lack of a rigorous evidence base to inform the use of such policies has been a major challenge for managing the crisis (Glasziou, Michie and Fretheim, 2021[31]) (Figure 4.5). Where efforts have been made to implement the necessary research, they have sometimes been stifled by inflexible regulatory and ethical requirements that are not adapted to emergency public health situations.[22] There exists a need to establish baseline data on the effectiveness and acceptability of PHSMs, which will often require large sample numbers and internationally co-ordinated studies. As illustrated with clinical trials, establishing the conditions for conducting social intervention studies in untroubled times can be an important step in preparing for future crises.

Figure 4.5. COVID-19 evidence for health decision and policy making



Note: The Living Overview of Evidence (L.OVE) data platform aggregates evidence for systematic reviews from multiple different sources, including the major scientific publication databases and clinical trial registries. It includes a dedicated collection for COVID-19 evidence, which classifies published materials according to treatment categories and is continually up-dated. The importance of behavioural, environmental, social and systems interventions (BESSI) in managing the epidemic is in contrast to the relatively limited amount of published scientific evidence in this field.
Source: Search results from the L.OVE [database on COVID-19 Evidence (https://iloveevidence.com/) accessed on1 Dec.2022.](https://iloveevidence.com/) Publications on behavioural, environmental, social and systems interventions (BESSI) articles are a sub-group of the Prevention & treatment articles category.

StatLink https://stat.link/dqnvik

The contrast between the rapid development and testing of new vaccines and the lack of evidence for the use of PHSMs is reflected in how the pandemic was perceived from the outset, and which scientific disciplines were (or were not) involved in setting the initial research agendas and priorities. The biomedical research community did its job well, but the need to integrate existing knowledge and insights from a breadth of other disciplines (including SSH) was not fully recognised, and the processes for achieving this were lacking in most countries (see section on partnerships). In most OECD countries, interdisciplinary or cross-agency bodies were only established after several months to provide advice on research needs and broaden the evidence base for policy making (see section on science advice).[23] Moreover, the historical legacy of relatively weak co-operation across the social sciences, in areas such as standards for data management and access, impeded the integration and synthesis of this knowledge with other disciplines (Research Data Alliance, 2020[11]).

Future preparedness measures should ensure societal engagement

Several countries conducted pandemic preparedness exercises prior to COVID-19, although most were led by public administrations and did not heavily involve the science community. For a variety of reasons, these exercises – some of which were very insightful – seem to have been largely ignored or forgotten.[24] Only a small number of economies established formal public consultation or foresight exercises to inform research priorities during the pandemic.[25] Citizens have valuable expertise and experience that can improve the scientific response to crises (as discussed above in relation to long COVID). Their input will be critical in preparing for future crises and establishing research agendas that address the needs of different communities. In this context, non-governmental organisations, representing patient groups and different (often marginalised) communities, have an important role to play in ensuring that the research community pays the necessary attention to critical issues such as health inequalities or access to indigenous knowledge. Trusted civil society partners have a role play both in co-designing research agendas and co-producing the research that will allow a more inclusive response to ongoing and future crises.[26]

Recommendations:

1. Ensure better planning and co-ordination between research actors and authorities with responsibility for policy making and crisis response. This starts with joint risk assessment and preparedness exercises, feeding into improved mechanisms and processes for working together during crises.
2. Establish more effective two-way communication mechanisms and processes to alert policy makers to the implications of scientific research and analysis (e.g. early in a crisis) and ensure that research is conducted to address urgent policy questions (often later in a crisis).
3. Ensure that emergency research agendas are not too narrowly focused and address all aspects of a crisis from a scientific perspective; adopt more inclusive co-design approaches in identifying research priorities so that citizen concerns are considered and addressed as necessary.
4. Adopt a research-portfolio approach not only to support different aspects of research that directly address an immediate crisis, but also to ensure that the fundamental scientific knowledge base across all scientific domains continues to expand as a motor for socio-economic development and basis for responding to future crises.
5. Ensure that national and international research agendas focus strongly on health inequalities/social determinants of health, recognising that public health (and other) crises tend to affect disproportionately individuals with pre-existing health conditions; likewise, prioritise the collection of baseline data and rigorous evaluation of PHSMs for specific contexts.

Science advice

The interface between science and policy making is complex. It operates at different scales and involves multiple actors, including scientists, policy makers, risk analysts and crisis managers. As mentioned in the introduction to this chapter, scientific expertise and evidence were required to respond to multiple different policy demands during the COVID-19 pandemic. Scientists involved in providing policy advice were also often expected to play a role in communicating directly with the public. COVID-19 highlighted the critical importance of trust between the various actors within science advisory ecosystems and the public at large. In ideal situations, a virtuous triangle of trust between science, politics and the public was established; in practice, most countries struggled to maintain this trust over the duration of the crisis (Jasanoff et al., 2021[32]). In the absence of such trust, sound scientific evidence was either poorly taken up into policies and/or evidence-based policies were poorly taken up by significant sections of the public.

There exist as many different ways of organising science advice as there are OECD countries, although two broad categories of centralised or distributed systems have previously been described (OECD, 2018[4]). Both include a mix of permanent and ad-hoc structures and may, or may not, report to the centre of government through a chief science advisor (CSA). Often, government-employed risk managers play a critical intermediary role in interpreting scientific evidence for their political masters. Many ministries have considerable in-house scientific expertise and their own science advisory structures and, in some economies, the health ministry played the lead role in managing the COVID-19 crisis and advising government more broadly.

Distinctions between science advice and public policy were often blurred

Scientific evidence is only one input into policy making. There exists an important distinction between the roles of scientific advisors, who provide evidence to inform policy, and policy makers, who use this evidence as one of multiple considerations in deciding policy action. In a rapidly evolving crisis such as the COVID-19 pandemic, this distinction can be difficult to maintain and, where policies are unpopular, “following the science” can quickly revert to “blaming the science” (Greer et al., 2022[33]). This is exacerbated when the science itself is uncertain and there are divergent views within the science community, as was the case for many issues relating to COVID-19. Science advisors were often at the frontline, having to defend or explain policy actions for which they were not responsible. At the same time, scientists did not hesitate to publicly criticise some of these policies when they conflicted with their own scientific views. For example, the initial decision to close schools in some economies was based on best available, but incomplete, scientific evidence concerning COVID-19 transmission and also had to take into account many other socio-economic factors that were weighted differently in different contexts. This was not a purely scientific decision, although it was frequently portrayed as such in the public discourse, and many scientists voiced their opposition publicly.

In some jurisdictions, individual science advisors, e.g. CSAs or chief medical officers (CMOs), had more or less direct influence or control over certain policy decisions, whereas in others, a distance was maintained between advisory and decision-making functions. In this regard, there exists an important distinction between scientists employed directly by government (e.g. CSAs, CMOs or directors of national public health institutions), who may be mandated to directly advise on (or make) policy decisions, and independent academic scientists (e.g. chairs and members of ad-hoc scientific advisory committees), who are invited to provide advice to inform policies (MacAulay et al., 2021[34]). Being clear on the roles and responsibilities of individual scientific advisors and advisory committees, including any direct role in policy formulation and decision-making, is critical during a crisis (OECD, 2015[35]). While it is important that government scientists are able to express disagreement and dissent with their political masters in relation to scientific evidence, they are also limited by their mandate and responsibilities towards their employer (National Science and Technology Council, 2022[36]). Independent advisors from academia have more freedom in this respect, and have a major responsibility to ensure the rigour and completeness of the evidence that informs policy. In a well-functioning advisory system, maintaining the balance between the roles of government scientists and independent academic scientists is critical; this is particularly true in a complex emergency such as the COVID-19 pandemic, where multiple scientific advisory structures may operate at different scales and with different remits (OECD, 2018[4]). Policy makers, scientists and the public at large need to develop a clearer understanding of the role of science in policy making, and how this operates in different jurisdictions.

A hierarchy of evidence emerged that favoured numerical data

As indicated previously, the early stages of the pandemic were characterised by the rapid mobilisation of the biomedical research community, which established the early research agendas and dominated the policy advisory processes. National and international scientific advisory committees mainly comprised researchers, epidemiologists, virologists, statisticians and mathematical modellers, with little room for behavioural and social sciences or humanities at the main table. Over time, as policy questions became clearer and the knowledge gaps were recognised, additional expertise was either brought to the main table, invited to set out its own table or simply self-organised to provide the necessary inputs.[27] However, the hierarchy of evidence that had been established from the outset, with a particular emphasis on "objective" numerical indicators, such as the "R factor", was difficult to resist, and social sciences have continued to struggle to make their voice heard in many contexts (Bardosh et al., 2020[27]). As discussed earlier, members of the SSH community were perhaps also less well-organised than their biomedical counterparts to respond collectively at the international level and influence the main policy messages coming from WHO and similar bodies that either directly or indirectly impacted national agendas.

Scientific consensus was often elusive under conditions of uncertainty and evidence gaps

The novelty of the infectious agent, the scale of the crisis and the absence of a prior knowledge base meant there was huge scientific uncertainty in the early stages of the pandemic. This decreased over time as fresh evidence was generated, data collection became more comprehensive, and models were refined to integrate a greater range of relevant variables. However, the SARS-Cov-2 virus has turned out to be highly unpredictable. Data gaps persist, particularly for certain countries and population groups, and pandemic models struggle to integrate behavioural insights, even when these are available.[17] The result is that there continues to be considerable uncertainty associated with much of the 'best available' scientific evidence that informs policy making. There are also different views within the scientific community as to the value of some of this evidence and, in particular, how it is translated into policy and decision-making. Hence, in the first few months of the pandemic, scientists could be heard advocating both for and against the use of face masks, and there have been several highly publicised disagreements by "experts" about the value of different COVID-19 treatments. While such differences in opinion are a normal part of the scientific process, the challenge in a crisis like COVID-19 is to manage them in such a way as to ensure that the 'best available' evidence is clear and can inform policy while additional evidence is collected, and at the same time, maintain public confidence and trust in science.

COVID-19 has taught us that reaching a scientific consensus on some of the critical issues in a complex crisis is not always possible, and that scientific uncertainties and ambiguities need to be openly discussed and debated (see Section 3.3.3 on science communication). Where advisory processes have not been completely transparent, or the scientific evidence informing policy has not been made openly available, this has led to considerable unease within both the scientific community and the public.[28] A lack of transparency, openness and accountability provides the ideal conditions for the development of conspiracy theories by those with an active interest in undermining science. In some economies, dissatisfaction with the transparency of the formal advisory processes led to the spontaneous creation of alternative science advisory mechanisms.[29]

The scientific response to the pandemic was “data-driven”; similarly, the policy response was dependent on having timely – ideally “real-time” – access to the necessary scientific data. The availability of data, and the ability to analyse and interpret them, were crucial for providing sound scientific advice. Two critical issues previously discussed in this chapter are worth emphasising again with respect to science advice:

1. *Data gaps and biases*. A lack of data from many countries, and from marginalised or vulnerable groups within countries, has translated into significant gaps in understanding the global epidemic and in the neglect of certain high-risk populations, such as migrants and homeless groups. In some countries, existing social surveys have been adapted or new data collection studies have been implemented to address specific data gaps.[11] However, even when inclusive data exist, there can be significant regulatory challenges to disaggregating them to identify particular population groups, severely limiting their usefulness.
2. *Integration and synthesis of information and data from different sources*. While many different disciplines and sectors have worked to make data FAIR, regulatory frameworks and privacy concerns often limit the integration of data from these different sources (OECD, 2020[14]). In addition to addressing technical and regulatory issues, there exists a need to develop the mindset, skills and science-based methodologies required to mediate and synthesise data and knowledge from different sources under emergency response timelines. Close engagement between disciplines using different and sometimes conflicting theories, terminologies and research approaches can generate tension. Emphasising and improving mediation and consensus-building abilities for both scientific experts and policy makers can help mitigate these tensions (Mulgan, 2021[37]).

International co-ordination around science advice has been patchy

Previous OECD work on scientific advice in crises identified systemic challenges for transnational co-operation and exchange of information (OECD, 2018[4]). Principal among these were:

1. a lack of domestic capacity in many countries
2. a lack of shared understanding of different advisory structures and mechanisms
3. a need for mutual respect and trust across countries.

It was also noted that crisis preparedness exercises have tended to focus on operational aspects and the role of crisis managers, and have rarely included scientists from outside government. All these issues were clearly apparent in relation to COVID-19 (OECD, 2020[38]). Science advice was required at different scales, from local to national, regional and global, but a lack of co-ordination was evident both within[30] and between countries, resulting in a lack of mutual learning.

No international agreement has been reached on some of the fundamental indices that have guided COVID-19 policies in all countries, such as the criteria for attributing a death to COVID-19, or how to measure the incidence and prevalence of infection (OECD, 2020[15]). Thus, drawing rigorous comparisons and monitoring the effectiveness of policy interventions has been difficult, even across countries with abundant data. Moreover, many countries have been unable or unwilling to share data. WHO health regulations provide a broad framework for the sharing of data during public health crises. WHO has worked with scientists to define international priorities for policy attention (see previously) but recognition has been poor in many countries, either owing to a lack of capacity or political will. This gap has been filled in some areas (e.g. genomics) by bottom-up science projects, but these have been largely dependent on existing infrastructure and relationships established on a voluntary basis prior to COVID-19. Hence, despite the best efforts of international infrastructure networks (e.g. ELIXIR and partners) and scientific co-ordination structures (e.g. GLOPID-R), substantial data gaps persist. Moreover, the use of international data to inform national policies has not always been sensitive to the perspectives of the countries from which the data originated. This was notably the case when South African scientists openly shared data on emerging

COVID-19 variants, leading some countries to take unilateral action to prevent travel to and from South Africa (The Lancet Infectious Diseases, 2022[39]).

Co-operation between countries in relation to science advice during the pandemic has tended to reflect prior political and economic alliances. Both the Group of Seven (G7) and the Group of Twenty (G20) made science-based declarations in the early stages of the pandemic, as did several public health monitoring and co-ordination structures in Europe and other regions.[31] As described earlier, WHO has its own science advisory mechanisms and released data and advice for all countries. In this respect, it has tried to provide a global scientific perspective and fulfil a global co-ordination role. Many of the scientific experts involved with WHO have played a leading role in providing scientific advice at the national or sub-national level and informally, this has helped to provide some coherence. However, for a global crisis, whose effects cannot be isolated to individual countries, the relative lack of effective international co-ordination around science advice has been striking (Piper, Gomis and Lee, 2022[40]).

Recommendations

1. Ensure that the full breadth of relevant scientific knowledge from different disciplines is readily available and taken into account to inform policy decisions. This begins with having the right people in the room, but also requires mechanisms for consensus-building and knowledge synthesis.
2. Ensure transparency and openness in science advisory procedures, acknowledging uncertainty and differences in scientific opinion. Holding open meetings, publishing full records of proceedings in a timely fashion and clearly presenting uncertainties and unknowns in public communications can all play a role in achieving this.
3. Establish procedures to improve real-time data collection and analysis in different scientific domains and enable information synthesis across domains with the aim of effectively informing policy makers.
4. Protect the autonomy and independence of science from political interference while at the same time ensuring that advisory processes are responsive to policy needs and societal concerns. The roles and responsibilities of science advisors, and the status and remit of different advisory bodies, should be clearly defined and understood.
5. Improve co-ordination of science advice across different scales, both between and within countries, and provide the necessary support to LMICs to build sustainable science advisory systems that leverage international expertise.

Public communication and engagement

The COVID-19 crisis has monopolised the public discourse worldwide for almost three years and continues to be a dominant subject of public debate in many countries. Science and science-based policy interventions have been the main focus for much of this communication activity. Scientists have become public celebrities in some countries, attracting both praise and criticism depending on the messages they communicate and how they are perceived by different sectors of society. In extreme cases, this has led to threats of violence, with measures needing to be taken to ensure the security of individual researchers and their institutions (Halverson et al., 2021[41]).

Building and maintaining public trust has been a critical challenge

The pandemic represented a new situation in terms of science communication, in that it is not just exciting breakthroughs and well-established facts that are being communicated to the public at the end of the scientific process, but rather the process itself that is in the public spotlight. The differing assumptions, hypotheses, uncertainties and corrections that are a normal part of how science advances are publicly exposed and widely discussed. Debates on technical issues that would normally be expected to take place within the scientific community have become legitimate topics for open, sometimes heated, discussion on social networks. At the same time, many citizens who would not normally consider themselves scientists have rallied to the cause and contributed to the scientific evidence base that has informed policy interventions. As previously highlighted, citizen engagement – or citizen science in the broadest sense – has made many important contributions, from the development of apps and collection of data to the identification of long COVID (Provenzi and Barello, 2020[42]). Responsible and effective science communication and citizen engagement help establish public trust in both science and evidence-based policies. Building and maintaining this trust has been a critical challenge for science policy makers during the pandemic and will continue to be in the face of other complex societal challenges.

Traditional and more novel communication intermediation approaches were important

A variety of intermediaries are engaged in the public communication of science, from journalists and mainstream media to social media platforms. They play a critical gatekeeping role at the interface between science and different publics. Where good working relationships between science and these intermediaries have been established, particularly where a variety of intermediaries target different audiences, the dissemination of rigorous scientific information has generally been effective.[32] While for some audiences in some countries, access to well communicated scientific information from trusted and authoritative bodies satisfies their main demand, it has become clear during COVID-19 that many sections of society have greater expectations and needs.[33] Many citizens have specific questions relating to their particular contexts and have "lived experiences" of the pandemic they would like to be considered. For these groups, top-down delivery of scientific "facts" is not enough: they need avenues through which they can question the facts, as well as engage with and contribute to the data and information on which these are based (Best et al., 2021[43]).

The legitimacy of scientific communications rests not only on their scientific rigour, but also on the processes by which they are derived and the way in which they are delivered. Accountability, transparency and openness are equally important. An effective messenger or intermediary whom the target audience trusts is an essential element of effective science communication (Seale et al., 2022[44]), and various digital tools can provide a mechanism for effective two-way communication and engagement. It is not surprising, then, that these digital communication tools and platforms have been the main focus of the science policy initiatives implemented in many countries to improve science communication and address misinformation during the pandemic.[34] Novel partnerships between multinational social media platforms (such as Facebook), scientists and public health agencies have successfully and rapidly drawn upon resources and expertise to test different communication strategies for different population groups.[35] Such approaches have been used effectively to promote vaccination and address misinformation (Lesher, Pawelec and Desai, 2022[45]). At the same time, there are many citizens who do not have access to, or do not routinely use, digital tools. In most countries, traditional mainstream media (television, radio and newspapers) have been the main communication tool and the only source of scientific information for large population groups. The role of journalists has been critical and establishing trusted relationships between scientists and journalists has also been an important focus for improving science communication in some countries (Capurro et al., 2021[46]).[36]

Citizen engagement in science has been limited

Moving beyond communication towards deeper citizen engagement has been necessary to identify priorities, accelerate research and address certain aspects of the pandemic. Citizen-led science was important in identifying and describing long COVID. Some observers have noted a shift during the early phases of the pandemic from the traditional model of citizen engagement – which mainly views citizens as data suppliers – towards a more dynamic transdisciplinary model – which acknowledges the experience and expertise of citizens, and their contributions across the whole research. However – at least in relation to long COVID – it has been suggested that the openness and inclusivity that characterised the first year of the pandemic response gave way to increasing polarisation as different parts of the scientific and medical establishment appropriated and "professionalised" citizens' knowledge.[37] The term "long COVID", which was initially coined in a scientific publication produced by citizens, has become a point of tension rather than a rallying point for the transdisciplinary research that will be needed to fully address a condition that is affecting millions of people worldwide.

In other areas, partnerships between scientists and non-governmental or civic organisations have been critical for accessing data and information from marginalised or neglected groups. Civic groups are often better positioned than governments or scientists to identify the needs of the public and marginalised population groups that might require specific services. Fact-checking and contact tracing can also be perceived as politicised activities that may create tension between governments and citizens. The general public does not like governments policing information (Kostka and Habich-Sobiegalla, 2022[47]). With contact tracing, citizens may perceive that their privacy is being invaded, but they may better tolerate such a policy if it is developed by a civic group they consider as trustworthy. Many citizen science or crowdsourcing initiatives during COVID-19 owe their success to the provision of open and transparent access to scientific and administrative data and resources.[23]

Knowledge deficits among citizens, scientists and communicators should be addressed

Effective science communication and citizen engagement hinge on scientific and digital literacy. As discussed earlier in relation to science advice, there exists a lack of common understanding among policy makers, scientists and the public at large concerning the role of science in policy making. The public also lacks an understanding of how science operates (e.g. the distinction between peer-reviewed and pre-print publications) and the digital literacy required to interpret data (e.g. grasping statistical significance and uncertainty). Most importantly, the scientific community itself does not always tap into the wealth of knowledge and expertise from behavioural and communications sciences when developing its public communication and engagement strategies. Educating and training scientists and the public is important to address these deficits. The pandemic has highlighted that facts alone are not sufficient to ensure effective science communication, and that relevant expertise and perspectives are not unique to scientists, particularly in relation to complex crises that affect the whole of society.

Recommendations

1. Support research integrity and efforts to ensure the rigour of the scientific information that informs public debate. The research community must establish the necessary quality control processes to ensure that publicly released research data and information can be trusted, and the caveats around their usage are clear and transparent.
2. Recognise that scientific communication cannot be restricted to hard data or "facts" – it must be contextualised for different publics. Behavioural and social scientists can play an important role in providing the necessary background for communicating relevant information to different communities.
3. Support the science community in building trusted and sustainable relationships with a variety of communication intermediaries, including journalists, non-governmental organisations and social media platforms.
4. Address scientific misinformation by improving the digital and scientific literacy of citizens and policy makers. This requires a cross-governmental approach, although science agencies have an important contribution to make in supporting and valuing public engagement and communication activities.

5. Recognise that the conditions for effective citizen engagement need to be established in "peacetime". This requires long-term support for citizen engagement as well as for open data and information infrastructures that can be mobilised and used by citizens in times of crisis.

Looking forward: Maintaining the best, improving the rest

At the time of writing, the COVID-19 pandemic is not over. Much scientific research is still focused on this area, although the attention of the public health and biomedical research community is also turning towards new epidemics, such as monkeypox or Marburg virus disease. At the same time, the immediacy of the climate crisis has become clearer, and biodiversity loss (on land and in the oceans) has accelerated, with enormous implications for societies. Natural disasters linked with geopolitical crises and wars are massively disrupting the global socio-economic system. Science has provided much of the evidence that informs our understanding of how these crises have arisen and are evolving. Scientists have developed realistic future scenarios to inform the policy response to environmental challenges, and related concerns such as energy and food security. The challenge today is for science to engage with other public- and private-sector actors and citizens to accelerate the development and implementation of the new knowledge and technological solutions required to address these issues. The scientific response to the COVID-19 pandemic can teach us a lot in this regard.

Science has a critical role to play in the transition to sustainable development trajectories. As with the response to COVID-19, this will depend on refocusing, adapting, accelerating, enabling and scaling up existing activities and processes. Four essential steps need to be taken to achieve this:

1. The importance of the full breadth of scientific knowledge needs to be clearly recognised. It will be essential for policy makers to continue supporting a broad range of discovery science and investigator-driven research, like that which underpinned the development of COVID-19 vaccines.
2. At the same time, there will need to be a significant shift from business-as-usual to rapidly scale-up research approaches that focus on urgently required solutions for complex socio-technical challenges. This means addressing some of the long-term structural challenges embedded in academia. It means implementing new incentive and evaluation systems that promote inter- and transdisciplinary research, and strengthening the three pillars of open science (access to scientific information, access to data and public engagement).
3. Sustained, long-term investment is required to ensure that underlying infrastructures, resources and methodologies are in place, and that inclusion and equity are embedded in science planning and throughout the research process.
4. It will be important to address entrenched geographical, disciplinary and sectoral silos. Actors from across countries, scientific disciplines and sectors must come together to better understand, navigate and develop solutions that advance the collective position, while engaging with conflicting priorities and interests. Shepherding such complex interactions will require new approaches to governance that are capable of facilitating, enabling, and uniting bottom-up and decentralised initiatives with broader top-down and future-focused strategies (see Chapter 5 on mission-oriented innovation policies for net zero).

Many of the required changes are already underway but are not yet being adopted at the necessary scale and speed. There is considerable inertia embedded in science systems. Over the past decades, science policy has mainly focused on incremental developments, which have enabled them to improve their performance as judged by traditional output measures (such as bibliometrics or patents). More radical change is now necessary to spur science to engage with other societal stakeholders to produce the broader range of outputs and solutions that are urgently required to deal with complex global challenges and crises.

Many countries and organisations have initiated their own evaluations of their response to COVID-19. The performance of science should be an important focus of such exercises. The four steps above, and the more detailed thematic recommendations in this chapter, provide a starting point for considering how national science systems can – and must – evolve to function as part of a balanced, well-connected and inclusive global science ecosystem. Sustainable investment will be critical, but this must be accompanied by institutional change and policy actions that support and incentivise science for the global good.

References

Abaluck, J. et al. (2022), "Impact of community masking on COVID-19: A cluster-randomized trial in Bangladesh", *Science*, Vol. 375/6577, https://doi.org/10.1126/science.abi9069. [30]

Baker, N., R. Van Noorden and A. Maxmen (2020), "Coronapod: The Surgisphere scandal that rocked coronavirus drug research", *Nature*, https://doi.org/10.1038/d41586-020-01790-y. [10]

Bardosh, K. et al. (2020), "Integrating the social sciences in epidemic preparedness and response: A strategic framework to strengthen capacities and improve Global Health security", *Globalization and Health*, Vol. 16/1, https://doi.org/10.1186/s12992-020-00652-6. [27]

Besançon, L. et al. (2021), "Open science saves lives: lessons from the COVID-19 pandemic", *BMC Medical Research Methodology*, Vol. 21/1, https://doi.org/10.1186/s12874-021-01304-y. [17]

Best, A. et al. (2021), "Institutional Distrust among African Americans and Building Trustworthiness in the COVID-19 Response: Implications for Ethical Public Health Practice", *Journal of Health Care for the Poor and Underserved*, Vol. 32/1, pp. 90-98, https://doi.org/10.1353/hpu.2021.0010. [43]

Bonneton, M. et al. (2022), "A national platform for Covid-19 vaccine studies recruitment in France: Covireivac volunteer's characteristics", *Human Vaccines & Immunotherapeutics*, Vol. 18/6, https://doi.org/10.1080/21645515.2022.2109364. [51]

Buchanan, N. et al. (2021), "Remote Work During the COVID-19 Pandemic: Making the Best of It", *Physiology*, Vol. 36/1, pp. 2-4, https://doi.org/10.1152/physiol.00035.2020. [1]

Callard, F. and E. Perego (2021), "How and why patients made Long Covid", *Social Science & Medicine*, Vol. 268, p. 113426, https://doi.org/10.1016/j.socscimed.2020.113426. [62]

Capurro, G. et al. (2021), "Communicating scientific uncertainty in a rapidly evolving situation: a framing analysis of Canadian coverage in early days of COVID-19", *BMC Public Health*, Vol. 21/1, https://doi.org/10.1186/s12889-021-12246-x. [46]

Centers for Disease Control and Prevention (2022), "CDC COVID-19 Response Health Equity Strategy: Accelerating Progress Towards Reducing COVID-19 Disparities and Achieving Health Equity", https://www.cdc.gov/coronavirus/2019-ncov/community/health-equity/cdc-strategy.html#:~:text=Overview,of%20health%20and%20healthcare%20disparities (accessed on 6 March 2023). [60]

Cohen, J. and Y. Rodgers (2020), "Contributing factors to personal protective equipment shortages during the COVID-19 pandemic", *Preventive Medicine*, Vol. 141, p. 106263, https://doi.org/10.1016/j.ypmed.2020.106263. [54]

Dai, Q., E. Shin and C. Smith (2018), "Open and inclusive collaboration in science: A framework", *OECD Science, Technology and Industry Working Papers*, No. 2018/07, OECD Publishing, Paris, https://doi.org/10.1787/2dbff737-en. [6]

Diamond, D. and N. Toosi (2020), "Trump team failed to follow NSC's pandemic playbook", https://www.politico.com/news/2020/03/25/trump-coronavirus-national-security-council-149285 (accessed on 6 March 2023). [53]

Dirnagl, U. (ed.) (2021), "The evolving role of preprints in the dissemination of COVID-19 research and their impact on the science communication landscape", *PLOS Biology*, Vol. 19/4, p. e3000959, https://doi.org/10.1371/journal.pbio.3000959. [9]

Dolgin, E. (2021), "The tangled history of mRNA vaccines", *Nature*, Vol. 597/7876, pp. 318-324, https://doi.org/10.1038/d41586-021-02483-w. [24]

EC-OECD (2021), *2020-21 OECD Survey on STI policy responses to COVID-19 powered by EC-OECD*, https://stip.oecd.org/stip/covid-portal (accessed on 6 March 2023). [61]

G20 (2020), *Extraordinary G20 Leaders' Summit: Statement on COVID-19*, https://www.consilium.europa.eu/media/43072/final-g20-leaders-statement-26032020.pdf (accessed on 6 March 2023). [59]

G7 (2020), *G7 Science and Technology Ministers' Declaration on COVID-19*, https://www.state.gov/g7-science-and-technology-ministers-declaration-on-covid-19/ (accessed on 6 March 2023). [57]

Glasziou, P., S. Michie and A. Fretheim (2021), "Public health measures for covid-19", *BMJ*, p. n2729, https://doi.org/10.1136/bmj.n2729. [31]

Gold, E. (2021), "The fall of the innovation empire and its possible rise through open science", *Research Policy*, Vol. 50/5, p. 104226, https://doi.org/10.1016/j.respol.2021.104226. [23]

Greer, S. et al. (2022), "Centralizing and decentralizing governance in the COVID-19 pandemic: The politics of credit and blame", *Health Policy*, Vol. 126/5, pp. 408-417, https://doi.org/10.1016/j.healthpol.2022.03.004. [33]

Halverson, P. et al. (2021), "Public Health Officials and COVID-19: Leadership, Politics, and the Pandemic", *Journal of Public Health Management and Practice*, Vol. 27/Supplement 1, pp. S11-S13, https://doi.org/10.1097/phh.0000000000001281. [41]

Ihlen, Ø. et al. (2022), "Transparency beyond information disclosure: strategies of the Scandinavian public health authorities during the COVID-19 pandemic", *Journal of Risk Research*, Vol. 25/10, pp. 1176-1189, https://doi.org/10.1080/13669877.2022.2077416. [56]

Jasanoff, S. et al. (2021), *LEARNING FROM COVID-19: A 23-Nation Comparative Study of COVID-19 Response, with Lessons for the Future of Public Health*, https://iserp.columbia.edu/sites/default/files/National%20Comparative%20Study%20Synthesis%20Paper.pdf (accessed on 6 March 2023). [32]

Kostka, G. and S. Habich-Sobiegalla (2022), "In times of crisis: Public perceptions toward COVID-19 contact tracing apps in China, Germany, and the United States", *New Media & Society*, p. 146144482210832, https://doi.org/10.1177/14614448221083285. [47]

Kreiling, L. and C. Paunov (2021), “Knowledge co-creation in the 21st century: A cross-country experience-based policy report”, *OECD Science, Technology and Industry Policy Papers*, No. 115, OECD Publishing, Paris, https://doi.org/10.1787/c067606f-en. [21]

Lesher, M., H. Pawelec and A. Desai (2022), “Disentangling untruths online: Creators, spreaders and how to stop them”, *OECD Going Digital Toolkit Notes*, No. 23, OECD Publishing, Paris, https://doi.org/10.1787/84b62df1-en. [45]

Lobanovska, M. and G. Pilla (2017), “Penicillin’s Discovery and Antibiotic Resistance: Lessons for the Future?”, https://www.researchgate.net/publication/315900937_Penicillin%27s_Discovery_and_Antibiotic_Resistance_Lessons_for_the_Future (accessed on 6 March 2023). [25]

MacAulay, M. et al. (2021), “Under the spotlight: understanding the role of the Chief Medical Officer in a pandemic”, *Journal of Epidemiology and Community Health*, Vol. 76/1, pp. 100-104, https://doi.org/10.1136/jech-2021-216850. [34]

Mulgan, G. (2021), “The Synthesis Gap: reducing the imbalance between advice and absorption in handling big challenges”, https://www.geoffmulgan.com/post/the-synthesis-gap-reducing-the-imbalance-between-advice-and-absorption-in-handling-big-challenges (accessed on 6 March 2023). [37]

National Science and Technology Council (2022), *Protecting the integrity of government science*, https://www.whitehouse.gov/wp-content/uploads/2022/01/01-22-Protecting_the_Integrity_of_Government_Science.pdf (accessed on 6 March 2023). [36]

Nature Computational Science (2021), “Fighting COVID-19 with HPC”, *Nature Computational Science*, Vol. 1/12, pp. 769-770, https://doi.org/10.1038/s43588-021-00180-2. [19]

OECD (2021), “Access to COVID-19 vaccines: Global approaches in a global crisis”, https://read.oecd-ilibrary.org/view/?ref=1069_1069384-ewmqrw9sx2&title=Access-to-COVID-19-vaccines-Global-approaches-in-a-global-crisis (accessed on 5 March 2023). [2]

OECD (2021), “Coronavirus (COVID-19) vaccines for developing countries: An equal shot at recovery”, *OECD Policy Responses to Coronavirus (COVID-19)*, OECD Publishing, Paris, https://doi.org/10.1787/6b0771e6-en. [3]

OECD (2021), *OECD Science, Technology and Innovation Outlook 2021: Times of Crisis and Opportunity*, OECD Publishing, Paris, https://doi.org/10.1787/75f79015-en. [16]

OECD (2021), *Recommendation on Enhanced Access to Research Data from Public Funding*, https://legalinstruments.oecd.org/en/instruments/OECD-LEGAL-0347 (accessed on 5 March 2023). [12]

OECD (2020), “Addressing societal challenges using transdisciplinary research”, *OECD Science, Technology and Industry Policy Papers*, No. 88, OECD Publishing, Paris, https://doi.org/10.1787/0ca0ca45-en. [18]

OECD (2020), “Ensuring data privacy as we battle COVID-19”, https://www.oecd.org/coronavirus/policy-responses/ensuring-data-privacy-as-we-battle-covid-19-36c2f31e/ (accessed on 5 March 2023). [14]

OECD (2020), “Greater harmonisation of clinical trial regulations would help the fight against COVID-19”, https://www.oecd.org/coronavirus/policy-responses/greater-harmonisation-of-clinical-trial-regulations-would-help-the-fight-against-covid-19-732e1c5c/ (accessed on 6 March 2023). [22]

OECD (2020), “Providing science advice to policy makers during COVID-19”, https://www.oecd.org/coronavirus/policy-responses/providing-science-advice-to-policy-makers-during-covid-19-4eec08c5/ (accessed on 6 March 2023). [38]

OECD (2020), “Why open science is critical to combatting COVID-19”, https://www.oecd.org/coronavirus/policy-responses/why-open-science-is-critical-to-combatting-covid-19-cd6ab2f9/ (accessed on 5 March 2023). [15]

OECD (2018), *Scientific Advice During Crises: Facilitating Transnational Co-operation and Exchange of Information*, OECD Publishing, Paris, https://doi.org/10.1787/9789264304413-en. [4]

OECD (2016), “Research Ethics and New Forms of Data for Social and Economic Research”, *OECD Science, Technology and Industry Policy Papers*, No. 34, OECD Publishing, Paris, https://doi.org/10.1787/5jln7vnpxs32-en. [13]

OECD (2015), “Making Open Science a Reality”, *OECD Science, Technology and Industry Policy Papers*, No. 25, OECD Publishing, Paris, https://doi.org/10.1787/5jrs2f963zs1-en. [5]

OECD (2015), “Scientific Advice for Policy Making: The Role and Responsibility of Expert Bodies and Individual Scientists”, *OECD Science, Technology and Industry Policy Papers*, No. 21, OECD Publishing, Paris, https://doi.org/10.1787/5js33l1jcpwb-en. [35]

Paunov, C. and S. Planes-Satorra (2021), “Science, technology and innovation in the time of COVID-19”, *OECD Science, Technology and Industry Policy Papers*, No. 99, OECD Publishing, Paris, https://doi.org/10.1787/234a00e5-en. [26]

Paunov, C. and S. Planes-Satorra (2021), “What future for science, technology and innovation after COVID-19?”, *OECD Science, Technology and Industry Policy Papers*, No. 107, OECD Publishing, Paris, https://doi.org/10.1787/de9eb127-en. [48]

Pearson, H. (2021), “How COVID broke the evidence pipeline”, *Nature*, Vol. 593/7858, pp. 182-185, https://doi.org/10.1038/d41586-021-01246-x. [49]

Perng, S. (2022), “Materialities of digital disease control in Taiwan during COVID-19”, *Big Data & Society*, Vol. 9/1, p. 205395172210973, https://doi.org/10.1177/20539517221097315. [55]

Piper, J., B. Gomis and K. Lee (2022), ““Guided by Science and Evidence”? The Politics of Border Management in Canada’s Response to the COVID-19 Pandemic”, *Frontiers in Political Science*, Vol. 4, https://doi.org/10.3389/fpos.2022.834223. [40]

Provenzi, L. and S. Barello (2020), “The Science of the Future: Establishing a Citizen-Scientist Collaborative Agenda After Covid-19”, *Frontiers in Public Health*, Vol. 8, https://doi.org/10.3389/fpubh.2020.00282. [42]

Research Data Alliance (2020), *RDA COVID-19 Recommendations and Guidelines on Data Sharing*, https://doi.org/10.15497/rda00052 (accessed on 5 March 2023). [11]

Seale, H. et al. (2022), “The role of community leaders and other information intermediaries during the COVID-19 pandemic: insights from the multicultural sector in Australia”, *Humanities and Social Sciences Communications*, Vol. 9/1, https://doi.org/10.1057/s41599-022-01196-3. [44]

Seidler, A. et al. (2021), “The landscape of COVID-19 trials in Australia”, *Medical Journal of Australia*, Vol. 215/2, p. 58, https://doi.org/10.5694/mja2.51148. [50]

The Lancet Infectious Diseases (2022), “Emerging SARS-CoV-2 variants: shooting the messenger”, *The Lancet Infectious Diseases*, Vol. 22/1, p. 1, https://doi.org/10.1016/s1473-3099(21)00770-2. [39]

Thornton, I., P. Wilson and G. Gandhi (2022), ““No Regrets” Purchasing in a pandemic: making the most of advance purchase agreements”, *Globalization and Health*, Vol. 18/1, https://doi.org/10.1186/s12992-022-00851-3. [52]

UK G7 (2021), “100 Days Mission to Respond to Future Pandemic Threats”, https://www.gov.uk/government/publications/100-days-mission-to-respond-to-future-pandemic-threats (accessed on 6 March 2023). [58]

Verdugo-Paiva, F. et al. (2022), “COVID-19 Living Overview of Evidence repository is highly comprehensive and can be used as a single source for COVID-19 studies”, *Journal of Clinical Epidemiology*, Vol. 149, pp. 195-202, https://doi.org/10.1016/j.jclinepi.2022.05.001. [8]

Veron, P. and M. Di Ciommo (2020), “Fit for purpose: The EU’s role in global health in the era of COVID-19”, https://ecdpm.org/work/fit-for-purpose-the-eus-role-in-global-health-in-the-era-of-covid-19 (accessed on 6 March 2023). [20]

WHO (2022), *Timeline: WHO’s COVID-19 response*, https://www.who.int/emergencies/diseases/novel-coronavirus-2019/interactive-timeline (accessed on 6 March 2023). [29]

WHO, W. (2020), “A Coordinated Global Research Roadmap: 2019 Novel Coronavirus”. [28]

Wu, F. et al. (2020), “A new coronavirus associated with human respiratory disease in China”, *Nature*, Vol. 579/7798, pp. 265-269, https://doi.org/10.1038/s41586-020-2008-3. [7]

Notes

[1] Several earlier OECD reports have reviewed the scientific initiatives and policies introduced in the initial phases of the COVID-19 pandemic response. See, for example, (OECD, 2021[16]), (Paunov and Planes-Satorra, 2021[26]) and (Paunov and Planes-Satorra, 2021[48]). Additionally, a catalogue of country-submitted COVID-19-specific science policies is available through the COVID-19 Watch portal of the EC-OECD STIP Compass (https://stip.oecd.org/covid/).

[2] Six international virtual workshops were organised in the context of the OECD "Mobilising science in response to crises: Lessons learned from COVID-19" project. These workshops addressed the following topics: 1) research data; 2) research infrastructures; 3) the interface between academia and the private sector; 4) research agenda-setting; 5) scientific advice; and 6) public communication and engagement. All background materials and resulting reports can be accessed online (https://www.oecd.org/sti/inno/global-science-forum.htm).

[3] The COVID-19 Open Research Dataset (CORD-19) provided the basis for the CORD-19 Challenge (https://www.kaggle.com/allen-institute-for-ai/CORD-19-research-challenge), a collaboration between NIH and the Allen Institute that uses the Kaggle platform. The challenge launches competitions in which the community uses AI and machine learning to analyse the literature and come up with new insights in response to specific questions. While the CORD-19 corpus is extensive, it does not include all articles relevant to the pandemic; there are gaps, for example, in relation to social sciences and humanities (SSH). There are also longer-term questions about its continuing availability and what will happen post-pandemic (see also the workshop report on research data (https://www.oecd.org/fr/sti/inno/improving-academia-private-sector-interactions.htm).

[4] Publications are identified as COVID-19 related based on the following PubMed search: ("COVID-19" OR "COVID-19"[MeSH Terms] OR "COVID-19 Vaccines" OR "COVID-19 Vaccines"[MeSH Terms] OR "COVID-19 serotherapy" OR "COVID-19 serotherapy"[Supplementary Concept] OR "COVID-19 Nucleic Acid Testing" OR "covid-19 nucleic acid testing"[MeSH Terms] OR "COVID-19 Serological Testing" OR "covid-19 serological testing"[MeSH Terms] OR "COVID-19 Testing" OR "covid-19 testing"[MeSH Terms] OR "SARS-CoV-2" OR "sars-cov-2"[MeSH Terms] OR "Severe Acute Respiratory Syndrome Coronavirus 2" OR "NCOV" OR "2019 NCOV" OR (("coronavirus"[MeSH Terms] OR "coronavirus" OR "COV"). Publications are identified as diabetes related based on the following PubMed search: "diabete"[All Fields] OR "diabetes mellitus"[MeSH Terms] OR ("diabetes"[All Fields] AND "mellitus"[All Fields]) OR "diabetes mellitus"[All Fields] OR "diabetes"[All Fields] OR "diabetes insipidus"[MeSH Terms] OR ("diabetes"[All Fields] AND "insipidus"[All Fields]) OR "diabetes insipidus"[All Fields] OR "diabetic"[All Fields] OR "diabetics"[All Fields] OR "diabets"[All Fields]) Publications are identified as dementia related based on the following PubMed search: "dementia"[MeSH Terms] OR "dementia"[All Fields] OR "dementias"[All Fields] OR "dementia s"[All Fields]

[5] The European Alliance of Medical Research Infrastructures (AMRI) is a novel collaboration between three European research infrastructure consortiums (ERICs): the Biobanking and Biomolecular Resources Research Infrastructure (BBMRI)-ERIC; the European Advanced Translational Research Infrastructure in Medicine (EATRIS)-ERIC; and the European Clinical Research Infrastructure Network (ECRIN)-ERIC. The Alliance aims to streamline access to services, tools and expertise. During the COVID-19 response, AMRI established a fast-response service to accelerate access to facilities and services.

[6] The Analytical Research Infrastructures of Europe (https://arie-eu.org/) is a consortium of 7 European research networks that collaborate to address missions that have been identified in the European Commission (EC) research programme “Horizon Europe”. The consortium has helped co-ordinate European efforts across many aspects of the COVID-19 response, from identifying the virus to developing countermeasures.

[7] NHLBI CONNECTS (https://www.nhlbi.nih.gov/science/collaborating-network-networks-evaluating-covid-19-and-therapeutic-strategies-connects) is the US-NIH National Heart, Lung, and Blood Institute’s (NHLBI) Collaborating Network of Networks for Evaluating COVID-19 and Therapeutic Strategies. The network was formed in response to the COVID-19 pandemic. It provides a centralised and adaptive platform and has established master protocols to integrate all major NHLBI clinical trial networks.

[8] During the COVID-19 pandemic, the UK-based Pirbright Institute supported the National Health Services in building diagnostic testing capacity. It supplied critical infrastructure, staff and scientists while also providing training to new staff on sample management, biosafety and scientific diagnostic procedures (see the workshop report on Research Infrastructures (https://www.oecd.org/sti/inno/research-infrastructures-mobilisation.htm).

[9] Several clinical research infrastructures have provided support for developing and testing new diagnostics and therapies during the COVID-19 response. The European Clinical Research Infrastructure Network established a COVID-19 Taskforce (https://ecrin.org/covid-19-taskforce) with national partners to perform a variety of tasks. These included developing a metadata repository for COVID-19 trials and a database of fast-track approvals (regulatory, ethical, data protection) across European countries. The European Research Infrastructure on Highly Pathogenic Agents (https://www.erinha.eu/access-our-services/covid19-services/) also provides targeted support for SARS-CoV-2 studies, including access to various high-containment in-vitro and in-vivo capacities, pre-clinical research co-ordination, and information on research protocols and design.

[10] Participants in the OECD “priority setting and funding workshop” (https://www.oecd.org/sti/inno/priority-setting-and-coordination-of-research.htm) attested that by November 2020, hundreds of clinical trials had been registered, with many lacking the size or standardisation required to produce robust results. By May 2021, more than 2 900 COVID-19-related clinical trials had been registered; however, many were underpowered and lacked the necessary conditions for developing robust, statistically significant scientific results (Pearson, 2021[49]), (Seidler et al., 2021[50]). The urgency of the situation in which the majority of trials were launched resulted in significant duplication of efforts.

[11] Aside from NHLBI CONNECTS (see Note 6), a variety of efforts have been undertaken to develop COVID-19 vaccination and therapeutic platforms capable of co-ordinating and streamlining countermeasure development and testing efforts. Randomised Evaluation of COVID-19 Therapy (RECOVERY) is an international clinical trial run by the University of Oxford aiming to identify and assess potential treatments for hospitalised COVID-19 patients (https://www.recoverytrial.net/). VACCELERATE is a pan-European clinical research network (including 29 national partners in 18 EU Member States) that co-ordinates the second and third phases of COVID-19 vaccine trials (https://vaccelerate.eu/). Accelerating COVID-19 Therapeutic Interventions and Vaccines (ACTIV) is a US-based public-private partnership created to expedite the development of COVID-19-specific vaccines and treatments (https://fnih.org/our-programs/ACTIV). In France, COVIREIVAC was established by the Innovative Clinical Research Network in Vaccinology (I-REIVAC), with support from several other national organisations, to enable academic and industrial COVID-19 vaccine trials (Bonneton et al., 2022[51]).

[12] The US COVID-19 High Performance Computing (HPC) Consortium (https://covid19-hpc-consortium.org/) is a network with members from industry, academia, and federal laboratories and agencies that share computing capabilities ranging from small clusters to large supercomputers. The consortium was established in March 2020, originally as a US-based public-private partnership between the Office of Science and Technology Policy, the Department of Energy, the National Science Foundation and IBM. Its goal is to provide a single point of access to HPC and cloud computing resources, technical expertise and other forms of support to underpin research on COVID-19.

[13] In Some countries, long-term investments in social-science data infrastructures and community-based surveys proved important in ensuring that scientists and policy makers had timely access to the necessary data. Examples from the United Kingdom and South Africa were discussed at the project workshop on scientific advice (https://www.oecd.org/sti/inno/scientificadviceincriseslessonslearnedfromcovid-19.htm). South Africa was able to draw on an extensive network of social science infrastructures to conduct timely surveys on public perceptions of interventions. The United Kingdom was able to accelerate its regulatory and ethical approval processes and rapidly adapt existing longitudinal household surveys to understand the local characteristics of viral transmission and individual experiences.

[14] The European life sciences infrastructure for biological information, ELIXIR, has supported the co-ordination and advancement of COVID-19 research efforts through services related to storing, sharing and accessing relevant data, publications and computing resources (https://elixir-europe.org/services/covid-19). The European and Developing Countries Clinical Trials Partnership is a research partnership between 14 European and 16 African countries founded in 2003 (https://www.edctp.org/). In 2020, the Partnership launched an emergency funding call to support 24 international COVID-19-related research collaborations. Since 2018, it has also supported ALERRT (African coaLition for Epidemic Research Response and Training) and PANDORA-ID-NET (Pan-African Network for Rapid Research, Response, Relief, and Preparedness for Infectious Disease Epidemics) in improving the pandemic preparedness and response capacities of sub-Saharan African countries.

[15] mRNA: Messenger RNA.

[16] The COVID Moonshot project (https://postera.ai/moonshot/), an international open science consortium of scientists, pharmaceutical research teams and students, is one of the few (at least partial) success stories regarding novel COVID-19 therapeutics. The collaboration was developed bottom-up: it was initiated through Twitter and supported at the institutional level by recognised stakeholders, including the University of Oxford, the UK Synchotron Diamond Light Source and the Wellcome Trust. The project has pioneered a novel approach to drug discovery, using informal and open collaboration in the absence of formal contracts or ex ante intellectual property rights agreements. It has managed to leverage the resources, knowledge and expertise of hundreds of scientists and other actors to develop and undertake early-phase testing of several promising drug candidates. However, the project has struggled to find a business model to move these products from the laboratory to the bedside, and in such a way as to provide equitable and affordable access.

[17] A number of these initiatives were presented as case studies in the September 2021 OECD workshop on academia-private-sector interactions (https://www.oecd.org/sti/inno/improving-academia-private-sector-interactions.htm), as well as in (Kreiling and Paunov, 2021[21]). These cases illustrate some of the novel collaboration models introduced to improve science-industry partnerships, many of which were also characterized by the participation of community groups or citizens.

[18] In Finland, the Fast Expert Teams initiative (https://oecd-opsi.org/covid-response/fast-expert-teams-vs-covid-19-how-to-help-finland-avoid-paralyzing-when-experts-cannot-meet-f2f/) leveraged digital tools and platforms to accelerate the development of trust across sectoral barriers, and align different expectations. The project used an informal "snowball" approach to accelerate the engagement of new participants.

[19] To streamline and accelerate applications for research grants during the COVID-19 pandemic response, several national agencies in Ireland shared the same application portal. Project selection and funding was determined at the "back end" in accordance with funders' specific mandates, but applicants submitted single proposals (see workshop on academia-private sector interface (https://www.oecd.org/fr/sti/inno/improving-academia-private-sector-interactions.htm).

[20] The engagement of super-forecasting experts may help integrate a broader array of variables into conventional statistical modelling efforts. Alternatively, the University of Hong Kong School of Public Health has used epidemic nowcasting during the COVID-19 response to inform policy decisions. This multidisciplinary approach has enabled scientists to assess and forecast transmissibility and epidemic size with greater accuracy, and to identify emerging variants (see workshop on research agenda setting, (https://www.oecd.org/sti/inno/priority-setting-and-coordination-of-research.htm).

[21] Nationalism has been a major barrier to international pandemic preparedness and response activities. Countries tend to prioritise only those activities that will advance domestic scientific standing and interests (see workshop on research agenda setting (https://www.oecd.org/sti/inno/priority-setting-and-coordination-of-research.htm). In addition, despite early consensus regarding the need for equitable allocation of countermeasures, many developed countries used advanced purchasing agreements to secure domestic supplies, delaying access for LMICs (Thornton, Wilson and Gandhi, 2022[52]).

[22] For example, attempts by the Norwegian Institute of Public Health to use randomized control trials to assess the effectiveness of PHSMs during the pandemic were thwarted by regulations that require individual consent from all participants (see workshop on research agenda setting, (https://www.oecd.org/sti/inno/priority-setting-and-coordination-of-research.htm).

[23] Most OECD countries initially focused on engaging experts from the biomedical and life sciences fields before it was recognised that broader disciplinary expertise was required to address some aspects of the evolving pandemic. In some countries, including the Netherlands, dedicated behavioural and social science research units were created, but they were not fully integrated into the formal apparatus informing policy makers (see workshop on scientific advice (https://www.oecd.org/sti/inno/scientificadviceincriseslessonslearnedfromcovid-19.htm).

[24] For example, the 2017-21 US administration was criticised (Diamond and Toosi, 2020[53]) for its failure to effectively apply guidelines outlined in the Playbook for Early Response to High-Consequence Emerging Infectious Disease Threats and Biological Incidents. The playbook was developed in 2016 by the National Security Council in response to the country's reaction to of the 2014 Ebola crisis. Similar pandemic preparedness exercises – often focused on the influenza virus – were conducted in other countries, including the United Kingdom, and at the European level, but the weaknesses identified, including shortages of protective equipment, were not addressed prior to COVID-19 (Cohen and Rodgers, 2020[54]).

[25] Based on an analysis of countries' COVID-19-specific science policies using the COVID-19 Watch portal of the EC-OECD STIP Compass (https://stip.oecd.org/covid/), only a small number of policies from the European Union, Germany and Belgium referenced foresight, preparedness or risk assessments. Regarding public communication and engagement, the reported policies focused mainly on making science advice accessible to the public, and only a handful explicitly engaged citizens.

[26] In Chinese Taipei, the participation of civilians and civil society organisations in COVID-19 mitigation activities has contributed in important ways to the initial success of the pandemic response. Civilians voluntarily engaged in efforts to monitor and trace transmission of the virus. In addition, private individuals and community groups led the development of inventory maps for personal protective equipment (Perng, 2022[55]) (see workshop on public communication and engagement (https://www.oecd.org/sti/inno/public-communication-engagement-in-science.htm

[27] For instance, like many OECD countries, behavioural science was not part of the initial response in the Netherlands. The country's Corona Behavioural Unit only came together in late March 2020, in response to rapidly increasing case numbers and recognition of the important role of human behaviour in the pandemic response. However, the new group moved quickly, securing funding and research grants, and assembling a scientific board over the course of several weeks (see workshop on scientific advice (https://www.oecd.org/sti/inno/scientificadviceincriseslessonslearnedfromcovid-19.htm) and behavioural science webinar, https://ianphi.org/news/2020/covid-19-behavioral-science-webinar.html).

[28] Norwegian public health officials adopted several tactics to communicate transparently regarding the COVID-19 response, including active participation in televised debates and direct engagement with the public through social media platforms (Ihlen et al., 2022[56]) (see workshop on scientific advice (https://www.oecd.org/sti/inno/scientificadviceincriseslessonslearnedfromcovid-19.htm).

[29] In the United Kingdom, concerns about the methods and procedures of the government Science Advisory Group on Emergencies (SAGE) led to the creation of an "alternative SAGE", which had no official mandate but was chaired by a former CSA. In the Netherlands, dissatisfaction with the formally mandated Outbreak Management Team led to creation of a shadow science advisory process by the so-called Red Team (see workshop on scientific advice (https://www.oecd.org/sti/inno/scientificadviceincriseslessonslearnedfromcovid-19.htm).

[30] Access to comparable data, disaggregated by location, was important to develop science advice and policies targeted to the local situation. However, some countries found this challenging for a variety of reasons, including poor compatibility between federal and local processes. For example, participants in the workshop on scientific advicenoted that in Australia, data gaps contributed to a lack of policy co-ordination and integration across different levels of governance (https://www.oecd.org/sti/inno/scientificadviceincriseslessonslearnedfromcovid-19.htm).

[31] The "G7 Science and Technology Ministers' Declaration on COVID-19", released on 28 May 2020, provides a shared vision for the use of science and technology to develop effective countermeasures, global co-ordination of R&D and improved access to data (G7, 2020[57]). Under the UK G7 Presidency, leaders also committed to a "100 Days Mission" targeting the development of diagnostics, therapeutics and vaccines (UK G7, 2021[58]). In November 2020, the G20 released the "Extraordinary G20 Leaders' Summit Statement on COVID-19 recognising the global need for a transparent and science-based response to COVID-19" (G20, 2020[59]).

[32] In some countries, scientists were able to rely on connections with the news media that had been established prior to the pandemic. For example, FactCheck Initiative Japan (https://en.fij.info/), established in 2017, brings together scientists and journalists to verify online information. A number of new science communication initiatives were also launched in response to the COVID-19 pandemic, including the Royal Society of Canada's Task Force on COVID-19 (https://rsc-src.ca/en/themes/rsc-task-force-covid-19), which has published over 150 opinion pieces in news publications (see workshop on public communication and engagement (https://www.oecd.org/sti/inno/public-communication-engagement-in-science.htm).

[33] The COVID-19 pandemic has highlighted the importance of health equity and social determinants of health, which help explain why certain population groups were more severely affected. It is important to take fuller account of these groups in the development of scientific advice, linking this to targeted communication campaigns that address specific needs. The US Centres for Disease Control has taken steps to integrate health equity into science activities across its portfolio, including the investigation of underlying drivers such as racism (Centers for Disease Control and Prevention, 2022[60]) (see workshop on scientific advice (https://www.oecd.org/sti/inno/scientificadviceincriseslessonslearnedfromcovid-19.htm).

[34] According to the snapshot of COVID-19-specific policies captured through the STIP Compass COVID-19 Watch, digital tools and platforms made up the bulk of the communication initiatives policy makers deployed to communicate or engage with the public. Approaches ranged from passive communication via websites to more active engagement through social media and mobile applications, including WhatsApp or chatbots (EC-OECD, 2021[61]).

[35] Social media companies have been involved in a variety of initiatives to amplify validated scientific narratives and address harmful or questionable claims across countries. For example, Facebook has: used COVID-19 vaccine profile frames to improve visibility and trust of vaccines; supported users in exploiting marketing tools for public health campaigns campaigns tailored to specific demographics; and subsidised the advertisement budgets of trusted public health authorities (see workshop on Public communication and engagement https://www.oecd.org/sti/inno/public-communication-engagement-in-science.htm).

[36] FactCheck Initiative Japan (https://en.fij.info/about/) is a coalition of academics, journalists and non-profit organisations created in 2017 to address the risks posed by misinformation. During the COVID-19 pandemic, the network focused on validating COVID-19 information originating in Japan and checking questionable claims that had spread to Japan from abroad. Several national and international media partners are engaged in the initiative, including SmartNews, Yahoo! Japan and BuzzFeed Japan.

[37] The term "long COVID" was coined on Twitter in May 2020 by Elisa Perego, a social scientist experiencing a chronic reaction to the virus (Callard and Perego, 2021[62]). Use of the term gained traction in a matter of weeks. However, the condition or syndrome and its symptoms have been contested within the scientific community and there have attempts to give it a variety of medical labels, with patients often excluded from pertinent discussions (see workshop on Public communication and engagement (https://www.oecd.org/sti/inno/public-communication-engagement-in-science.htm).

5 Reaching Net zero: Do mission-oriented policies deliver on their many promises?

Mission-oriented innovation policies are increasingly popular as a policy response to meeting net-zero targets. They have clear objectives and measurable targets, promote broader co-ordination of policy plans across administrative silos, and better integrate various support instruments across the different stages of the innovation chain than more traditional and fragmented policy approaches. These policies remain unproven, however, and early indications suggest they lack sufficient scale and reach to non-STI policy domains to have wide-ranging impact. The challenge remains to move these initiatives from effective co-ordination platforms to integrated policy frameworks that mobilise and align a wide range of actors. Overcoming many of the barriers – including administrative and legal rules, accounting structures and governance models – requires changes that are far beyond the reach of STI authorities alone and will need significant political support.

Key messages

- A growing number of countries are experimenting with mission-oriented innovation policies (MOIPs) to help them reach net-zero targets. Most of these have only been launched recently and have yet to demonstrate their differential impact with respect to more traditional and fragmented policy approaches. Providing evidence of their contribution to long-term objectives in a timeline compatible with short- to medium-term political cycles is, however, a challenge for most net-zero missions.
- This chapter uses a "theory of change" policy framework to track the effects of 83 net-zero missions, from their specific design features to their contribution to achieving net-zero. It shows that net-zero missions produce some of their expected outputs and outcomes and in most cases, represent a marked improvement over traditional science, technology and innovation (STI) policy mixes. However, they are not yet well-suited to producing the needed transformative changes to achieve net-zero.
- Net-zero missions entail a co-designed agenda, a dedicated governance structure and finally, a tailor-made and integrated policy mix. Compared to traditional policy mixes, net-zero missions are characterised by:
    - Stronger orientation, with clearer objectives and measurable targets related to GHG emission reduction – although only a few correspond to expected specific, measurable, achievable, relevant and time-bound (SMART) goals. Such initiatives are characterised by co-developed strategic agendas that are directly associated to financial resources and implementation modes, which is rarely the case in other strategic frameworks.
    - Broader co-ordination of policy plans across administrative silos, bringing together the authorities in charge of research and innovation policy, and the "owners" of the challenges they tackle – for instance, the policy and regulatory bodies in charge of transport or environment. To date, however, budgets are not commensurate with the transformative objectives of net-zero missions and originate almost exclusively from public authorities in STI.
    - Higher integration of various support instruments across the different stages of the innovation chain, from supporting research to skill strengthening and, for some of them, market deployment through price-based mechanisms and public procurement. A significant value added of net-zero missions is their result orientation, which leads mission partners to integrate societal needs and demands at different stages of the mission life cycle.
- Building on these early results and learning from good practices, net-zero missions will accomplish their transformative potential if they can find a way out of two common traps:
    - The "STI-only trap": despite displaying some systemic features, most net-zero missions remain focused on supporting research and innovation, are led by STI authorities and draw almost exclusively on STI funds.
    - The "orientation trap": so far, most net-zero missions have had success in defining strategic agendas and setting up governance structures. Evidence of joined-up implementation remains rarer and limited.
- The MOIP theory of change presented in this chapter should be further developed and translated into decision-support tools to facilitate public policy experimentation and adaptive, real-time policy learning.

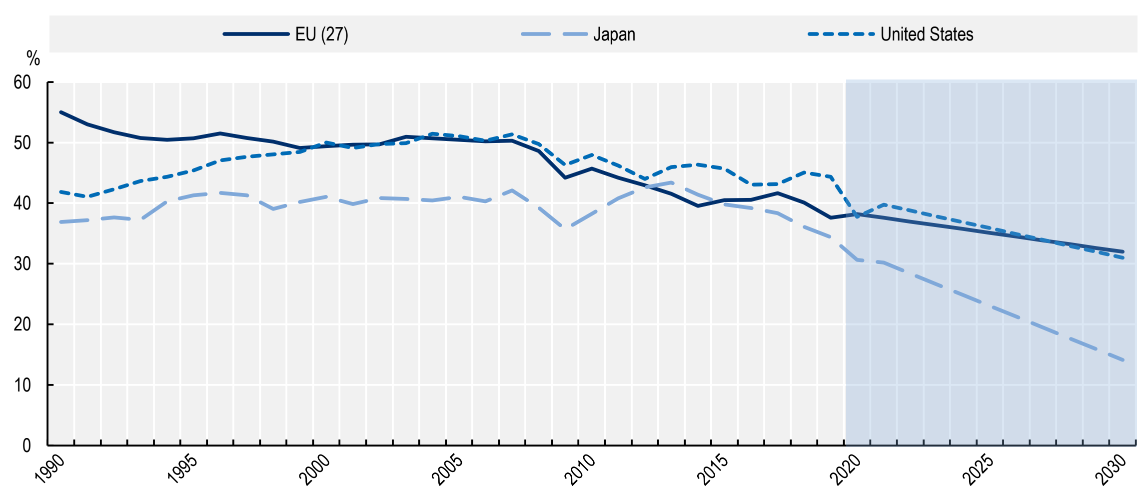
Introduction

Current STI policy and governance frameworks are unfit to help deliver sustainability agendas

Despite technological progress that has helped lower the costs of low-carbon technologies and increase their performance in areas such as buildings and transportation (IPCC, 2022[1]), it is increasingly clear that "change as usual" is no longer an option to tackle systemic societal challenges such as climate change. While 33 countries and EU Member States have set net-zero targets, mostly for 2030 and 2050, to attempt to limit global warming to 1.5˚C by the end of the century, at the current rate of emission reduction, countries are not on the path to meet their international commitments for 2030 (Figure 5.1). Furthermore, in the unlikely case that all countries will implement their 2030 pledges and continue at the same pace, recent simulations show that global warming is likely to reach about 2.7°C by 2100 (IPCC, 2022[1]).

Figure 5.1. Gap between GHG emissions and 2030 national targets for selected countries, 1990-2020, and linear projections 2021-30

In percentage of GHG emissions



Note: Annual difference between GHG emissions and NDC 2030 target is calculated by subtracting target estimates from GHG emissions each year. The figure shows the annual difference as a percentage of GHG emissions in each year. GHG emissions levels are aligned to the scope and unit of NDC targets, including the coverage of sectors, gases and global warming potential factors (GWP). Emission levels are therefore not directly comparable across countries. Projections are based on the trends observed during the last five years for each series of data; emission data for China, – which are increasing rapidly – are not regular enough to allow projections.
Source: OECD (n.d.), International Programme for Action on Climate, Climate Action Dashboard, https://www.oecd.org/climate-action/ipac/ (accessed on 3 March 2022).

StatLink https://stat.link/ht4rfx

Many countries are trying to translate their net-zero commitments into concrete actions, which requires immediate decisions (Jeudy-Hugo, Lo Re and Falduto, 2021[2]). However, climate actions to date fall significantly short of what is necessary to achieve these targets (Lebling et al., 2020[3]). Recent OECD work highlights the marked levelling out of concrete climate policy measures across OECD countries, particularly innovation-related policies (Criscuolo, Dechezleprêtre and Cervantes, 2023[4]), (Kruse et al., 2022[5]). International Energy Agency (IEA) data demonstrate a clear flattening of public expenditures for research, design and development (RD&D) for low-carbon technologies as a percentage of gross domestic product since around 2010 (IEA, 2022[6]). This trend coincides with a slowdown of patenting in low-carbon technologies (Criscuolo, Dechezleprêtre and Cervantes, 2022[7]).

Despite announcements regarding the increasing proximity to climate tipping points (OECD, 2022[8]), multiple pathways to limit global warming to 1.5°C are still available. These pathways correspond to various mitigation approaches, with different combinations and timelines for the development and diffusion of social and technological innovations (IPCC, 2022[9]). Both the diffusion of currently available technologies, and new advances and scale-up of those still in laboratories or at the demonstration stage, can help achieve the 2030 emission-reduction targets (IEA, 2022[10]). However, these will need to be combined with behavioural, regulatory, political and social changes. Changes in a wide range of domains, involving different communities on multiple levels, will have to co-evolve in conjunction towards similar objectives to allow such co-ordinated systemic transformation.

In past decades, however, policies have mainly consisted of individual policy instruments targeting specific market failures (Mazzucato, 2018[11]), for instance by raising the level of private R&D, supporting feasibility or strengthening the knowledge base. This "one objective – one policy instrument" framework has resulted in a fragmented policy and governance landscape that has exacerbated co-ordination problems. Without a framework to co-ordinate different modes of intervention, these dispersed policy mixes are ill-suited to bring about the systemic changes required to ensure the transition to net-zero (OECD, 2021[12]), (Hynes, Lees and Müller, 2020[13]).

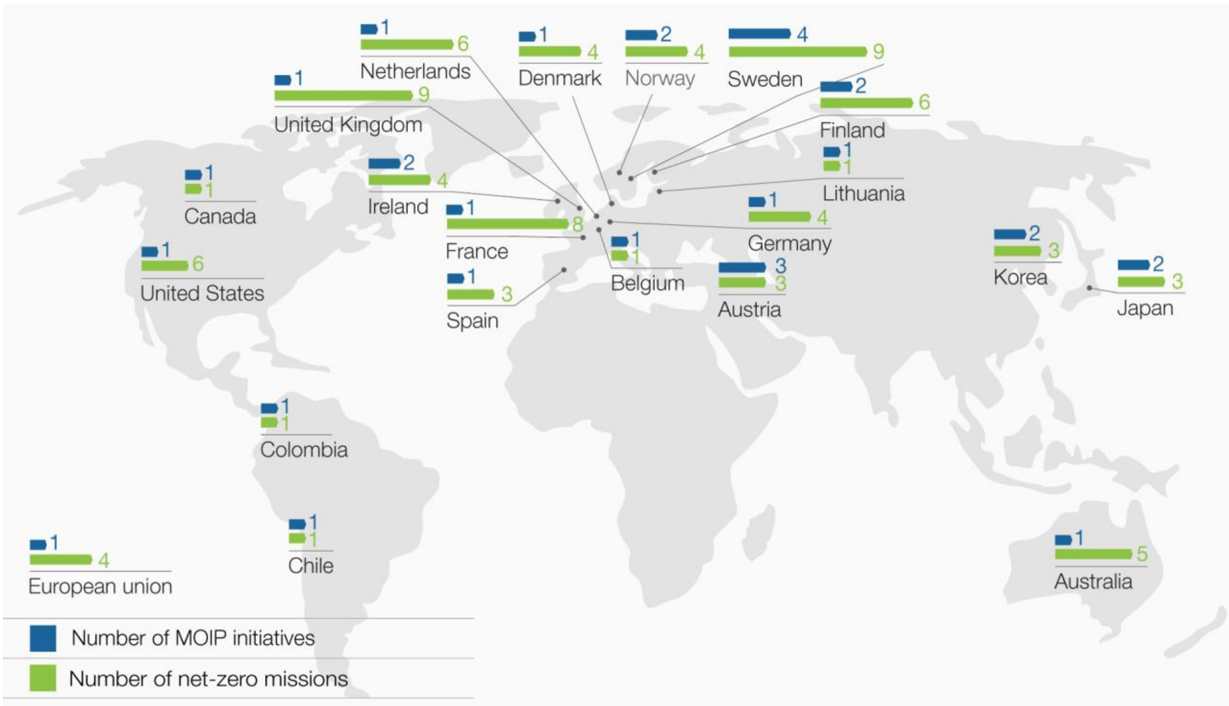
A wealth of "mission-oriented" systemic policy experimentations

Acknowledging the limitations of current policies to address "wicked" challenges such as climate change, several countries are piloting systemic policy approaches that promote (to various degrees) cross-governmental, cross-sectoral and multidisciplinary collaboration in STI policy formulation. These initiatives consider linkages between issues that are generally treated separately within different "silos" to address a specific challenge. In Norway, a country where many sectoral ministries and their agencies have responsibility for their own STI policy, three agencies have since 2016 gathered their respective instruments to fast-track the development, testing and deployment of new green energy solutions in a single integrated scheme (Pilot-E). In France, the "Investments for the Future" programme (PIA)[1], initiated in 2010, was redesigned in 2020 to focus on specific technology areas through integrated support across all stages of the innovation chain, from exploratory research to market deployment. Each of these so-called "acceleration strategies" has its own strategic agenda, budget and governance structure, with a dedicated inter-ministerial co-ordinator. In the United States, several agencies have been created to emulate the "Defense Advanced Research Projects Agency (DARPA) model", where a co-ordinated portfolio of projects are proactively managed to solve complex energy or health-related challenges (among others). In the energy area, the systemic dimension of these initiatives was enhanced in 2021 by integrating various relevant programmes and agency schemes into "Energy Earthshots", which adopt an "all-R&D-community" approach to addressing complex challenges such as affordable grid storage for clean power and low-cost clean hydrogen. Under different forms, systemic policy experimentations occur in many European countries, in Asian countries and in Australia.

While these initiatives vary in terms of focus, scope and design, they have in common the goal of promoting proactive action across disciplinary, sectoral and administrative silos to address collectively a challenge too complex to be solved by any individual measure. They have generally been gathered under the "MOIP" label, a concept that has attracted a great deal of attention from policy makers and analysts. OECD defines MOIPs as a "co-ordinated package of policy and regulatory measures tailored specifically to mobilise STI in order to address well-defined objectives related to a societal challenge, in a defined timeframe". These measures may span different stages of the innovation cycle, from research to demonstration and market deployment; feature a mix of supply-push and demand-pull instruments; and cut across various policy fields, sectors and disciplines (Larrue, 2021[14]). Using this definition as a reference, the OECD has identified 83 net-zero missions in 30 MOIP initiatives implemented in 20 countries (Figure 5.2).

Figure 5.2. Map of MOIPs and their net-zero missions

An increasing number of countries have engaged in systemic policies to reduce GHG emissions



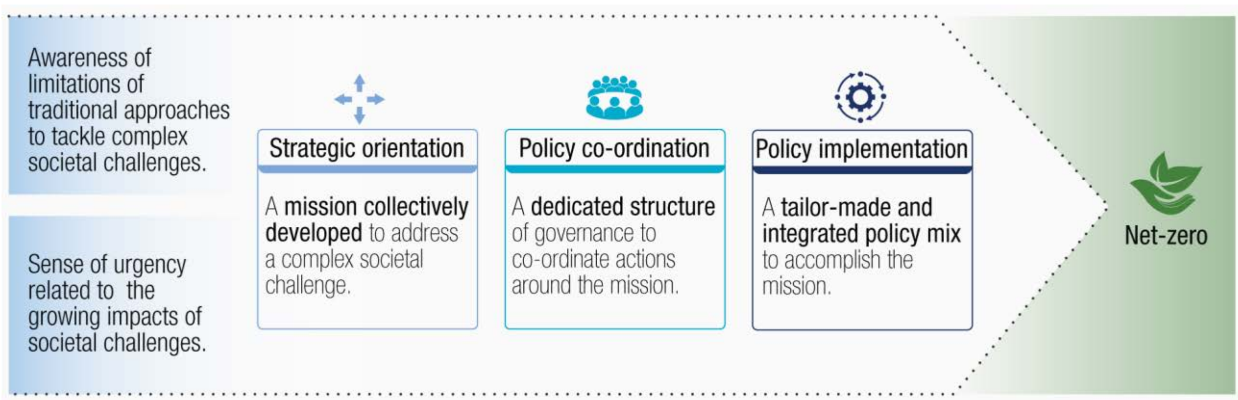
Note: For instance, Ireland currently operates two MOIP initiatives which include a total of 4 missions. The list of MOIP initiatives, as well as their net-zero missions, is available at: https://www.oecd.org/sti/inno/Online%20list%20of%20NZ%20missions.pdf.

This definition relates to an ideal type that can be characterised by three main features:

1. *Strategic orientation*: the main objective of MOIPs is to develop and set well-accepted objectives regarding a complex challenge to be addressed, to lay the foundation for targeted and co-ordinated collective action. While MOIPs are still often wrongly characterised as top-down, their objectives can only be defined by involving and reaching a consensus among a wide array of public and private stakeholders.
2. *Policy co-ordination*: MOIPs co-ordinate the strategies and plans of various public authorities in charge of different components (e.g. knowledge, technologies, funding, skills, regulations, markets) that are essential to reaching collectively agreed objectives. These public authorities belong to different policy fields (such as research, innovation and different sectors that “own” the societal challenges, including energy, mobility and health) and different levels of governance. Co-ordination arrangements are negotiated in different types of governance bodies at the strategic and operational level, as well as at the level of the overall initiative or specific mission.
3. *Policy implementation*: MOIPs are implemented through a comprehensive mix of policy interventions and various initiatives to support a range of activities (from research to market launch and the acquisition of required skills) deliberately designed to achieve their objectives. For the most part, these policies do not substitute, but rather build upon and co-ordinate pre-existing policy interventions to tackle a specific challenge.

All national innovation systems include many components that perform various functions pertaining to these three dimensions (e.g. a hydrogen strategy, a cross-ministerial committee and a collaborative programme). The main novelty of the MOIP approach resides in the proactive and intentional integration of these components within a dedicated common institutional framework to tackle a selected challenge. Concretely, a MOIP is a "platform for collective actions" that articulates, for each selected challenge, a collectively developed agenda; a dedicated structure of governance for taking (and monitoring the effects of) common or mutually consistent decisions; and a tailor-made, integrated policy mix (Figure 5.3).

Figure 5.3. MOIPs as an integrated framework to steer, co-ordinate and implement collective action toward net-zero



Can MOIPs help countries implement the sociotechnical changes needed to transition towards net-zero?

MOIPs are reaching a critical pivotal time. While most of these policies are still at an early stage, there already exists strong political demand to demonstrate results, not only because these initiatives are more visible, but also because they have raised high expectations and sometimes have larger budgets. However, knowledge about the extent, the means and the conditions under which MOIPs produce the expected impacts is still limited.

Although it is impossible to assess the effects of initiatives that established a goal for 2030 or beyond and have been in existence for only two or three years, a first step is to validate the policy approach itself: to what extent – and why – is a MOIP approach justified in comparison to existing strategic and policy frameworks? In other words, legitimising the adoption of a MOIP approach requires capturing the benefits of their systemic dimension to orient and co-ordinate plans, and take action.

A theory of change of net-zero missions has been developed to this end that sets out the causal relationship between net-zero missions and their expected outputs, outcomes and impacts (Box 5.1 and Figure 5.4). This theory is used to analyse the database of 83 net-zero missions and 20 in-depth case studies[2]. It also structures this chapter, providing insights on the contribution of net-zero missions to three expected outputs, followed by three expected outcomes[3]. The chapter concludes by highlighting two traps that net-zero missions will need to overcome if they are to fulfil their promise.

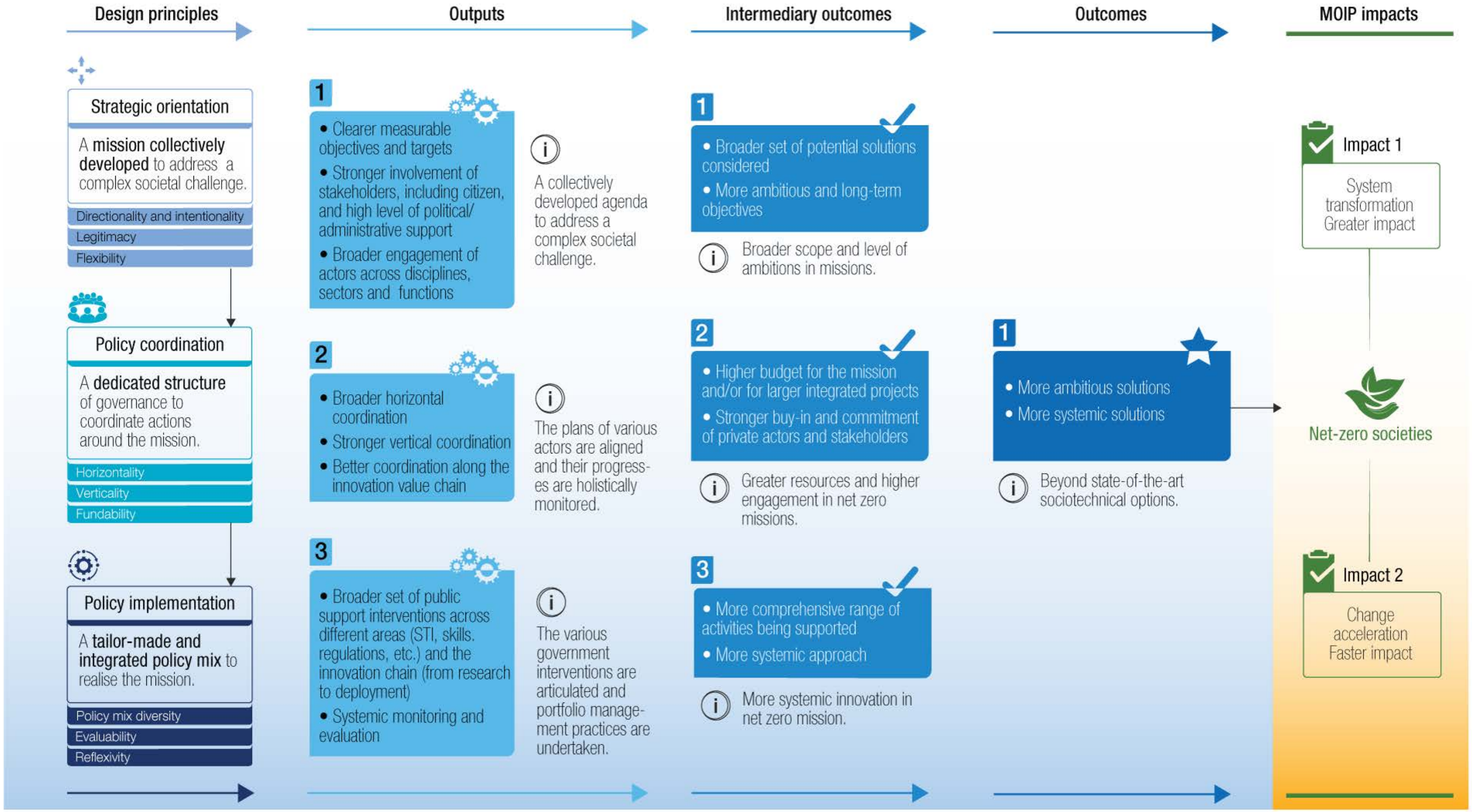
Box 5.1. A theory of change of net-zero missions

The OECD has studied and categorised the different designs of MOIPs, as well as analysing and benchmarking their main processes through cases studies (Larrue, 2021[15])[4]. However, there exist almost no evaluations of these policies that could provide evidence of whether they meet their ambitious objectives. Building upon previous work on MOIP design, it is necessary to develop a "theory of change" for MOIPs that will surface the causal relationships between the problems they tackle and their desired goals, inputs, outputs, outcomes and impacts (Janssen et al., 2021[16]), (Hekkert et al., 2020[17]). In its most general understanding, a theory of change is a set of beliefs about how change happens (Church and Rogers, 2006[18]).

In the case of MOIPs, the theory of change seeks to capture their *additional* effects on top of those produced by existing fragmented policy instruments, as they build upon and integrate existing policies. The legitimacy of this policy approach, therefore, depends on successfully passing a stringent double test: not only must they accomplish their missions, but they should do so more effectively and more efficiently than would have been the case without them, or they should fulfil missions that are beyond the reach of traditional approaches.

The net-zero theory of change (Figure 5.4) describes how MOIPs are expected to produce their impacts, in direct relation to their characteristics. It starts with the MOIP "design principles" as formalised in previous OECD work (Larrue, 2021[15]) and presents the expected causal relationships to outputs (i.e. the previously mentioned collectively developed agenda, dedicated governance structure and integrated policy mix), outcomes and intended impacts. Building on the distinction between acceleration and transformative missions (Kuittinen, Polt and Weber, 2018[19]), it is possible to distinguish two main types of impact – system transformation and change acceleration..

Figure 5.4. The theory of change of a net-zero mission: From MOIP design principles to net-zero achievements



What are the outputs of net-zero missions?

In direct relation to their design principles, MOIPs are expected to deliver three policy outputs: a collectively developed strategic agenda, a dedicated governance structure to co-ordinate actions towards this agenda, and a consistent package of policy and regulatory interventions to implement the mission. This section questions each of these outputs successively. Table 5.2 summarises the results of these missions.

Table 5.2. Synthesis of the main outputs of net-zero missions

Outputs

Net-zero mission effects	Main results
A) Collective development of a strategic agenda to address a complex societal challenge	
Clearer measurable objectives and targets	Missions have enabled clearer goals to be set than in traditional programmes, although few correspond to the expected "SMART" goals. Only half of these goals have clear targets. Strategic agendas allow "continuous directionality" and complement mission objectives in a context of high uncertainty and contestation. In stark contrast with traditional strategies and roadmaps, strategic agendas are directly associated with mission budgets, co-ordination structures and modes of implementation, increasing their influence on interventions.
Higher level of political/administrative support	Missions are political by nature, owing to normative goals related to societal impacts. Broad national missions attract more attention from politicians and high-level administrative levels, which strengthens their legitimacy but can add pressure to obtain early results.
Broader engagement of stakeholders	Strategic agendas are developed by a wide range of actors from different communities, increasing their ownership of the mission and subsequent engagement.
B) Alignment and holistic monitoring of various actors' plans	
Broader horizontal co-ordination	Almost all net-zero missions subject to a case study have significantly expanded the scope of co-ordination between different actors across the government structure. Leadership is assumed by the STI authorities that have launched the mission. Cross-sectoral co-ordination is the main challenge of net-zero missions, generating significant transaction costs in the largest and most integrated missions.
Stronger vertical co-ordination	Most net-zero missions are led by national (or EU) authorities; some include local authorities in their governance. Local authorities are involved in many mission activities to enable demonstrating solutions and their early transition to market. A few net-zero missions are implemented at the regional level, particularly in the context of the new generation of EU Smart Specialisation Strategies.
Better public-private co-ordination	Missions complement (and often benefit from) the existing public-private STI concertation platforms. They add a well-targeted purposive framework and ensure a more direct link to policy interventions.
C) Articulation and management of a portfolio of activities	
Broader set of public support interventions across different areas	All net-zero missions are bundled under a common strategic and governance framework featuring different types of interventions, from R&D grants to skill formation or advocacy. Only a few missions include policy instruments that support the market deployment of current or new solutions. Net-zero missions allow co-ordinating public support for different aspects of systemic solutions.
Broader set of public support interventions across the innovation chain	Several net-zero missions map and connect the various support instruments across the different technology readiness levels, with a view to providing more continuous support to different stages of the innovation chain.
Novel systemic monitoring and evaluation approaches	There is a pervasive perception among mission partners that new evaluation methodologies and processes are needed to evaluate this approach, but very few MOIP evaluations have been undertaken to date, and they do not significantly depart from traditional STI policy evaluations.

Develop collective and strategic agendas to address societal challenges

Mission objectives and targets

MOIP objectives can take various forms. In theory and ideally, a mission's objectives are operationalised by measurable targets (Mazzucato, 2018[11]). In practice, only around half (46%) of the net-zero missions identified have set targets. In some cases, targets and objectives can be combined in a "mission statement" encapsulating in a short – and if possible inspirational – formulation an ambitious result to be attained in a precise timeframe. These statements serve as "entry points" and "identifiers" to the mission.

> The Japanese Moonshot Programme has nine Moonshot goals covering various societal challenges. For instance, Moonshot Goal 5 aims for the "creation of industry that enables sustainable global food supply by exploiting unused biological resources by 2050."
>
> In the United States, the Hydrogen Earthshot has formalised its main objective as the "1 1 1" goal, i.e. the objective of "reducing the cost of clean hydrogen by 80% to USD 1 per 1 kilogram in one decade".

Regardless of the form these objectives take, programme managers claim that their missions set clearer and more inclusively developed goals than do the usual programmes and schemes developed by their organisations. In other words, the goals are formulated to be more impactful (i.e. to "deliver" a result), rather than simply focusing on inputs or immediate outputs (i.e. to "do" something). As one programme manager put it, "Usually the goal is to do something, here the goal is to deliver something". Against this backdrop, all activities are geared towards the desired outcomes. Even in the most research-intensive mission, the intended results are the heart of the projects and a cornerstone of research activities. These clearly enunciated objectives also act as a "focusing device" and a reference point for interactions between the different actors all along the innovation chain, and across the various involved communities.

Missions set common objectives in uncertain and contested environments

Setting clear objectives at the outset is not limited to adopting "good project management practices". The goals – and when they exist, the targets that accompany them – enshrine the results of negotiations on the objectives. They also reflect hypotheses regarding the evolution of sometimes uncertain variables (e.g. carbon and energy prices, availability of raw materials, geopolitics, capacity to overcome scientific and technological bottlenecks, evolution of users' perceptions and preferences) that influence these sociotechnical options, and their even more uncertain results on the state of the world. The mission therefore appears as a locus of debates, providing a platform for public-private, cross-ministerial and inter-sectoral negotiations, with direct consequences on public intervention. These debates are essential when it comes to choosing long-term futures that directly affect people's well-being. In this light, focusing only on scientific and technological uncertainties would diminish missions' social and political complexity, and underestimate the underpinning power conflicts and disagreements that are important drivers of their implementation (Wanzenböck et al., 2020[20]). While modern innovation systems offer many instances where these negotiations can take place (such as committees, industrial associations and unions), the specific added value of missions is that they integrate mission orientation, co-ordination and implementation in the same institutional space. The mission formalises and renders directly "actionable" the results of the negotiations. The different actors can directly refer to the ensuing actions to strengthen their positions. And the government can tie its financial commitment to achievement of the mission's objectives, in order to defend choices that incorporate certain social values which may not always be aligned with the individual interests of companies or other stakeholder groups.

The development of objectives requires significant information and knowledge to strengthen their underlying hypotheses. However, some missions do not have a dedicated budget and therefore rely on the capacity and resources of specific actors, potentially reducing the acceptability of the results regarding controversial issues. Furthermore, very few missions use formal foresight approaches to support the formulation of objectives, despite their potential to capture broad sociotechnical issues.[5] In most cases, a mission's strategic agenda is defined using technology road-mapping techniques rather than a full-fledged foresight exercise.[6] This reflects, in part, countries' limited experience of using foresight in policy making. Moreover, foresight exercises take time, and the missions are often under high political pressure to start functioning as soon as possible. Another reason for the limited use of foresight is the narrow techno-centric scope of many net-zero missions.

> It took more than a year for the French authorities to develop the "clean hydrogen Acceleration Strategy". This time was used to conduct preliminary studies to calibrate and strengthen the legitimacy of the targets; run extensive consultations to assess needs; and issue calls for expressions of interest to identify potential solutions and project partners, and negotiate common objectives with them despite a wide diversity of views and interests. As a result, the mission deliberately includes some strong choices that exclude certain options. For example, the strategy focuses only on clean hydrogen for applications where battery storage technologies are ill-suited (hence mainly heavy vehicles), which would be produced with electrolysers plugged into the electricity network. The mission objectives also include clear choices regarding the type, capacity and distance of the electrolysers to the application site.

The mission-oriented strategic agendas and roadmaps act as collective action frameworks

In several cases, the objectives are not the starting point but rather a first result of the mission itself. Many missions start with broad objectives, priorities or "mission areas". The first step of the mission is to develop or refine the objectives, most often embedding them in a strategic agenda or roadmap. The five EU missions,[7] for instance, started with five broad mission areas and a mandate for groups of high-level specialists in each area (the mission boards) to first devise a strategy featuring objectives and targets (the mission board reports) and then a plan (the implementation plans). These loose directional elements do not really aim to set a clear orientation, but rather incentivise and facilitate the formation of large partnerships, wherein public and private actors jointly set attainable objectives and develop the collective strategy to meet them. This is particularly true of ecosystem-based MOIPs, which start with a call for strategic agendas, followed by the selection and implementation of some of these agendas.

A strategic agenda almost always complements a mission's initial objectives and targets to ensure the directionality and consistency of its different activities. These agendas (under different denominations and formats) are key to the expression of top-down and bottom-up dynamics. While governments still play a strong role at the political stage of setting the mission's objectives and targets, it is almost always the stakeholders who develop the strategic agenda which maps the different pathways towards fulfilling these objectives. What differentiates these mission-oriented strategic agendas from traditional strategies is that they are developed, implemented and monitored in an integrated way, allowing the strategic agenda to become the authoritative framework for action. In several missions, some components of the strategic agendas are directly used to develop the call for proposals; they can also be used on a regular basis to monitor progress on the different activities against the roadmap and identify gaps in the mission.

> In the Netherlands, the implementation of the "Carbon-free Built Environment" mission under the Mission-driven Top Sector and Innovation Policy (MTIP) is guided by four multi-annual mission innovation programmes (MMIPs) covering different sub-areas. The MMIPs include not only the activities to be performed but also the map of public financial resources deployed across the entire innovation chain, from fundamental and applied research to pilots and demonstrators. The call for proposals for the implementation of the mission are *directly based on* these MMIPs (some calls include copy-pasted text from the initial mission document). Since all the 25 top sectors' missions have developed such MMIPs, they are also used to identify and strengthen synergies among them.

While strategic agendas are never binding and there is no "stick", peer pressure among the mission partners in the broad governance bodies can exert a significant influence on possible opportunistic behaviours by the different partners.

An underlying condition for the effectiveness and legitimacy of strategic agendas is that they should be both directional and flexible. They must be a “living document” that evolves regularly to adapt to new internal and external conditions. In this regard, some missions, such as the Danish Green Carbon Capture Storage or Utilisation (CCSU) mission or the Japanese Moonshots, have established procedures to revise their strategic agendas every year.

Missions’ net-zero objectives interact with a broader set of objectives

An analysis of the main rationales for net-zero missions shows that the objective of combating climate change is always intertwined with other environmental, economics or health ambitions. This analysis is useful in highlighting how countries frame their arguments for missions, what aspects they showcase as the most important, and what they believe missions can help them achieve.

All net-zero missions aim by definition to tackle climate change by reducing GHG emissions;60% link their aims to wider environmental objectives and 54% to economic impacts (e.g. creating jobs). For instance, Australia’s Commonwealth Scientific and Industrial Research Organisation’s (CSIRO) mission to end plastic waste aims to reinvent the way plastic is made, processed and recycled to stop it from entering the environment. Some missions clearly enshrine the expected economic impacts in their main objectives and targets. Further, while not always officially emphasised, strengthening national competitiveness and creating new jobs always feature among the missions’ rationales.

> The German High-Tech Strategy (HTS) 2025, implemented during the 2017-21 legislative period, aimed to “Make Germany into the leading supplier and market for electromobility” by defining and following concrete missions, particularly the mission to “Develop safe, networked and clean mobility”.
>
> Korea’s mission The Alchemist “Low-cost carbon dioxide (CO_2)-free hydrogen production facilities” aims to “Develop fundamental technologies and processes for mass-producing cost-effective and eco-friendly hydrogen in order to secure the leading position of Korea in global market in hydrogen car production and energy production”.
>
> The first of the six objectives of the French acceleration strategy for industry decarbonisation is to “Ensure the emergence of a competitive French offer of decarbonisation solutions for industry”.

These diverse objectives primarily reflect the multidimensional and systemic nature of societal challenges. They are also related to the mission process itself. To engage a wider range of policy sectors, the initial mission champions have to negotiate the mission objectives, and take onboard new goals and targets. One of the main intrinsic trade-offs of missions is this balancing between ensuring a broad range of partners on one side, and directionality and consistency on the other. Ensuring the effective participation of sectoral ministries and agencies in the mission – not only in terms of time and attention in meetings, but also of financial and technical assistance – requires it to include objectives that are consistent with their mandate. The resulting bargaining between different policy sectors creates a risk of diluting the mission.

A diversity of challenges is also the norm at the level of MOIP initiatives, with around three-quarters of MOIP initiatives combining net-zero missions with missions related to other societal challenges (most often related to health, but also to food security and ageing). The high prevalence of such diversified multi-mission initiatives suggests that policy dynamics – i.e. the desire to explore a new type of policy approach – have a strong influence on the adoption of this policy approach, together with the imperative of tackling climate change and other societal challenges. This is related to the fact that STI authorities – which have a functional, rather than sectoral or thematic, mandate – lead almost all MOIPs.

Align and monitor various actors' plans

Missions gather a broad range of policy sectors around common objectives

It is now well-accepted that complex societal challenges, such as GHG emissions reduction, require broad cross-sectoral co-ordination, a fact that underpins the rationales for adopting a mission-oriented policy approach. Policy fragmentation greatly hinders the capacity of innovation systems to respond adequately to wicked societal challenges, such as those included in the 2030 Agenda for Sustainable Development (OECD, 2019[21]).

Almost all net-zero missions represent a significantly expanded scope of co-ordination between different public policy actors. These missions gather around the table not only the public authorities in charge of research and business innovation, but also some relevant sectoral ministries and agencies. This co-ordination takes place primarily in dedicated governance bodies with various advisory, decision-making or monitoring roles. In the larger mission-oriented policy initiatives, these groups can be replicated at different levels (political, strategic and operational).[8]

> The EU Climate-Neutral and Smart Cities mission (Cities Mission) is led by two high-level managers from the Directorate-General for Environment and the Directorate-General for Research and Innovation. Besides the leadership, several groups and committees – notably the "mission owners groups" at working and director levels – co-ordinate actions between the 12 directorates more or less directly involved in the mission. This is said to have significantly reduced the number of overlaps between different directorates' activities related to cities. The mission's mode of governance is new, as climate neutrality has traditionally been addressed by different parts of the European Commission (transport, energy, urban planning, etc.). The "EU Cities" mission provides a legitimate authority at the systemic level (a "climate neutrality interlocutor"). The mission also supports cross-sectoral co-ordination aspects within each of the selected 100 cities, which are asked to develop and sign a "Climate City Contract" (CCC) between the different city partners. These contracts include an overall net-zero transition plan across all sectors (energy, buildings, waste management and transport), together with related investment plans. This holistic co-ordination is an essential component of the common guidelines and requirements that cities must follow in developing these contracts. The CCCs embed and officialise the systemic dimension for each city participating in the mission.

STI public authorities champion all net-zero missions

STI public authorities in charge of research or business innovation policy have initiated all 30 MOIP initiatives that include net-zero missions. They are undoubtedly "champions" of mission-oriented policies, experimenting and arguing for this new policy approach to tackle societal challenges featuring an unprecedented level of urgency and complexity.

In-depth fieldwork for 20 of those net-zero missions shows that almost all have provided an institutional space and concrete platform for cross-ministerial co-ordination. However, STI public authorities lead the missions, finance them and provide the bulk of policy instruments to implement them. Sectoral ministries and public agencies are "at the mission table", which allows more informed and holistic decisions. To date, however, they have barely committed their own financial resources to the collective endeavour. In other words, while the co-ordination of net-zero missions is broad and extends beyond the public authorities in charge of research and innovation, the missions' budgets remain largely confined to "STI funds".

Cross-sectoral co-ordination faces many costs and challenges

The OECD study shows that cross-sectoral co-ordination is not only one of the main expected added values of MOIPs, but also one of the main practical challenges. This is confirmed by a recent survey of mission practitioners and stakeholders, who rank "silo effects" as the highest risk for a mission's success (OECD and DDC, 2022[22]). This is not new: holistic co-ordination has been acknowledged as a key weakness of national innovation systems, as highlighted in all OECD Reviews of Innovation Policy and confirmed by other types of STI policy assessment at the thematic, regional or initiative levels. Almost all point to the core issue of co-ordination between public authorities in charge of research and those responsible for business innovation. However, the upswing in societal challenges (such as global warming) has broadened the scope of co-ordination to include other sectoral policy and regulatory administrations with closely related mandates (the "challenge owners"). While mission-oriented policy is seen as a possible response to this new imperative, in many countries, it occurs in a context where previous challenges related to the functioning of the innovation system and economic growth remain unresolved.

When fully applied to broad missions, the governance of the mission involves a number of meetings and numerous items that must be collectively decided by a wide set of actors. It is therefore necessary to strike a "sustainable" balance between the benefits of co-ordination on the one hand, and transaction costs on the other. While net-zero missions are almost all very recent, some have already started to readjust this balance. In the Netherlands, the MTIP has been praised for its very comprehensive governance structure, which allows co-ordinating a wide range of actors across 2 main axes (with 9 top sectors and 25 missions) at different levels (high-level/political and operational) in several governance bodies (e.g. mission teams, top sector teams, programme advisory groups to support MMIPs and transversal teams across several missions) (Janssen, 2020[23]). However, several actors involved in this policy have pointed to a growing "mission fatigue" owing to the high number of meetings of these bodies. The policy is now being reformed to simplify this governance structure and increase its efficiency.

As is traditionally the case in cross-sectoral co-ordination, bringing a large set of actors to the negotiation table is only the first challenge. A second challenge is for each representative in mission governance bodies – especially those in "non-core", often sectoral, departments – to engage colleagues in mission activities, share information and possibly commit funding. The mission competes for time and resources in administrations that would not normally be involved in such activities as they are not traditionally considered central to their sectoral mandate. Some of these actors, who act not only as contact points but also as "ambassadors" for the mission within their administration, struggle to engage the leaders of related programmes and activities in the mission, and convince them to commit resources.

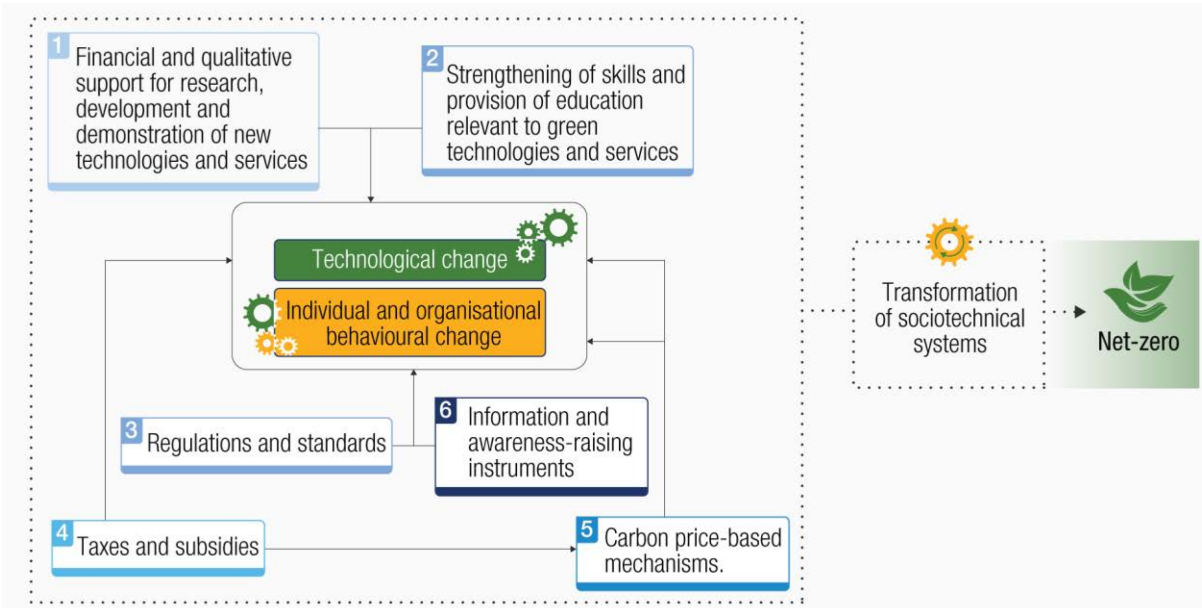
Delivery and management of a portfolio of activities

Different types of public support interventions need to be integrated to fulfil the mission

As outlined in the OECD definition of MOIPs, missions involve a package of policy and regulatory measures (Larrue, 2021[14]). In almost all cases, missions do not create new instruments, but integrate existing ones in a coherent bundle to meet their objectives.

It is widely acknowledged that the societal transformation that conditions the achievement of net-zero will require a combination of different types of interventions for any given sociotechnical option (D'Arcangelo et al., 2022[24]). The different interventions can be categorised under six different types, as shown in Figure 5.5.

Figure 5.5. Different types of public interventions to support the transition towards a net-zero society



Although net-zero missions vary greatly in terms of scale and scope, they always combine several of these intervention types under a common strategic and governance framework. Grants for research and innovation activities remain one of the main policy instruments for channelling mission funding to project partners. They are, however, accompanied by a wealth of other measures designed to support (among others) specific projects, competence or excellence centres, regulatory reforms, competitions and prizes, demonstration sites, training or communication, and awareness-raising activities. For example, the UK industry decarbonisation missions dedicate specific actions to skill strengthening. The Danish CCSU mission performs studies to better understand and shape public acceptance of these technologies. Several missions, such as the Finnish Growth Engine "Green E2", support the emergence of new ecosystems around the mission, which constitute "interest groups" that help promote the necessary regulatory reforms.

An important rationale for integrating complementary instruments is to provide continuous support across the different stages of the innovation chain, from R&D to market deployment. Pilot-E in Norway is one such initiative where the three agencies in charge of research and research-based innovation (Research Council of Norway), innovation and demonstration (Innovation Norway), and early-market deployment of energy technologies (Enova) have teamed up to provide a one-stop-shop for sustainable energy projects, such as green ships (Larrue, 2021[15]).

Although they integrate a wider set of policy instruments, very few missions currently include instruments to support mass deployment of the newly developed solutions. The French clean hydrogen acceleration strategy, for instance, compensates early adopters for the higher price of clean hydrogen. This allow managing and monitoring within a common strategic framework the balance to be struck, and the complementarities to be exploited, between research for new solutions and market introduction of available ones.

Levels of integration vary significantly among missions

An important distinction between missions is not only the range of these instruments but their level of integration, i.e. the extent to which decisions regarding their implementation follow the commonly developed strategic agenda and are collectively monitored. Some missions can be loosely integrated in this respect, with the mission acting as a common heading for all relevant activities falling under its remit. This was the case for the missions of the former German "Hightech" strategies (2009-21), which were categorised as "umbrella missions" by (Wittmann et al., 2021[25]).

MOIPs are generally less integrated at the implementation level than at the orientation and co-ordination levels. In many cases, the funding and implementation of activities belong to specific agencies, which use their own portfolio of instruments in keeping with the orientations and guidance decided at a higher governance level.

What are the outcomes of MOIPs?

MOIPs are expected to build upon their three main outputs discussed above (i.e. strategic agenda, governance structure and policy package) to essentially "aim higher", benefit from more resources and engagement from all partners, and explore more systemic solutions. The extent to which net-zero missions contribute to these three outcomes is assessed in this section and synthetised in Table 5.3.

Table 5.3. Synthesis of the main outcomes of net-zero missions

Outcomes

Net-zero mission effects	Main results
A) Broader scope and level of ambitions in missions	
Broader set of potential solutions considered	The scope of the mission is a matter of important debate to strike a balance between the benefits of 'open' missions (characterised by neutrality and exploration) and more narrowly defined missions (characterised by directionality and integration between different mission activities). Few missions are open, and some are evolving towards more narrowly defined and directional missions.
More ambitious and long-term objectives	Most missions have set objectives geared towards impacts in 2030 and 2050. The differences in different missions' levels of ambition are difficult to assess.
B) Greater resources and higher engagement in net-zero missions	
Higher and longer-term funding	Missions generally benefit from longer-term funding compared to traditional research and innovation schemes. Funding is only informally earmarked for missions in the long run, but public funding announcements tend to generate some pressure for public authorities to commit the promised resources. Net-zero mission budgets mainly originate from STI public authorities. Few sectoral public authorities have committed additional funding to achieve the missions. There is limited financial innovation in leveraging public funding to attract private funding (through blended finance, equity funding, etc.)
Stronger buy-in and commitment of private actors and stakeholders	There is strong engagement of stakeholders in developing the strategic agenda. Insufficient information on private-sector financial contributions to conclude on mission leverage effect.
C) More systemic innovation in net-zero mission	
Better integration of the demand and impact dimensions	Connection to needs and demands is one of the aspects most frequently raised as a novelty of net-zero missions. Net-zero missions provide various means to articulate demands at different stages of the mission life cycle, from mission definition to mission evaluation.
More comprehensive and consistent range of activities	Net-zero missions allow a wider and more consistent range of activities, from basic research to deployment, capacity-building, communication and advocacy. Proactive portfolio management practices in missions are necessary to reap the systemic benefits of missions but require significant resources, new skills, and new rules and procedures in ministries and agencies.

Broader scope and level of ambitions in missions

There exists a need to strike the right balance of openness

The scope of a mission is one of the most difficult factors to comprehend conceptually and handle in practice. One reason for this is the apparent paradox at the core of the mission principle: missions must be open to all solutions for a given objective, but the framing of the objective itself greatly influences the range of potential solutions. The scope of options greatly varies according to the positioning of the mission's objective in the "problem tree", from a totally open mission ("solving climate change") to narrower missions addressing the issue of emissions in certain areas, and even within specific technologies.

In theory, the only specific mission objective that would not restrict the range of potential solutions would be "to achieve net-zero by 2050", without any mention of any sector or technology that might hinder actors from helping to find net-zero solutions within the framework of their own capabilities and experience. Another rationale for mission openness is that a narrow scope can create doubts about the mission's neutrality. When support increasingly targets a more narrowly defined problem, the "level playing field" can be altered (Boon and Edler, 2018[26]).

In practice, several factors conspire against overly "open" missions:

- Relevance: some strategic narrowing-down of the problem allows a better alignment with national priorities (themselves related to international commitments), as well as greater coherence with a country's research and industry systems. While these criteria could, in theory, be integrated ex post when selecting the projects, rather than ex ante when specifying the problem, in practice, this would generate inefficiencies both for the project partners and the policy makers.
- Commensurability: a mission's objective must be aligned with the available national financial resources and capabilities. A small innovation system will struggle to pursue a net-zero mission with the necessary scale and scope to cover several emission sectors (e.g. agriculture, industry and transport). Of course, this does not preclude using more traditional policy instruments to support innovation in emission reduction in other sectors. In most countries, however, the mission approach, which involves significant budgets and transaction costs, will need to be reserved for areas where the problem is particularly acute.
- Consistency of the option portfolio: an overly open mission could result in a set of options that are too dispersed to work synergistically. Reaping the expected benefits of integrated activities within a mission requires some degree of proximity (either through similarities or complementarities) between the different options proposed to solve its objectives.

In practice, "open" missions do exist. For example, the "Towards net-zero" mission of CSIRO in Australia focuses on advancing net-zero technologies to the point of demonstration, without specifying what those technologies should be. What is particularly interesting is that the earliest open missions have already learned from their experience, and are now evolving towards (or will be replaced by) a less open, more strategic definition of their objectives. This is notably the case with the Swedish strategic innovation programmes and "Challenge-driven Innovation" schemes.

Choosing the right scope of missions is, therefore, a matter of striking the right balance. Some pilot "multi-mission MOIPs" have been experimenting with various scopes.

> Science Foundation Ireland (SFI) has debated how to determine the "right" scope for the missions under its new "Challenge Research" programmes. The agency has deliberately launched missions with varying degrees of openness to draw lessons on this key issue. The Zero Emission Challenge, for instance, was very open as it aimed to "Support interdisciplinary teams to develop disruptive solutions that accelerate progress towards net-zero greenhouse gas emissions in Ireland by 2050". It attracted a project to create a carbon-neutral, resilient dairy farm ("Farm Zero C", the winning project at the end of the competition), as well as projects on the recycling of lithium cobalt batteries or new solar panel technologies. Other missions were more narrowly

> defined, such as the Food Challenge or the Plastics Challenge. Some further specifications allowed fine-tuning the degree of openness: the Zero Emission Challenge was open to all solutions to reduce GHG emissions, but a specific "bonus" of EUR 1 million (euros) was announced for projects that would succeed in developing CO_2 removal technologies

Another way in which missions manage their degree of openness is through stage-gate funding and other procedures that take a gradual approach to problem resolution (such as calls for expression of interest). A mission can start with broad objectives to "test" the potential ecosystems and explore different pathways, some of which will be selected and expanded at later stages. In these missions, the more systemic aspects are developed within the projects that make it to the final stage.

Open exploratory research is placed inside or outside missions

The scope of options can vary depending on the types of activities supported within a given mission. Missions often pursue in parallel different generations of technologies to fulfil staged objectives, often related to GHG-reduction commitments for different time horizons (2030 and 2050 in most cases) Mission co-ordinators usually emphasise that they try to remain more open and flexible with regard to the scope of solutions under investigation for future technologies, as they require more exploratory research.

While such an approach can appear to be in line with the "common wisdom" of research management, it has implications for the design of the mission. Since the focused and integrated features of the mission-oriented framework are less suited for exploratory research, then it may be better placed either outside the mission or in a specific sub-programme with its own operating principles and governance, although still directed towards mission goals.[9] In both cases, regardless of whether exploratory research is positioned inside or outside the mission, it is essential to set up institutionalised linkages between these upstream activities and the mission's "core" development, demonstration and deployment activities. Concretely, this involves periodical progress reviews of these activities, and subsequent critical decisions as to which avenues should be terminated, redirected or integrated into the mission plan.

> Within the French Acceleration Strategies, exploratory research is conducted in the Priority Research Programmes and Equipment (PEPRs) which are attached to one or several acceleration strategies to support them. PEPRs function as "upstream sub-programmes", embedded within the acceleration strategies but with their own operating principles, budget and structure of governance. This provides PEPRs with a significant level of freedom to investigate new uncertain basic research avenues that could lead to new solutions to the acceleration strategies' objectives. The PEPR "Support innovation to develop new low-carbon industrial processes", which is attached to the industry decarbonisation acceleration strategy, covers technology-readiness levels 1-4 through breakthrough research on (for instance) the storage and valorisation of CO_2. The PEPR has a budget of EUR 70-80 million out of a total budget of EUR 610 million. The results, and the new information and opportunities originating from the PEPR, are discussed in the context of the mission "Task Force" (the mission's operational governance structure), and therefore in an inter-ministerial setting. This is hardly the case in more traditional programmes, where exploratory research is connected to authorities in charge of R&D, but rarely to other actors located at later stages of the innovation process.

Greater resources and higher engagement in net-zero missions

Missions attract longer-term funding

All missions with formal targets related to GHG reduction targets have set their final mission deadline for 2030 or 2050, in line with their country's international CO_2 reduction commitments. While administrative budgeting processes and political cycles do not allow securing budgets until these deadlines are reached, the analysis of the missions' funding horizon shows that they generally benefit from longer-term funding compared to traditional research and innovation schemes. Among the net-zero missions for which information is available, a majority (61%) are funded for more than four years on average, with 38% of these receiving funding for more than six years. For purposes of comparison, OECD analysis of competitive research-funding schemes shows that the majority of research awards are granted for a period of three to five years, although there are reports of increasing grant durations in more recent funding schemes. Financial support awarded for longer durations (seven years or more) is most often directed at ”excellence centres” with lower application numbers or is associated with institutional funding (OECD, 2018[27]). The comparison with EC-OECD STIP Compass data confirms this result: about 45% of public research grants and 34% of business R&D grants have a funding duration above three years.[10]

Since most funding organisations (ministries, agencies) are still subject to an annual budget cycle, multi-year funding is most often only announced (or in the best case earmarked), but not appropriated. However, even if non-binding, they are announced publicly, and therefore usually represent fairly reliable budget commitments that reduce the level of uncertainty of the partners and stakeholders involved in the mission, allowing them to plan ahead and set more ambitious and long-term objectives. Missions are too recent to allow assessing whether they can withstand several budgetary restrictions, such as those experienced after the 2008 financial crisis. The likely tightening of budgets in coming years, owing to the difficult economic conditions related to the COVID-19 pandemic and Russia’s war against Ukraine, will be their first robustness test.

Most missions’ budgets remain in the range of large-scale climate R&D programmes, but are better integrated

Sixty percent of the mission initiatives assessed in the OECD study had budget information available.[11] The most frequent annual budget ranges were EUR 1-20 million (23 missions, 50%) and EUR 20-200 million (12 missions, 26%).

As for other policies, the diversity in mission budgets owes primarily to overall differences in the size and level of development of country STI budgets. Another important factor in determining budget ranges is the scope of the mission. Large systemic missions, such as those defined in an overarching mission-oriented strategic framework, feature a wide number of programmes that are relevant to the mission. This was the case of the former German HTS mission, “Achieve substantial greenhouse gas neutrality in industry (‘GGNII’)”, which had an annual budget of EUR 6.25 billion. However, the budget figure alone can be somewhat misleading in such cases as the mission’s overall budget is the aggregation of different funding sources, and the influence of these “umbrella programmes” on the different budgets falling under the mission is unclear.

A mission’s budget envelope correlates with its content. Notably, the few missions that also support the market deployment of new solutions generally require far greater budgets than missions focusing on research. As mentioned earlier, this is the case for France’s “clean hydrogen” and “industry decarbonisation” acceleration strategies, whose respective budgets of over EUR 1 billion per year are largely allocated to providing price-based incentives for adopting new (more costly) technologies. On the other end of the spectrum, the Irish “Zero Emissions Challenge” research programme, which aims to include the demand dimension in its research activities but remains focused on R&D, has an annual budget of EUR 1.5 million.

Public funding data are not readily available for comparable initiatives, but comparing selected examples of climate change-related research and innovation “programmes” provides some meaningful orders of magnitude.[12] This comparison shows that (“non-mission-oriented”) thematic programmes in renewable energy, CCSU or sustainable transport technologies have budgets in the EUR 5-100 million range, as it is the case for most missions.

However, here again the comparison should be treated with caution, as some of these programmes might be closer to the level of MOIP initiatives (which often include several missions) than that of individual missions. Annual funding levels of whole MOIP initiatives are actually higher, ranging from EUR 11 million for Pilot-E in Norway to over EUR 1 billion for the UK Industrial Strategy Challenge Fund (EUR 1.3 billion) and the Dutch mission-driven "Topsector" policy (EUR 1.4 billion).[13]

While the comparisons above are imperfect, they tend to suggest that the funding envelopes available to net-zero missions, while significant, remain somewhat in the same order of magnitude as more traditional large climate-related research and innovation programmes.

However, further investigations should also be performed at the level of the projects and activities within missions. It often happens that the financial support provided for given activities or projects is greater than what it is in traditional project funding. For instance, more targeted joint action between the three agencies involved in Norway's Pilot-E scheme makes it possible to fund a smaller number of large consortia. The Dutch MTIP is also one of the very few cases where a specific instrument has been specifically created to complement the mission policy mix. Specifically, the "Mission-oriented research, development and innovation" scheme supports multidisciplinary consortia that undertake projects combining various technological and non-technological sub-solutions, including activities related to their commercialisation and societal acceptance (Janssen, 2020[23]).

Besides funding levels, an important dimension is the nature and composition of mission budgets. Many missions do not have a dedicated budget and are funded by different funding sources. This is confirmed by the survey of mission practitioners and stakeholders performed by the OECD Mission Action Lab and the Danish Design Center (OECD and DDC, 2022[22]). While the bulk of funding comes from national actors, most missions receive funding from multiple sources, showing a "scattered image of funding resources". Furthermore, around one-third of respondents consider that "aligning resources across government or organisations" is the biggest financial challenge, ahead of the mismatch between investment and strategic mission objectives, the lack of risk capital and high-risk, high-reward investments, and the lack of targeted resources.[14] This is especially the case for the larger national missions, despite some notable exceptions.

> The budget of the French clean hydrogen acceleration strategy is an order of magnitude higher than past funding of hydrogen RD&D, notably due to the support provided to market deployment. The increase is from around a few hundred million euros in the last 10 years to over one billion euros per year for the acceleration strategy. Furthermore, during the French "Investments for the Future" programmes (*Programmes d'investissements d'avenir* [PIA]) 1 to 3 (from 2010 to 2020), the budgets used to be integrated by sectors of intervention (e.g. higher education, business innovation, technology transfer) and/or broad sectors (transport, energy). With the adoption of the "acceleration strategies" in the PIA4, the budgets now target each strategy, covering different industries and stages of the innovation chain. This makes it easier to co-ordinate the plans of different actors, mobilising and staging various actions or sectors as required, in accordance with the progress made.

Contrary to what might be expected from experimental and ambitious initiatives, missions have not been supported by financial innovation. To a large extent, funding sources remain traditional, without recourse to equity funding, blended finance or other types of public-private financial partnerships. Innovative public procurement is also seldom used, despite some early prototypes. Attracting funding at the right scale to additionally support the mass deployment of novel solutions will require finding new ways to fund missions at a time when public budgets are under pressure.

The leverage effect of missions will be essential to determine their success

Uncertainty around the unfolding of net-zero pathways, and consequently the development of the mission strategic agenda or roadmap as a "living document" in many missions, requires some degree of financial flexibility. Firm long-term financial commitments from public authorities must be in place, while still preserving a significant margin for changes to adapt to new internal and external developments. However, this can prove difficult due to existing rigid public budgetary and accounting rules. One workaround is to commit a portion of the announced funding and earmark another portion to be awarded under certain conditions, notably the ability to form a wide and solid partnership that gathers the necessary capabilities and resources to meet the mission objectives. A more common solution is to use a gated funding model, where projects must achieve pre-determined assessment milestones to progress to the next phase and receive the associated instalment.

> In the Danish CCSU Innomission, 40% of the budget is not included at the start (compared to 10% usually), but rather earmarked for allocation to the selected partnership over five years. The main condition for the allocation of this funding is the proven ability of the partnership to attract new relevant activities and partners. To do this, the partnership may need to face administrative and legal issues.

Mission funding should therefore be considered from a dynamic perspective. Ultimately, a mission's success depends on the funding it is able to attract, using the governance and policy frameworks it has built with its initial budget: some mission managers view the initial budget of their missions, in almost all cases originating from the leading STI authorities, as "seed money". Given the transformational objectives of net-zero missions, the finance needed to scale up the sociotechnical solutions that have been developed are vastly higher than their endowment at the outset. Some missions have invested in developing a "map" of potential funding sources that could be mobilised as the mission's strategic agenda unfolds. To date, however, few missions have been able to secure significant financial commitments beyond the initial STI funding. The EU "Climate-neutral and smart cities" mission has set up an innovative procedure to label cities that comply with some criteria established collectively in order to ease their access to complementary funding.

> The initial EU Cities mission budget (EUR 360 million over 2021-23) originates only from Horizon Europe. To date, no other directorates have committed or even earmarked funds for the mission. This initial budget is mainly dedicated to setting up the overall framework for developing and normalising the process to be followed by the 100 participating cities to become "smart and climate-neutral", and supporting the cities in implementing this process through the Mission Platform. The platform provides participating cities with the necessary expertise and assistance for developing and implementing their CCCs, as well as financial and technical advisory services to develop a tailor-made investment plan to access public and private funding. A key component of the mission's leverage effect consists in awarding a "Mission label" to selected cities that have signed a CCC. This label aims to "unlock synergies with other programmes" by facilitating the creation of targeted funding opportunities in other EU funding programmes (not least the European Investment Bank and the European Regional Development Fund). Cities are invited to refer explicitly to their mission label in their award procedures (calls for proposals, prizes, etc.). It is also expected that in the second phase of the mission starting in 2023, when the vast majority of CCCs are in place, linkages will be established to calls for proposals under other EU funding programmes. Labelled cities could receive privileged access to some relevant EU calls or additional "points" in the award criteria under these calls' evaluation process. The Council of the European Union, in its "Conclusions on European missions" adopted in June 2022, proposed that this labelling procedure be used for other EU missions in the context of calls for proposal outside Horizon Europe, in order "to facilitate the construction of missions' portfolios, to increase the visibility of the related initiatives and to gather their results" *(Council of the European Union, 2022[28])*.

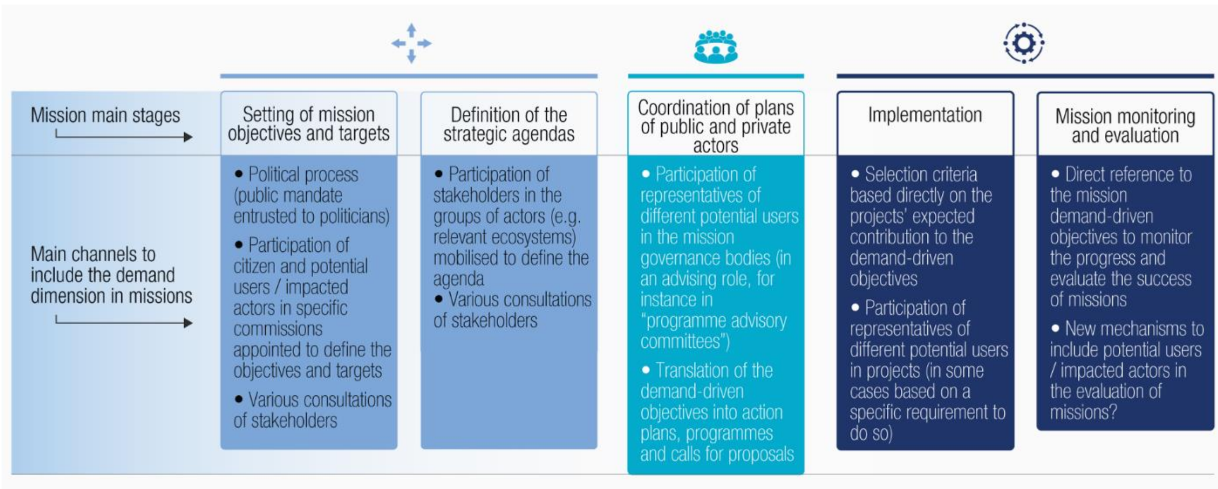
More systemic innovation in net-zero missions

Needs and demands are articulated throughout the mission's life cycle

Although different types of STI policies have made progress in the way they identify the needs and demands to be addressed, and how they use these to calibrate their objectives and design, the demand conditions are still not given full consideration when designing the policies to support missions (Boon and Edler, 2018[26]). The systematic review of net-zero missions in this chapter draws a less negative picture of missions. It finds that in many cases, the missions tend to be effective platforms for demand articulation in the specific context of systemic and complex societal challenges.

The mission's demand-driven nature is one of the aspects most frequently highlighted as a novelty of the mission-oriented policy approach. There exist various means to articulate demands in missions at different stages of their life cycle, from mission definition to mission evaluation (Figure 5.6).

Figure 5.6. Integration of the demand dimension in net-zero missions at different stages of the mission lifecycle



During their early stages of definition, missions use different ways (e.g. consultation workshops and platforms, committees and studies) to determine and integrate the interests of society and various stakeholders' views.[15] Through these various channels, the demand and use dimensions are embedded by design in mission objectives and targets. While the mission targets can be sometimes politically driven (as for the 25 missions of the Dutch MTIP), in many missions, the development of the strategic agendas is the main channel for integrating the demand and use dimensions. This is especially true for ecosystem-based MOIPs. In these initiatives, large communities of actors coalesce to develop an agenda that is consensual enough to reconcile the interests of the broadest part of the ecosystem, and ambitious enough to maximise the chances to be selected by public authorities for implementation.

The governance of the mission can also serve as a channel to connect more continuously to the potential user community and various interest parties. Although these co-ordination structures most often involve representatives from various public authorities, the presence of sectoral ministries or agencies can help integrate the use dimension in missions. Again, ecosystem-based MOIPs are an exception, as their governance structure features large representation from the ecosystem itself. Some of the largest overarching mission schemes can also have a dedicated advisory body, comprising stakeholders and experts with strong consultation mandates.

During the course of implementation, some missions – even the most research-intensive – have integrated policy support into the upstream and downstream stages of the innovation chain at the project level.

> In the Irish net-zero mission ("Challenge Research" programme), project applicants are strongly encouraged to include users in the proposal. While this is not compulsory, it is clearly recommended. Even during the so-called "seed phase" (first phase in the programme's stage-gate funding), SFI promotes interactions between the "challenge teams" and potential "solution beneficiaries" so that they can test whether their ambitions are realistic, and also navigate non-technical issues relating to challenges (e.g. stakeholder engagement) and solutions (e.g. barrier identification). A "societal impact champion" is nominated for each project, to provide a strong societal perspective for team members as they develop their solution, and build relationships between scientific researchers and their stakeholders and beneficiaries.

> In addition, SFI strives to identify and map the “impact actors” related (in a broad sense) to the various applications and use of the technologies being developed, and support connections between the researchers involved in the mission and these organisations. SFI strongly encourages the mission teams to engage with these actors so that they better understand the challenges and start building connections. This has a significant acceleration effect, bringing projects closer to the market and impact. SFI also organises “meet and greet” events with investors, to familiarise researchers with their way of thinking.

Missions support a more comprehensive and consistent range of activities

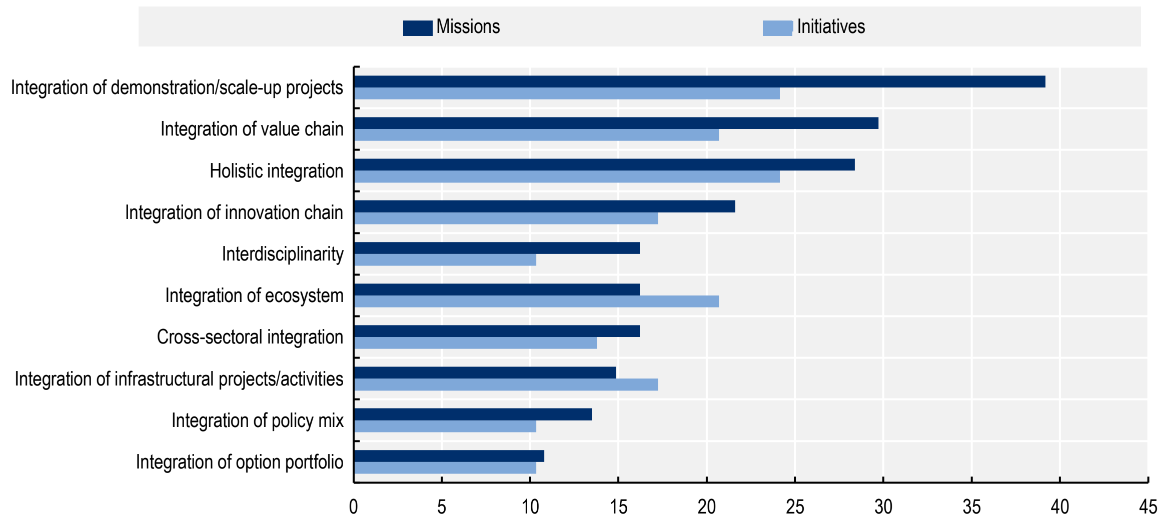
Depending on a mission’s objectives, its tailor-made policy mix supports a wide range of activities, from basic research to deployment, capacity-building, communication and advocacy. However, the added value of the mission approach does not only reside in the diversity of activities it covers, as more traditional initiatives like large-scale programmes or clusters may also cover a wide spectrum of activities. Rather, the mission enables greater consistency in the pool of projects geared towards achieving its objectives and often guided by a specific strategic agenda.

> The Atmosphere and Climate Competence Centre (ACCC) is a Finnish flagship programme that aims to mitigate climate change by increasing forest and soil carbon sequestration, and improve global air quality. The ACCC consortium brings together three universities and one research institute, and over 40 key stakeholders. The mission sustains a diverse array of activities, which run the gamut from education, research and impact programmes, to engagement and citizen science, and solution development and prototyping. Among these activities, the Verified Climate Safety initiative verifies climate neutrality based on observation systems; the GlobalSMEAR initiative integrates 1 000 atmospheric-earth system stations to provide data from various ecosystems around the world; the Citizen Science Initiative allows the general public to contribute to problem definition, data collection and analysis in climate science; the Initiative for “Safer Climate” works at the intersection between civil society, academia and art; the Climate University develops climate change and sustainability education in higher education; and ACCC Impact Week promotes dialogue between earth system scientists and society stakeholders interested in the co-creation of science-based solutions for climate change and air quality.

Most (if not all) net-zero missions illustrate the additionality of the mission approach, compared to traditionally more fragmented policies, when it comes to designing and directing a consistent pool of activities towards a shared goal. It is therefore worth delving further into the subject and attempting to debunk this notion of portfolio consistency and determine what type of complementarities are expected in the various missions. Figure 5.7 provides such an analysis, using an ad hoc typology of the announced rationales for integrating activities within missions.

Figure 5.7. Breakdown of net-zero MOIP initiatives and missions by scope of integration

In percentage of MOIP initiatives and missions



Note: MOIP initiatives are the overarching MOIP frameworks that "host" the missions. For instance, the Dutch "Mission-driven Topsectors" programme has 25 missions, while the United States Department of Energy has launched 6 Energy Earthshots.
Source: Authors' own calculations based on authors' desk reviews.

StatLink https://stat.link/idze6x

First, around 40% of the missions included in the OECD study also target demonstration and market deployment phases. This shows that the net-zero missions' scope extends beyond R&D and seeks to better bridge the demonstration or scale-up stages, ensuring continuity. Second, almost 30% of missions aspire to connect together different segments of the value chain. Third, the most frequent type of integration in net-zero missions is "holistic integration" (28%). As already noted, missions introduce in a systemic way various forms of activities into their remit by including social, legal, behavioural and educational aspects.

Some net-zero missions add new formal criteria to traditional criteria for selecting activities (e.g. team excellence, relevance and experience) in order to capture each project's expected contribution to the mission's objectives. However, this new approach is still in its infancy, and there are few precise comparative studies on the different ways of assessing the "fitness" of a mission portfolio within a given project.

> The four EU missions – all of which aim directly or indirectly to reduce GHGs – represent a step change in the way the projects are selected in framework programmes. As stipulated in the Horizon Europe Implementation Strategy *(European Commission, 2020[29])*, mission evaluation modalities will be designed to ensure the selection of a coherent portfolio of projects. The plan is to proceed via two-stage calls, first, by evaluating the intrinsic quality of each individual proposal submitted and second, by identifying high-quality proposals that work together to maximise the expected impact of the portfolio as a whole. The evaluation committees will have more flexibility to adapt to a mission-oriented approach. For instance, Article 26 of the Programme regulation stipulates that the "evaluation committee may rank the proposals having passed the applicable thresholds according to their contribution to the achievement of specific policy objectives, and may also propose any substantial adjustments to the proposals in as far as needed for the consistency of the portfolio". Actions are also encouraged before a call (e.g. using an expression of interest mechanism) to support the building of a consistent portfolio. Another novelty is the tailor-made approach for selecting projects, which will vary from mission to mission to take into account each mission's inherent characteristics.

Missions encourage hands-on portfolio management

The implementation of such portfolio approaches calls for a change in established practices, not only to select projects according to mission objectives and strategic agendas, but also to manage the projects and complementary activities more proactively and strategically. These so-called “portfolio management practices” originate from large-scale projects in the public and private sectors (notably in defence and aeronautics), and entered the realm of STI public policies through the DARPA agency and, later on, DARPA-like agencies (Wallace and Rafols, 2015[30]). As documented by a voluminous literature, portfolio management in these agencies is greatly predicated not only on the rare combinations of competencies among the programme staff, but also on the conditions offered to them within their agencies (notably in terms of support resources, empowerment and autonomy) to allow them to perform active project management (Azoulay et al., 2018[31]).

Many MOIP initiatives adopt such proactive and hands-on portfolio management practices and engage in frequent interactions with mission partners, including during the calls for proposals. This is less the case of the ecosystem-based MOIPs, whose success depends more on co-operation among the wide range of ecosystem partners in the framework of a co-developed strategic agenda than on the competencies and prerogatives of a key individual co-ordinating their actions. In these missions, such as the Finnish Growth Engine “Green E2”, significant funding (sometimes the whole budget) is dedicated to supporting the formation and structuring of the ecosystem partnership, and providing resources for its “orchestration”. Similarly, the “Swedish Innovation Platform for Textile Sorting” also dedicates one stage (Stage 2) of a three-step stage-gate funding process to stakeholder collaboration.

While it is difficult to quantify, several mission managers emphasised that proactive portfolio management calls for significantly greater resources than traditional practices. They also mentioned that these practices are often hindered (or in some cases made impossible) by organisational procedures – and in Europe, by R&D state aid rules that require a fair treatment of project applicants to ensure a level playing field among potential beneficiaries.

Conclusions

Applying a theory of change, this chapter has provided the first comprehensive analysis of the additionality of MOIPs in helping countries meet their GHG emission-reduction pledges, building on a purpose-built database and in-depth case studies of net-zero missions. Although further work is needed to finalise the analysis of this rich material, the chapter has identified key strengths and weaknesses, and possible future evolutions of net-zero missions.

Most net-zero missions produce many of their expected results. In most cases, they represent a marked improvement over traditional STI policy mixes. They allow different mixes of – and a stronger focus on – common objectives and strategic agendas, broader co-ordination of policy plans across administrative silos and higher integration of various support instruments across the different stages of the innovation chain. However, these improvements will not be sufficient to scale up and deploy these innovations on a massive scale. Net-zero missions focus on technological innovation. In essence, they remain led by STI authorities, relying almost exclusively on STI policy interventions and budgets. While sectoral policy and regulatory authorities have a hand in the mission structure of governance, and can share information – and to some extent, influence – decisions, they have not yet contributed their own resources and programmes to the mission. To bring about the transformative changes needed to achieve the goal of net-zero (as opposed to simply reducing overlaps and speeding up technological innovation), net-zero missions will require investments of a far greater scale and scope. They will also need to balance, align and accompany the mass deployment of these innovations with solutions to promote social and behavioural changes, which is prerequisite for reducing GHG emissions rapidly and significantly.

The success of net-zero missions will depend on their ability to expand beyond STI programmes and budgets (the “STI-only trap”) and move from co-developed strategic agendas to joined-up action (the “orientation trap”). Encouragingly, recent existing experimental and pilot mission initiatives with significant reflexive activities have already generated important learning, and are starting to move away from these traps.

The MOIP “STI-only trap”

Net-zero missions are broader in scale and scope that traditional programmes, but remain focused on more or less narrowly defined “technological innovation”. While mission managers often claim that social innovation is as important as technological innovation in their mission – and far more prominent than in other STI initiatives – the social components are mainly limited to advocacy, information and communication campaigns, as well as various studies at the individual and societal levels to prepare technology scale-up and market transition. Given the importance of combining both types of innovation, the transformative potential of these missions remains unclear. This is consistent with other studies, such as the study on the missions of the former German HTS 2025 during the 2017-21 legislative period, which showed that stakeholder involvement remained limited in the mission formulation process to traditional research and innovation actors, thus not fully realising its transformative potential (Roth et al., 2022[32]).

Even in the broader and most ambitious missions, a closer scrutiny of leadership and financial commitments shows that in practice, they are also funded strictly with “STI money” and pertain to programmes with an STI mandate. For instance, the EU “Soil” mission plans to focus its actions on specific communities, including land managers, citizens, consumers and companies (European Commission, 2021[33]). Stakeholders need to be mobilised far beyond the scope of STI, which raises the question of whether the Horizon Europe research and innovation framework programme is the best location to “host” such ambitious objectives. At the EU level as well as in countries, the funding of activities “beyond STI but with STI money” has already generated some concerns among researchers who usually benefit from these programmes.

These observations raise the question of where missions aiming to transform sociotechnical systems to achieve net-zero should be anchored in government structures. The three main options are STI public authorities (research and/or innovation), “challenge owners” (sectoral authorities) or centre-of-government (president, prime minister or cabinet offices). Although this does not apply to all national institutional settings, positioning the MOIP leadership “above ministries” seems relevant, to raise their level of ambition and broaden their systemic scope beyond STI authorities. This option is also more compatible with integrated multi-year budgets originating from different sources (including centralised budgets and “common pots”) across policy fields. It is also important to strengthen high-level political buy-in and citizen ownership of ambitious net-zero missions. A few countries with longer experience of this policy approach – such as Sweden, where missions lie within the research and innovation agencies – have tried to “elevate” missions to a higher and broader level of governance, although with mixed results. The French missions (the acceleration strategies), which are led by an autonomous agency attached to the prime minister’s office, with strong support from the president and a dedicated budget covering a broad systemic portfolio of actions over different generations of sociotechnical solutions, offer a different model of institutionalised missions. Countries have not yet been sufficiently innovative in institutionalising missions. Novel options to steer, govern and possibly manage large systemic missions still need to be designed and experimented on different levels across government structures. Options include a dedicated agency linked to several ministries, a large public-private partnerships/platform or an autonomous organisation with foundation status.

The MOIP "orientation trap"

Most missions have been successful at setting legitimate and powerful objectives and targets, as well as a widely shared systemic strategic agenda to fulfil their objectives. Each mission has set up dedicated holistic governance structures, under which a range of policy makers from different sectors align their plans and monitor their actions against the mission's strategic agenda. However, whether the strategic agenda actually influences collective decision-making on budget allocation and policy implementation is less clear.

In ecosystem-based missions, which are less directional and empower partners to define their own agendas, a significant share of resources are dedicated to forming the ecosystem and various partnerships by supporting networking, co-ordination and orchestration. Nevertheless, the large financial resources necessary for R&D, and especially scale-up and market take-up, are provided through traditional instruments that sometimes fall outside the sphere of the mission's holistic decision-making and influence. In the large national missions, the link to implementation can also be lessened, due to loose co-ordination in expansive and diluted "umbrella" missions.

Beyond the issue of missions' influence on public policies, their implementation will depend on their ability to mobilise the private sector, which will need to provide huge resources to fund and engage as a key change agent in sustainability transitions. While policy makers and analysts in this phase still focus on public funding and cross-ministerial co-ordination, the ultimate test of missions will be whether they can garner contributions and financial commitments from private businesses and investors. Thus, missions also need to innovate in the way they are funded. Innovative financial models for missions, including public-private partnerships, blended finance options and equity financing, should be investigated and tested to increase and broaden the scope of funding. These new financial models would be combined with new targeted policy instruments and comprehensive funds for solution scale-up and market deployment.

Learning by mission orientation

MOIPs are still in their infancy and limited in number. Among the MOIPs that have been identified in the climate change area, an overwhelming majority were launched between 2018 and 2020. Furthermore, 'early' MOIPs, which were developed even before the policy concept itself gained salience, are not only less numerous but also more remote from the 'ideal' MOIP type.

These often experimental and pilot initiatives with significant reflexive activities have already generated important learning, and continue to evolve. In Germany, the missions of the former HTS 2025, which were criticised for their weak directionality and loose co-ordination, will be followed by the 'Future research and innovation strategy'. This new strategy will feature dedicated governance structures which will materialise the mission-specific goals, establish milestones and assess their achievement through continuous monitoring, as requested by the advisory High-Tech Forum prior to its dissolution. In Austria, the mission-oriented thematic programmes "Building of tomorrow", "Mobility of the Future" and "City of Tomorrow" will be taken over by (or embedded within) four national directional and cross-ministerial missions. In Ireland, the SFI Challenge Research programmes will benefit from the funding and institutional dynamics of the Irish Recovery and Resilience Plan, expanding and "deepening" their mission-oriented approach within the newly created "National Challenge Fund". The latter will be characterised by greater directionality to allow a more consistent and interrelated project portfolio. The Dutch mission-driven "Top Sector" policy will also be improved to render it more strategic and efficient.

These are only a few initiatives, and more work remains to be done to make missions "fit" to support the transition to net-zero. This process will require significant monitoring and evaluation frameworks to develop adequate methodologies and processes that can not only assess their results, but also capture the added value and weaknesses of their mission-oriented features.

Transitioning missions to their next stage in order to escape the "STI-only" and "orientation" traps mentioned above will also depend on making changes to their underpinning environment. Missions often "stall" not because they are ill-designed, but because they come up against ministries' and agencies' mandates, administrative and legal rules, accounting structures and governance models that cannot easily adapt to the mission approach (Aagaard, Norn and Stage, 2022[34]). Changes at this level are far beyond the reach of STI authorities alone, and will require significant political support and active engagement. There is also a need to make relevant changes within the public administrations themselves, such as adapting incentive structures, procedural rules and practices (e.g. rules governing calls for proposal, selection criteria, project management and reporting) to the requirements of missions, and strengthening the relevant resources and skills (e.g. portfolio management).

Finally, future evaluations of MOIPs related to climate change (and other areas) should investigate and incorporate the system-level benefits provided by missions. Some of the new practices and mindsets generated by the adoption of a mission-oriented policy approach have structural effects at a higher level. In Norway, for instance, the positive experience of cross-agency co-operation in Pilot-E and other "Pilot X" schemes has paved the way for two types of initiatives. First, the revised STI national strategic framework now includes two new high-level and systemic missions (Larrue and Santos, 2022[35]). Second, the four main agencies involved in supporting research and innovation activities have reached a broader co-operative agreement.

References

Aagaard, K., M. Norn and A. Stage (2022), "How mission-driven policies challenge traditional research funding systems", *F1000Research*, Vol. 11, p. 949, https://doi.org/10.12688/f1000research.123367.1. [34]

Azoulay, P. et al. (2018), *Age and High-Growth Entrepreneurship*, National Bureau of Economic Research, Cambridge, MA, https://doi.org/10.3386/w24489. [31]

Boon, W. and J. Edler (2018), "Demand, challenges, and innovation. Making sense of new trends in innovation policy", *Science and Public Policy*, Vol. 45/4, pp. 435-447, https://doi.org/10.1093/scipol/scy014. [26]

Channell, D. (1999), "Pasteur's Quadrant: Basic Science and Technological Innovation", *Technology and Culture*, Vol. 40/2, pp. 390-392, https://doi.org/10.1353/tech.1999.0093. [38]

Church, C. and M. Rogers (2006), *Designing for Results: Integrating Monitoring and Evaluation in Conflict Transformation Programs*, Search for Common Ground, https://www.sfcg.org/Documents/manualpart1.pdf (accessed on 6 March 2023). [18]

Council of the European Union (2022), *Council conclusions on European Missions*, https://www.consilium.europa.eu/media/56954/st10124-en22.pdf (accessed on 6 March 2023). [28]

Criscuolo, C., A. Dechezleprêtre and M. Cervantes (2023), "Driving low-carbon innovations for climate neutrality", *OECD Science, Technology and Industry Policy Papers*, No. 143, OECD Publishing, Paris, https://doi.org/10.1787/8e6ae16b-en. [4]

Criscuolo, C., A. Dechezleprêtre and M. Cervantes (2022), *Driving low-carbon innovations for climate neutrality*, https://doi.org/10.1787/8e6ae16b-en. [7]

D'Arcangelo, F. et al. (2022), "A framework to decarbonise the economy", *OECD Economic Policy Papers*, No. 31, OECD Publishing, Paris, https://doi.org/10.1787/4e4d973d-en. [24]

European Commission (2021), *EU Mission Soil Deal for Europe: Implementation plan*, https://research-and-innovation.ec.europa.eu/system/files/2021-09/soil_mission_implementation_plan_final_for_publication.pdf (accessed on 6 March 2023). [33]

European Commission (2021), "Foresight in support of the EU Missions", *Directorate-General for Research and Innovation*, https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/foresight-support-eu-missions-2021-10-21_en (accessed on 6 March 2023). [36]

European Commission (2020), "Implementation Strategy for Horizon Europe Version 1.0", https://www.radionet-org.eu/radionet/implementation-strategy-for-horizon-europe-version-1-0-published/ (accessed on 6 March 2023). [29]

Hekkert, M. et al. (2020), "Mission-oriented innovation systems", *Environmental Innovation and Societal Transitions*, Vol. 34, pp. 76-79, https://doi.org/10.1016/j.eist.2019.11.011. [17]

Hynes, W., M. Lees and J. Müller (eds.) (2020), *Systemic Thinking for Policy Making: The Potential of Systems Analysis for Addressing Global Policy Challenges in the 21st Century*, New Approaches to Economic Challenges, OECD Publishing, Paris, https://doi.org/10.1787/879c4f7a-en. [13]

IEA (2022), *Energy Technology RD&D Budgets*, https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2 (accessed on 6 March 2023). [6]

IEA (2022), *Net Zero by 2050: The need for net zero demonstration projects*, https://iea.blob.core.windows.net/assets/76426d5e-0c9c-4f9f-809f-feca6bde702e/Theneedfornetzerodemonstrationprojects.pdf (accessed on 26 February 2023). [10]

IPCC (2022), *Climate Change 2022: Mitigation of Climate Change*, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf (accessed on 5 March 2023). [1]

IPCC (2022), *Summary for Policymakers*, Cambridge University Press, https://doi.org/10.1017/9781009157940.001. [9]

Janssen, M. (2020), "Post-commencement analysis of the Dutch 'Mission-oriented Topsector and Innovation Policy' strategy", Utrecht University, https://www.uu.nl/sites/default/files/Post-commencement%20analysis%20of%20the%20Dutch%20Mission-oriented%20Topsector%20and%20Innovation%20Policy.pdf (accessed on 6 March 2023). [23]

Janssen, M. et al. (2021), "The promises and premises of mission-oriented innovation policy—A reflection and ways forward", *Science and Public Policy*, https://doi.org/10.1093/scipol/scaa072. [16]

Jeudy-Hugo, S., L. Lo Re and C. Falduto (2021), "Understanding countries' net-zero emissions targets", *OECD/IEA Climate Change Expert Group Papers*, No. 2021/03, OECD Publishing, Paris, https://doi.org/10.1787/8d25a20c-en. [2]

Kruse, T. et al. (2022), "Measuring environmental policy stringency in OECD countries: An update of the OECD composite EPS indicator", *OECD Economics Department Working Papers*, No. 1703, OECD Publishing, Paris, https://doi.org/10.1787/90ab82e8-en. [5]

Kuittinen, H., W. Polt and M. Weber (2018), "Mission Europe? A revival of mission-oriented policy in the EU", *in RFTE (ed.), RE:thinking Europe*, No. September 2018, pp. 191-207, https://www.researchgate.net/publication/334446593_KUITTINEN_H_POLT_W_WEBER_KM_2018_Mission_Europe_A_revival_of_mission-oriented_policy_in_the_European_Union_In_RFTE_-_Council_for_Research_and_Technology_Development_Ed_RETHINKING_EUROPE_Positions_on_S (accessed on 6 March 2023). [19]

Larrue, P. (2021), "Mission-oriented innovation policy in Norway: Challenges, opportunities and future options", *OECD Science, Technology and Industry Policy Papers*, No. 104, OECD Publishing, Paris, https://doi.org/10.1787/2e7c30ff-en. [15]

Larrue, P. (2021), "The design and implementation of mission-oriented innovation policies: A new systemic policy approach to address societal challenges", *OECD Science, Technology and Industry Policy Papers*, No. 100, OECD Publishing, Paris, https://doi.org/10.1787/3f6c76a4-en. [14]

Larrue, P. and R. Santos (2022), "Towards a new stage in Norway's science, technology and innovation system: Improving the long-term plan for research and higher education", *OECD Science, Technology and Industry Policy Papers*, No. 133, OECD Publishing, Paris, https://doi.org/10.1787/ce07b7c3-en. [35]

Lebling, K. et al. (2020), “State of Climate Action: Assessing Progress toward 2030 and 2050”, *World Resources Institute*, https://doi.org/10.46830/wrirpt.20.00001. [3]

Mazzucato, M. (2018), “Mission-oriented innovation policies: challenges and opportunities”, *Industrial and Corporate Change*, Vol. 27/5, pp. 803-815, https://doi.org/10.1093/icc/dty034. [11]

OECD (2022), *Climate Tipping Points: Insights for Effective Policy Action*, OECD Publishing, Paris, https://doi.org/10.1787/abc5a69e-en. [8]

OECD (2021), *Transport Strategies for Net-Zero Systems by Design*, OECD Publishing, Paris, https://doi.org/10.1787/0a20f779-en. [12]

OECD (2019), *Governance as an SDG Accelerator : Country Experiences and Tools*, OECD Publishing, Paris, https://doi.org/10.1787/0666b085-en. [21]

OECD (2018), “Effective operation of competitive research funding systems”*, OECD Science, Technology and Industry Policy Papers*, No. 57, OECD Publishing, Paris, https://doi.org/10.1787/2ae8c0dc-en. [27]

OECD and DDC (2022), *Mission-oriented innovation needs assessment survey - Highlights & insights on mission work*, https://oecd-opsi.org/wp-content/uploads/2022/02/OECD-DDC_Results-Mission-Needs-Assessment-Survey-2022.pdf (accessed on 6 March 2023). [22]

Pietrobelli, C. and F. Puppato (2016), “Technology foresight and industrial strategy”, *Technological Forecasting and Social Change*, Vol. 110, pp. 117-125, https://doi.org/10.1016/j.techfore.2015.10.021. [37]

Roth, F. et al. (2022), *Putting Mission-Oriented Innovation Policies to Work: A case study of the German High-Tech Strategy 2025*, https://www.researchgate.net/publication/361209236_Putting_Mission-Oriented_Innovation_Policies_to_Work_A_case_study_of_the_German_High-Tech_Strategy_2025 (accessed on 6 March 2023). [32]

Wallace, M. and I. Rafols (2015), “Research Portfolio Analysis in Science Policy: Moving from Financial Returns to Societal Benefits”, *Minerva*, Vol. 53/2, pp. 89-115, https://doi.org/10.1007/s11024-015-9271-8. [30]

Wanzenböck, I. et al. (2020), “A framework for mission-oriented innovation policy: Alternative pathways through the problem–solution space”, *Science and Public Policy*, https://doi.org/10.1093/scipol/scaa027. [20]

Wittmann, F. et al. (2021), “Governing varieties of mission-oriented innovation policies: A new typology”, *Science and Public Policy*, Vol. 48/5, pp. 727-738, https://doi.org/10.1093/scipol/scab044. [25]

Notes

[1] The "Programme d'Investissements d'Avenir" (PIA) is now included in the "France 2030" recovery plan

[2] The list of net-zero missions in the database is available at: https://www.oecd.org/sti/inno/Online%20list%20of%20NZ%20missions.pdf. Synthetic information on each case study is available at: https://www.oecd.org/sti/inno/Online%20list%20of%20NZ%20missions%20case%20studies.pdf.

[3] The format of this chapter provides insufficient space to lay out the whole analysis of the different contribution claims of net-zero missions, and do justice to the rich material collected through desk research and interviews. The chapter focuses on selected components of the theory of change. The full analysis and results will be presented in the forthcoming report.

[4] The strengths and weaknesses of MOIPs by type are presented in detail in (Larrue, 2021[15]) and are summarised in the annex available at https://www.oecd.org/sti/inno/Online%20typology%20of%20MOIPs.pdf.

[5] For instance, the European Commission engaged in a multi-year foresight analysis in five mission areas to strengthen reflexivity in the policy preparation process (European Commission, 2021[36]).

[6] Technological road-mapping is a normative tool that makes detailed projections about future technological developments and their socio-economic impacts. Foresight, on the other hand, is a "systemic" exercise that analyses the long-term impacts of STI developments in order to contribute to "better-informed policy decisions" (Pietrobelli and Puppato, 2016[37]).

[7] "Adaptation to Climate Change": support at least 150 European regions and communities to become climate resilient by 2030; "Cancer": work with Europe's "Beating Cancer Plan" to improve the lives of more than 3 million people by 2030 through prevention, cure and solutions to live longer and better; "Restore our Ocean and Waters by 2030"; "100 Climate-Neutral and Smart Cities by 2030"; "A Soil Deal for Europe: 100 living labs and lighthouses to lead the transition towards healthy soils by 2030".

[8] The different mission co-ordination structures are analysed in (Larrue, 2021[14]).

[9] This type of research is often referred to as "use-inspired basic research" in Stokes' quadrant model of scientific research (Channell, 1999[38]).

[10] Team calculation based on data retrieved on 20 September 2022 for 289 policy instruments with the grant duration question filled in the STIP Compass database, in the same countries with net-zero missions covered in the OECD study (https://stip.oecd.org/stip/).

[11] Not all policies and their respective missions had their budgets readily available. In order to develop a budget range for individual net-zero missions where possible, the individual mission funding was taken either "as is" (if explicitly given) or (if necessary) extracted from the overarching policy initiative, and divided by the years in the mission's individual funding horizon. A simple conversion into euros was then made to ensure that values were comparable across currencies.

[12] Information retrieved on the STIP-Compass Net Zero Portal, an inventory of 289 STI policy initiatives for reaching net-zero (https://stip.oecd.org/stip/net-zero-portal).

[13] Information retrieved on the MOIP Online Toolkit (https://stip.oecd.org/moip/).

[14] 36% of the 131 respondents consider that "aligning resources across government or organisations" is the biggest financial challenge, ahead of the mismatch between investment and strategic mission objectives (34%); the lack of risk capital and high-risk, high-reward investments (31%); or the lack of targeted resources (28%) (OECD and DDC, 2022[22]).

[15] The different means of stakeholder engagement in mission definition were systematically reviewed in the previous OECD MOIP report (Larrue, 2021[14]).

6 Emerging technology governance: Towards an anticipatory framework

Emerging technologies can be pivotal for much needed transformations and responses to crises, but rapid technological change can carry negative consequences and risks for individuals, societies and the environment including social disruption, inequality, and dangers to security and human rights. The democratic community is increasingly asserting that "shared values" of democracy, human rights, sustainability, openness, responsibility, security and resilience should be embedded in technology, but questions remain on how this should be accomplished. Using "upstream" design principles and tools can help balance the need to drive the development of technologies and to scale them up while helping to realise just transitions and values-based technology. This chapter documents and analyses a set of design criteria and tools that could guide this approach to elaborate an anticipatory framework for emerging technology governance.

Key messages

- Emerging technologies are reshaping our societies. While they can be key to much-needed transformations and responses to crises, they also present certain risks and challenges that must be addressed if their potential is to be realised. Faced with this double-edged nature of emerging technology, good technology governance can encourage the best from technology and can help prevent social, economic, and political harms.
- Actors at both the national and international levels are seeking guidance and agreement on how to promote shared values in technology development and make innovation more responsible and responsive to societal needs. A range of anticipatory governance mechanisms present a way forward. Working further upstream in the innovation process, these tend to shift the focus of governance from exclusively managing the risks of technologies to engaging stakeholders – funders, researchers, innovators and civil society – in the innovation process and co-developing adaptive governance solutions. While regulators are a key stakeholder group in emerging technology governance, a whole range of other actors can facilitate responsible innovation.
- Emerging technologies have unique governance needs. However, while there is no one-size-fits-all approach, a general and anticipatory framework for the governance of emerging technologies could be useful at the national or international level. For instance, it could help provide a common language and tools built from experience to help address recurrent policy issues across emerging technologies and ensure wider stakeholder engagement.
- The proposed framework aims to help guide the development of emerging technology governance at both the national and international levels. It consists of a three-tiered structure, comprising (i) values, (ii) design criteria, and (iii) tools. Discussion around the framework may facilitate international technological co-operation in the governance of emerging technologies. Suitable tools are necessary to operationalise design criteria. The chapter discusses a selected tool for each of the three design criteria:
    - *Anticipation through strategic intelligence*. Countries and the international community should assess and enhance their strategic capacity to anticipate technological developments and technology governance needs. They should aim to deepen strategic intelligence on new, emerging and/or key technologies through forward-looking technology assessment (TA). Forward-looking TA both depends on and supports the expression of key values, which underpin the analysis of potential benefits and harms, and the trajectories of emerging technology.
    - *Inclusion and alignment through societal and stakeholder engagement upstream*. Societal and stakeholder engagement can enhance the democratic governance of emerging technology, enabling deliberation on the values that should support and guide technological development. Countries might not only sponsor programmes to advance communication and consideration of emerging technology in public fora, but also build the necessary linkages for exchange and co-development.
    - *Adaptivity through co-development of principles, standards, guidelines, and codes of practice (soft law mechanisms)*. Countries and stakeholders could strengthen professional guidelines, technical and normative standards, codes of conduct and good practices during technological development, to promote an agile and adaptive system of governance.

Introduction

Emerging technologies have a central role to play in our collective future. They will help reshape the infrastructure and capacities of our societies and help drive our economies and our behaviour in new ways. While problems like climate change and global health disparities cannot be solved by technology alone, technology policy can be a pivotal factor in the responsiveness and resilience of our sociotechnical systems in the face of crisis. section

In addition to the great promise of emerging technologies for green transitions and other crucial societal objectives, rapid technological change can carry negative consequences and risks for individuals, societies, and the environment. Relevant threats include social disruption, various kinds of inequity, privacy, and human rights. For example, facial recognition and spyware are becoming a tool in mass surveillance (Ryan-Mosley, 2022[1]), social media is a known vector for the active propagation of misinformation (Matasick, Alfonsi and Bellantoni, 2020[2]), and reported mandatory involvement in genomics research violates human rights standards (Wee, 2021[3]).

Emerging technology also carries major implications for distributive justice, geopolitics, and security. While COVID-19 vaccines have been so critical in alleviating illness in high-income countries, they have reached low- and middle-income countries unevenly. As previous chapters have discussed, calls for technological independence – at best, "technological sovereignty" (Crespi et al., 2021[4]) and at worst, new forms of techno-nationalism (Capri, 2019[5]) – have strained international science and technology co-operation, in the same vein as what might be called a "security turn" in innovation policy (see Chapter 1). The globalisation of emerging technologies has also revealed supply chain vulnerabilities, with implications for economic resilience.

Given the double-edged nature of emerging technology, good technology governance might encourage the greatest societal benefit from technology and help prevent social, economic, and political harms. Technology governance can be defined as "the process of exercising political, economic and administrative authority in the development, diffusion and operation of technology in societies" (OECD, 2018[6]). In the context of emerging technologies, the concept of governance has evolved in response to high uncertainty (Folke et al., 2005[7]), risk (Baldwin and Woodard, 2009[8]), complexity (Hasselman, 2016[9]) and the need for co-operation (Sambuli, 2021[10]). From setting rules on the integrity of science to establishing norms for biosecurity and responsible neurotechnology (OECD, 2019[11]), technology governance provides norms and standards for both the bottom-up research that drives discovery, and the application and use of technologies in society.

Perhaps for these reasons, technology governance has attracted increasing attention at a high political level. In recent years, several international fora have focused on the topic of technology governance, including France's "Technology for Good" initiative (Tech For Good Summit, 2020[12]), the United Kingdom's "Future Tech Forum" under its 2021 Group of Seven Presidency (HM Government, 2022[13]) and the initiative on "Democracy-Affirming Technologies" launched at President Biden's Summit on Democracy (The White House, 2021[14]). At the OECD, the Global Forum on Technology was initiated in 2022 to foster multi-stakeholder collaboration on digital and emerging technology policy (see Box 3.7), and the 2021 Recommendation of the Council for Agile Regulatory Governance to Harness Innovation sets norms for rethinking governance and regulatory policy to better harness the societal impacts of innovation (OECD, 2021[15]). Furthermore, the United States and the United Kingdom recently announced an initiative on "privacy-enhancing" technology (The White House, 2021[16]). In the same vein, the need for "human-centric" artificial intelligence (AI) has become a refrain across the public and private sectors and the subject of an influential soft-law instrument at the OECD (OECD, 2019[17]).

These nascent efforts at international technology governance often frame the challenge as one of better regulation. Although it is no doubt one component of the technology governance challenge, this framing arguably does not address a general and recurring problem across critical and emerging technologies such as AI, robotics and synthetic biology: as their development advances, their impacts on society become more profound, and their effects more entrenched (OECD, 2018[18]). It follows that shaping them, without undue restriction, *during the innovation process* could carry great societal utility.

Efforts to exercise political, economic, or administrative authority during the innovation process might be called “upstream” or “anticipatory technology governance”. Such an approach to governance shifts the locus from exclusively managing the risks of technologies to engaging in the innovation process itself. It aims to anticipate concerns early on, address them through open and inclusive processes, and align the innovation trajectory with societal goals (OECD, 2018[18]). Of course, a balance must be struck between preserving space for serendipitous technology development and shaping technology trajectories through upstream governance.

Actors in the field of international technology governance invoke the need to promote “shared values” – which in the context of these initiatives tend to include the values of democracy, human rights, sustainability, openness, responsibility, security and resilience (e.g. (Council of Europe, 2019[19]) or the (US State Department, 2020[20]). To the extent that it can help embed values within the innovation process itself, the anticipatory approach to technology governance might be better positioned to enact a stated goal of values-affirming technology rather than post-hoc regulatory approaches.

This chapter does not aim to identify the core substantive values that should guide technological development, or to reconcile different positions on them. Instead, it analyses the following question: given that the democratic community is increasingly asserting that values should be embedded in and around technology (e.g., non-discrimination in A.I. algorithms), how should this be accomplished? Governments are increasingly recognising and aiming to address this challenge. All these initiatives are based on an important premise: technology should no longer be viewed as an autonomous agent, but as a system which, through governance, can better serve societal goals and values.

This chapter documents and analyses a set of design criteria and tools that could guide this approach to elaborate an anticipatory framework for emerging technology governance. It is not intended to provide an exhaustive review of design criteria and tools. Rather, it provides a framework for further analytical and normative work, suggesting ideas for the design of good technology governance systems. Figure 6.1 shows this framework, linking values, design criteria, and mechanisms and tools. The chapter explores how actors can implement these design criteria for governance, using policy tools.

An anticipatory policy framework for emerging technology governance

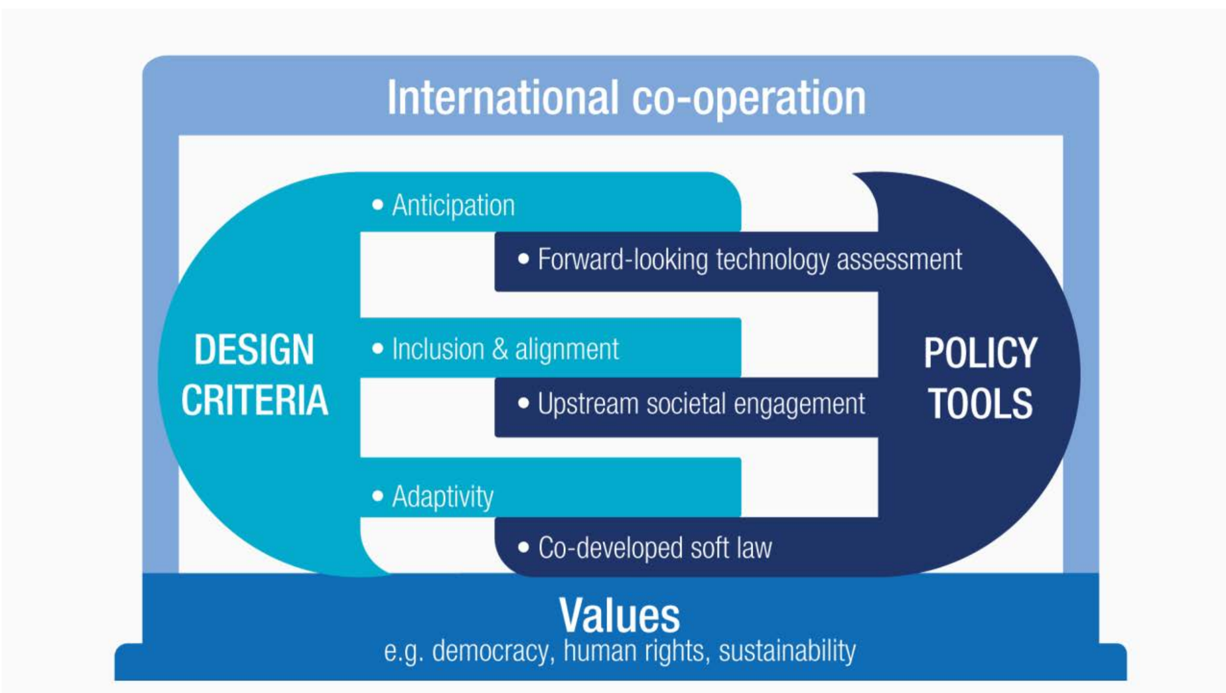
In areas other than science, technology, and innovation (STI), anticipatory governance has emerged as a key challenge for governments as they try to move from a reactive stance towards addressing the complexities and uncertainties of the economic and political present (OECD, 2022[21]). Likewise, actors in the STI system have been laying the groundwork for anticipatory technology governance for some time (Guston, 2013[22]), in part under the banner of responsible research and innovation (von Schomberg, 2013[23]). An important aim of this upstream approach is to align research and development (R&D) of cutting-edge technology with key societal goals, whether related to energy transitions, health systems or mobility. To do so, anticipatory governance aims to identify possible stakeholder concerns and values, address them through open and inclusive processes, and embed shared values in the development of new technologies.

The responsible research and innovation approach argues that embedding responsibility and accountability in the activities of researchers, firms and other actors can help orient new technologies towards meeting grand challenges, rather than just decreasing the likelihood of undesirable effects of technologies (Shelley-Egan et al., 2017[24]; Owen, von Schomberg and Macnaghten, 2021[25]). This is consistent with the turn towards mission-oriented Innovation policy (Larrue, 2021[26]) and is the cornerstone of the Recommendation of the OECD Council on Responsible Innovation in Neurotechnology (OECD, 2019[11]).

Actors in both the public and private sectors are starting to take a more proactive approach to technology governance, engaging in activities like anticipatory agenda-setting, test beds, and value-based design and standardisation as a means of addressing societal goals upstream (OECD, 2018[6]). National actors are beginning to promote a holistic view of the challenges and opportunities inherent to the governance of emerging technologies. They are developing frameworks to address recurring concerns and approaches, thereby facilitating learning across technology areas. The National Academy of Medicine in the United States, for instance, recently published a framework for the governance of emerging medical technologies (Mathews, Balatbat and Dzau, 2022[27]). In addition, regulatory communities have already convened at the OECD with the objective of reforming regulatory governance to better harness innovation (OECD, 2021[15]).

Taken as a whole, recent activities in emerging technology governance can be grouped under a policy framework comprising values, design criteria and tools to putting shared values into practice (see Figure 6.1). These components lay the foundation for discussions on emerging technology governance. Each of these elements is outlined below.

Figure 6.1. Elements of a framework for emerging technology governance



Source: Developed by the authors

Shared values: The foundation of emerging technology governance

Key values orient governance systems, and therefore ground the model. They are not always explicit, and the tools described below may be necessary to surface them. This element answers the question of what is worth ensuring, enabling, and embedding – and why. The (OECD, 2021[28]) has affirmed, among others, democracy, human rights, good governance, security, sustainability, and open markets as shared values. However, it is not the purpose of this chapter to posit particular values for the governance community. This policy framework advances techniques of a *process-based approach*, laying out tangible strategies for promoting values through design criteria and tools at different stages of the innovation process (OECD, 2018[6]). In practice, it sets out what might be considered guidance for responsible innovation and the development of "values-based technology".

Design criteria for emerging technology governance

Design criteria define the generalisable characteristics of good technology governance and responsible innovation. Although this is not a comprehensive list, they should be based on the design criteria of anticipation, inclusivity and alignment, adaptivity and international co-operation.

- **Anticipation**. Technology governance faces a dilemma. Governing emerging technologies too early in the development process could be overly constraining, while governing them later can be expensive or impossible. Navigating the so-called "Collingridge dilemma" (Worthington, 1982[29]) requires a form of governance that operates "upstream" and throughout the process of scientific discovery and innovation. Prediction of a particular technological trajectory is notoriously difficult or even impossible, but exploration of possible technologic developments is necessary and can create policy options.
- **Inclusivity and alignment**. Involving a broad array of stakeholder groups, including actors typically excluded from the innovation process (e.g., small firms, remote regions, and certain social groups, including minorities) is important to *align* science and technology with future user needs and values. Inclusivity encompasses access both to technology itself and to the processes of technology development, where enriching the diversity of participants is linked to the creation of more socially relevant science and technology (OECD, forthcoming[30]). A related point is the need to *include* and *integrate* diverse disciplines and approaches in the R&D process in order to build richer understandings and fit-for-purpose design (Kreiling and Paunov, 2021[31]; Winickoff et al., 2021[32]), (OECD, 2020[33]).
- **Adaptivity.** The pace, scope and complexity of innovation pose significant governance challenges for governments (Marchant and Allenby, 2017[34]) and technology firms. As emerging technologies can have unforeseen consequences, and adverse events or outcomes may occur, the governance system must be adaptive to build resilience and stay relevant – a central tenet of the Recommendation of the Council for Agile Regulatory Governance to Harness Innovation (OECD, 2021[15]). Adaptivity as a design criterion is closely related to anticipation, in that adaptive principles and guidelines might be better suited to the fast pace of technological development.

Tools: Concrete means for action

An array of tools could help realise the above design criteria and embed values in the innovation process (see Figure 6.1). They are the operational element of the framework, the means to take action and govern emerging technologies. The following sections introduce three sets of tools that seek to advance the design criteria: forward-looking technology assessment (TA) promotes anticipation; societal engagement encourages inclusivity and alignment; soft law mechanisms can bolster adaptivity; for international co-operation, all three tools are important. These tools have strong corollaries with known tools for regulators (OECD, 2021[35]), but explicitly seek to engage STI actors – including research funders and agenda setters, researchers and engineers, entrepreneurs and small business, and industry – further upstream, i.e., during the technology development process. Together, these tools constitute a non-exhaustive package of policy interventions to implement anticipation, inclusion and alignment, adaptivity and international co-operation.

The importance of international co-operation

The framework in this chapter (as shown in Figure 6.1) aims to guide both national and international policy makers. The development, use and effects of technologies span national borders. The global scope of technological challenges creates a need for an international approach to the governance of emerging technologies. This scope carries implications for the design of both national and international technology governance systems. For national governments, this means that effective governance will require international policy engagement. This engagement is already a clear policy trend, exemplified by the numerous international activities noted above. International co-operation can grow around shared values, and the sharing of tools and good practices, and these in turn can guide national approaches (see Chapter 2).

Tailor to the case

The treatment of different technologies under such a holistic framework must not be a one-size-fits-all approach. Governance needs for advanced nanomaterials will differ from those relating to new digital platforms or synthetic biology. Indeed, the appropriate approach will depend on the technology's characteristics, such as:

- its level of readiness for commercialisation
- the profile of risks and potential benefits in the short and long term, as viewed by experts and the public
- the nature of local, national, and international matters of concern
- the level of public concern.

Nevertheless, applying a common framework at the national and international levels is important as these emerging technologies share certain characteristics, such as uncertain trajectories and impacts, enabling broad areas of follow-up work, potential issues of public trust and the need for value-based reflection (Mathews, 2017[36]). These common characteristics make common tools – including those that follow – highly relevant.

Anticipation: Building strategic intelligence through technology assessment

The governance of early-stage technologies poses a set of challenges that require forward-looking knowledge and analysis. This strategic intelligence can be defined as usable knowledge that supports policy makers in understanding the impacts of STI and potential future developments. (Kuhlmann, 2002[37]) identified several processes that could provide such "futures intelligence", such as technology assessment (TA), technology foresight, anticipatory impact assessment and formative approaches to evaluation.

Emerging and early-stage technologies not only carry inherent uncertainties and complexities, but there are also situations where their desirability is unclear (e.g., human germline gene editing) because the promised novelty may well transcend existing ethical and political evaluations. The Collingridge dilemma sums up the challenge to find the right *time* to govern technology using dedicated standards, rules, regulations and/or laws. To navigate this dilemma, new kinds of anticipation and strategic intelligence are essential (Robinson et al., 2021[38]).

This section focuses on TA as a source of strategic intelligence. It presents the rationales for TA, the trends shaping TA-based strategic intelligence and concludes with a review of challenges and policy considerations.

Rationales

TA is an evidence-based, interactive process designed to bring to light the societal, economic, environmental, and legal aspects and consequences of new and emerging science and technologies. TA informs public opinion, helps direct R&D, and unpacks the hopes and concerns of various stakeholders at a given point in time to guide governance. Informally, various forms of TA have been in operation since the dawn of science and technology policy. Formally, TA began 50 years ago with the establishment of the Office for Technology Assessment (OTA) within the United States Congress.[1] Its mission was to identify and consider the existing and potential impacts of technologies, and their applications in society. OTA emphasised the need to anticipate the consequences of new technological applications, requiring robust and unbiased information on their societal, political, and economic effects.

Following in the footsteps of OTA, parliamentary TA institutions also emerged in Europe. The Netherlands Organisation for Technology Assessment, for example, was established in 1986 to inform the Dutch Parliament on the developments and potential consequences of new technologies.[2] Parliamentary TA institutions proliferated around the globe throughout the 1990s and 2000s. TA and TA-like processes have diversified with different (or expanded) objectives and are conducted in different situations and settings. One evolution is the expansion from expert-oriented TA activities to more *participatory TA* approaches. Participatory TA acknowledges that technology and society are entwined, further proof that underlying values should be part of the TA process (Delvenne and Rosskamp, 2021[39]).

The main rationales of TA for emerging technology governance can fit into three broad and sometimes overlapping categories.

TA for informing decision makers on key technology trends. One role of TA is as a process of sense-making around emerging technologies, their state-of-the-art and their potential benefits and risks, be they economic, societal, or environmental. When addressing emerging and converging technologies such as synthetic biology, neurotechnology and quantum computing, TA must grapple with high degrees of uncertainty along multiple dimensions. It therefore serves an important function in structuring disparate and unclear information and translating it into usable information that can inform decision-making.

TA for deliberation by gauging stakeholders' hopes and concerns. Some forms of TA, such as participatory TA, brings together different stakeholder groups, which not only stimulates public and political opinion-forming on the societal and ethical aspects of STI, but also helps promote public trust through engagement and inclusion, one of the key design criteria in the framework. Participatory TA approaches are particularly relevant for probing and highlighting hopes and concerns around potentially disruptive and controversial technologies. Here, the inclusion of relevant stakeholders is key not only for providing democratic legitimacy and building trust, but also for deepening knowledge and expertise. Such stakeholders include associations of small and medium-sized enterprises (SME), civil society organisations, non-governmental agencies, trade unions, consumer groups and patient associations. Thus, integrating a variety of stakeholders and insights can help create a form of "distributed intelligence" (Kuhlmann et al., 1999[40]). However, critics of participatory TA highlight potential weaknesses, such as the lack of impact on decision-making, the lack of support of mainstream science and technology policy, and the exclusion of diverse kinds of knowledge (Hennen, 2012[41]).

TA as means of building and steering technological and industrial agendas. Building national competitiveness through targeted investment in different areas of science and technology R&D is a key aspect of STI policy, in which TA can play a supportive role. For example, following the Portuguese Resolution of the Council of Ministers, the Ministry for Science and Higher Education commissioned the Portuguese Foundation for Science and Technology (FCT) to develop 15 thematic research and innovation agendas. Among them, the Industry and Manufacturing Agenda 2030 mobilised experts from R&D institutions and companies to prospect potential opportunities and challenges for the Portuguese research and innovation system in the medium and long term. The agendas' main objective was to promote collective reflection on the knowledge base required to pursue the scientific, technological, and societal goals in a given thematic area. FCT facilitated a bottom-up approach through an inclusive process involving experts from academia, research centres, companies, public organisations, and civil society.[3]

Some TAs combine all three rationales. One example is the Novel and Exceptional Technology and Research Advisory Committee (NExTRAC) at the National Institutes of Health (NIH) in the United States. NIH undertakes horizon-scanning and sense-making of new technologies; deliberates on ethical, legal, and societal issues with a variety of stakeholders; and directly informs the NIH director in agenda-setting (National Institutes of Health, 2021[42]).

Trends reshaping needs for TA-based strategic intelligence

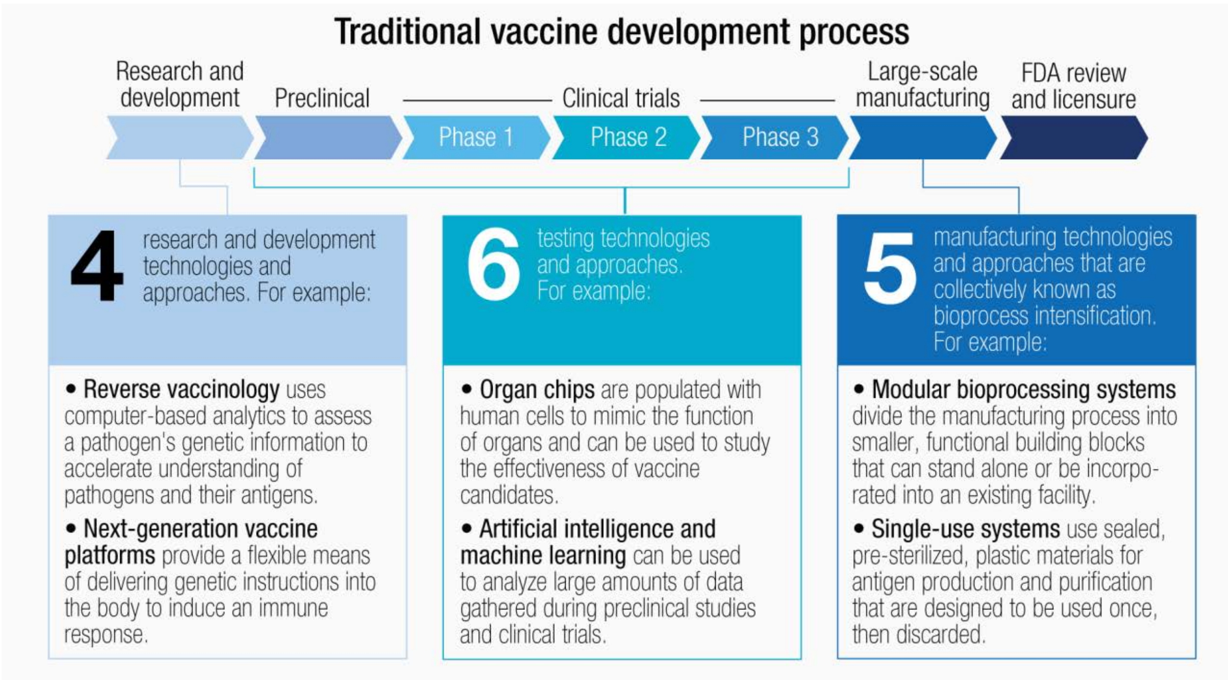
Since the founding of the OTA 50 years ago, there has been growing recognition that timely intelligence for STI policy and governance is necessary. Not only are technologies becoming more complex and more pervasive, but they are evolving rapidly with potential new and disruptive risks to the economy, environment, and society. While prudent STI policy and governance for emerging technologies mobilises strategic intelligence in various ways (Tuebke et al., 2001[43]), new trends are challenging established strategic intelligence practices to incorporate new needs. Stemming from a mixture of technological developments, new STI policy approaches and exogenous shocks, these trends produce new requirements for TA processes and outcomes.

Technology trends: The pace of convergence. The escalating and transformative interaction among seemingly distinct technologies, scientific disciplines, communities, and domains of human activity are achieving new levels of synergism (Roco and Bainbridge, 2013[44]). This “convergence” at different loci of the STI system means that ideas, approaches, and technologies from widely diverse fields of knowledge become relevant and necessary for analysing the potential impacts of such convergent systems (National Research Council, 2014[45]). Thus, convergence is placing new demands on strategic intelligence and TA to capture its implications for sociotechnical change.

Innovation policy trends: Mission-orientation. One major STI policy trend is the shift towards greater directionality (Borrás and Edler, 2020[46]), a theme treated in detail in Chapter 5. So-called “mission-oriented” innovation policies seek to steer research and innovation systems so that they contribute to achieving a societal goal (Robinson and Mazzucato, 2019[47]; Larrue, 2021[26]; Mazzucato, 2018[48]). Such approaches require expounding values within ambitious, clearly defined, measurable and achievable goals within a binding time frame (Lindner et al., 2021[49]). Missions envision large transformations. They pressure TA to move from techno-centric approaches focusing on a particular technology and its ramifications, to exploring portfolios of technologies (e.g., related to mobility, energy production and waste management) and how they might impact and drive transformations in value chains, industries, and whole sociotechnical systems. In Germany, the federal government’s most recent funding instrument, “INSIGHT”, promotes a holistic, forward-looking impact assessment of innovations. In addition to the natural and technical sciences, the assessment includes ethical, social, legal, economic, and political considerations. Acknowledging the increasing importance of social innovations, the focus shifts from “pure” technology analysis to including societal developments in the innovation processes.

Crises and societal missions are driving what could be termed “solution-centric” TA. In the Netherlands, the Rathenau Institute develops TAs focusing on problems such as deepfakes (synthetic media) (STOA, 2021[50]) and cyber resilience (van Boheemen et al., 2020[51]). In the United States, the Government Accountability Office (GAO) has been focusing on problems like reducing freshwater use in hydraulic fracturing and power plant cooling and tracing the source of chemical weapons (GAO, 2020[52]). One recent TA by GAO assesses the vaccine development chain for infectious diseases (see Figure 6.2). Here, the goal was to identify key technologies that could enhance the ability of the United States to respond rapidly and effectively to high-priority infectious diseases through rapid vaccine development.

Figure 6.2. GAO: Assessment of vaccine development technologies



Source: (GAO, 2021[53]).

Exogenous forces: A proliferation of crises. Proliferating crises – e.g., the COVID-19 pandemic, Russia's war of aggression against Ukraine and the subsequent energy crisis, and the local effects of extreme events such as droughts, flooding and forest fires linked to climate change – reshape the requirements for strategic intelligence. As a recent example, the rapid spread of COVID-19 caught most nations off guard, requiring accelerated technology development and deployment of vaccines and defibrillators, as well as knowledge about the virus, its spread, and mutations. Governments around the world had to deal with a crisis featuring high scientific uncertainty, making rapid decisions that would affect national populations and beyond, owing to mobility restrictions. Crises require urgent action. They put pressure on the production of useful and timely strategic intelligence to shape actions in near-real time. TA practitioners are also challenged to incorporate detailed investigations in the rapid scaling and diffusion of new and emerging technologies, and to consider the societal, economic, and environmental effects of rapid scaling.

Challenges and policy considerations

While global TA practice is still rife with techno-centric TA activities, solution-based and crisis-driven TAs are increasing, bringing with them many questions regarding tools and processes. How wide a portfolio of technologies is there to explore? What is the scope of the TA study? What sort of inclusion is needed to build trust and harness collective intelligence? How rapidly is the intelligence from TA needed for decision-making, and how does this balance with the depth and breadth of TA analysis?

The trend towards mission-oriented innovation policies (see Chapter 5) requires identifying and enacting core societal values that should drive technical change. TA is well placed to spell out these values, particularly around controversial technologies. However, the increasing complexities of emerging technologies and their impacts make it necessary to move beyond techno-centric perspectives. Adopting a socio-centric approach, in turn, increases the complexity and information requirements of not only technology options, but also of the value chains and systems involved.

Crises increase demands on rapid sourcing and scaling of technology solutions. However, uncertainty in both the emerging technology options and the impacts generated as they scale increases the need for controlled speculation on both the mechanisms for rapid scaling and the various facets of scaling. TA and other intelligence sources, such as Foresight, are potential approaches to this end.

Box 6.1. Considerations for Robust Technology Assessment

1. **Fitness for purpose.** TA processes should be aligned with goals, such as (1) promoting deliberation and gauging opinions, (2) providing information on key trends, and (3) building agendas. Clear articulation of the different steps and activities that will fulfil the goals of the TA will be valuable in determining the appropriate methods and approaches.
2. **Clarity in scope.** TA must be clear about which level of analysis it undertakes. Is it technology-centric (e.g., quantum computing), does it have a value chain focus (e.g., food supply chains), or does it take a sociotechnical-system perspective (e.g., mobility)? The scope and granularity of the TA activity should be connected to the goal of the TA exercise, since each perspective requires a different range of expertise, evidence tools and processes.
3. **Smart and inclusive participation.** TA requires participation of stakeholders with different kinds of expertise and experience. The inclusion criteria depend on several constraints - the resources available (i.e., staffing and funding), the scope (identifying relevant social groups based on the topic and scope of TA), and the time available (limited time may require restricting and focusing inclusion). Robust TA mobilises approaches such as the European Parliament's STEEPED approach (Van Woensel, 2021[54]), which undertakes a comprehensive scan of social, technological, economic, environmental, political, ethical and demographic aspects (Van Woensel, 2020[55]) as a means to identify relevant stakeholders.
4. **Explicit with regards to values, frames, and biases.** Some forms of TA bring together stakeholders to explore the impacts of technology on their professions, their personal lives, and the broader sociotechnical systems that make up society. Naturally, different stakeholders will have their own perspectives, and it is therefore important to understand (a) the contexts in which professionals and lay persons operate, and (b) the various biases that may shape both their opinions and reactions to others. Trustworthy TA brings to light values, frames, and biases.
5. **Usability.** TA is important for structuring disparate and unclear information, thereby providing decision makers with understandable interpretations. Robust TA should demonstrate careful consideration of the target audience for the intelligence produced, and of this audience's absorptive capacity.

Inclusion and alignment: Engaging stakeholders and society upstream

Achieving an anticipatory system of technology governance will require recognising the central role of citizens and stakeholders in ensuring the use of trusted and trustworthy technology in society. Contemporary sociological accounts of the relationship between science, technology and society demonstrate that knowledge is increasingly produced in contexts of application, publics are aware of how STI affect their interests and values, and these interests can shape innovation (Jasanoff, 2007[56]). The numerous forms of stakeholder participation in the communication and making of science and technology contradict the so-called "deficit model" of publics as largely ignorant and irrational (Wynne, 1991[57]). But misunderstandings still exist (Chilvers and Kearnes, 2015[58]). Upstream stakeholder engagement can help frame – and reframe – the issues at stake (Jasanoff, 2003[59]) and "open up" important new questions

(Stirling, 2007[60]). It must also be translated into practice, so experimentation and knowledge sharing will be important. Reviewing a large body of literature on societal engagement in the context of emerging technologies, this section focuses on how to engage societal stakeholders upstream in technology development to promote trust and trustworthiness.

Rationales: The need for upstream stakeholder engagement in innovation

Why is engagement necessary from the perspective of achieving an anticipatory and inclusive technology governance system? First, engagement can surface societal goals for emerging technology at different points in the complex innovation system, from agenda-setting to product design and diffusion, contributing to a better alignment of technological development with social needs (von Schomberg, 2013[23]). Such alignment, unfolding in an iterative process, is one of the key functions of emerging technology governance and responsible innovation.

Second, engaging societal stakeholders earlier in the development process can help spot public sensitivities and ethical shortcomings. Societal stakeholders bring experiential knowledge to societal problems (OECD, 2020[33]) and offer the perspectives of future users (Kreiling and Paunov, 2021[31]). This diversifies the types of expertise that are included during technology development, potentially pointing to application challenges, or raising questions that innovators do not anticipate, even with their knowledge and expertise. Such diversity has the potential to locate certain biases that are built into digital and other technologies. Subsequent design considerations could help foster societal acceptance and avoid backlashes and controversies that could lead to adoption failures (OECD, 2016[61]), and manage expectations for future products and services.

Third, stakeholder engagement promotes public understanding of science and technology, and enhances the societal capacity for deliberating on technological issues. Such deliberation and consultation can breed trust and enrich the relationship between science and society – although pre-ordained consultation can undermine engagement as a trust-building exercise (Wynne, 2006[62]).

Fourth (and related to the first point), societal engagement presents an opportunity to bring representatives from diverse cultures, demographics, ages, social structures, and skill levels to the innovation process. Including their views, and building stakeholder capacity, not only addresses forms of rooted exclusion but could render technologies more relevant to broader social groups.

Trends in upstream societal engagement

Use of new digital technologies. Digitalisation advanced the use of atypical engagement formats, such as online tools or immersive virtual-reality technologies and simulation, although traditional paper-based or face-to-face approaches are still used most frequently (BEIS, 2021[63]).

Iterative and sequenced engagement. Staged approaches have become more frequent. One example is the “IdeenLauf” (“flow of ideas”) initiative during German Science Year 2022, which collected societal impulses to inform science and research policy. First, citizens submitted over 14 000 questions for science. Second, the questions were consolidated, complemented by additional texts to provide relevant context, and discussed among scientists and selected citizens. Third, citizens commented on the text via online consultation. The final report was presented to policy makers and researchers in November 2022.[4]

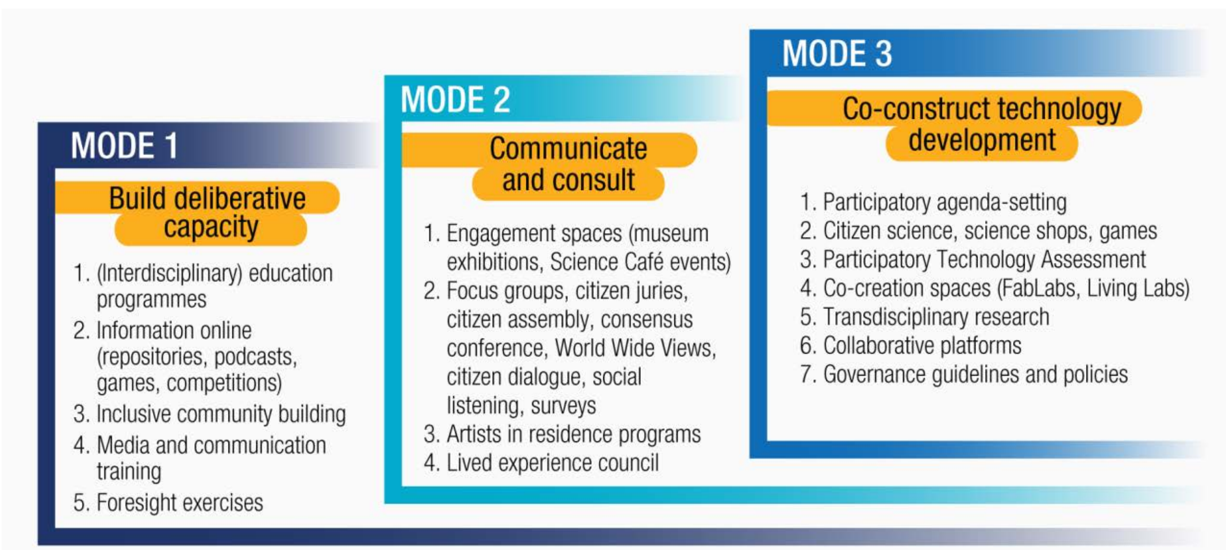
Directionality: Focus shifts from technologies to missions, goals, and future products. Emerging technologies are often not yet embodied in future products or services, complicating exchanges between technology experts and broader publics. One trending response to this challenge has been to focus the engagement exercise on issues that societal stakeholders can more easily relate to. An example in the area of future mobility is the “GATEway” project in the United Kingdom, which conducted live public trials on connected and autonomous vehicles resulting in insights on public acceptance of, and attitudes towards, driverless vehicles (BEIS, 2021[63]).

Focus on diversity. There exists momentum to ensure age, ethnic, gender, cultural and other forms of diversity in the make-up of the "publics" engaged in consultation. However, practitioners still perceive a diversity gap both in the theory and practices of engagement, resulting in problems for both sides. On the one side, some communities are not solicited and are thus unable to provide inputs. On the other side, technology experts do not learn about the needs and values of these future users.

Upstream societal engagement: Three modes and examples

Engagement techniques can be categorised under three main groups, corresponding to their different purposes (Figure 6.3). Mode 1 (capacity-building) can be viewed as a prerequisite that establishes the conditions for effective societal engagement and democratic governance. Mode 2 (communicate and consult) gathers the views of citizens or informs them, which may have an indirect influence on technology governance decisions. Mode 3 (co-construct technology development) engages societal stakeholders more directly in the construction of science and technology.

Figure 6.3. Each engagement mode comes with a set of engagement techniques



Source: Developed by the authors.

Clarity on the rationale for stakeholder engagement and its timing – during, before or in parallel to the technology development process – is essential when deciding on the suitable societal engagement technique. Deliberative capacity-building (Mode 1) acts as foundation or enabler of societal engagement and occurs during and alongside innovation processes. Societal engagement exercises before or during the research planning phase tend to focus on communicating with or consulting societal stakeholders (Mode 2). Engagement efforts to co-construct science and technology pathways (Mode 3) occur during development, e.g., of prototypes or testing at scale.

Mode 1: Building deliberative capacity

Anticipatory governance has been defined as "a broad-based capacity extended through society that can act on a variety of inputs to manage emerging knowledge-based technologies while such management is still possible" (Guston, 2013[22]). Mode 1 activities (see Table 6.1) help build the capacity of publics and innovators to engage in deliberative processes and contribute constructively to governance discussions. They can include techniques (such as communication training) aimed at scientists and innovators, programmes to involve them in the science policy process, and multidisciplinary work that embraces the social sciences and humanities. Other engagement techniques (like science and science policy training) focus on journalists and the media.

Table 6.1. Engagement techniques and rationales: Mode 1

Mode 1: Building deliberative capacity	
Techniques and rationales	• interdisciplinary education programs (e.g., in high school; higher education; science, technology, engineering and mathematics [STEM]; or lifelong learning) to create interest in science, scientific literacy and science policy • education for STEM trainees in social science, humanities, and the policy process • inclusive community-building around research infrastructures • online information available to public in accessible formats (repositories, podcasts, games, competitions) • media and communication training to build the capacity of innovators and scientists to engage with the public • foresight exercises to identify early warning signs and enable governance debate.

These activities also tend to focus on assembling and empowering specific stakeholder groups around technology development, design, and governance. For instance, the European Human Brain Project built an inclusive community for the EBRAINS research infrastructure. This network of external collaborators (including patient associations, clinicians, and industry) brings together those who are particularly concerned by future technology applications.[5] The project also provides information platforms and games to build knowledge and skills at the interface of science and society. Two examples in the field of synthetic biology are the citizen game "Nanocrafter" and the annual "iGem" student competition,[6] both of which also feature community-building elements. The European Commission's e-learning platform, "Digital Skillup", is designed for both beginners and advanced users. It helps them explore emerging technologies and their impact on everyday life and offers training on topics like cybersecurity or the digital revolution.[7] In the United States, the Science and Technology Policy Fellowships of the American Association for the Advancement of Science place talented scientists and engineers in positions of federal policy making, furthering the training of a cadre of communicators and contributors across the science and society divide.[8]

Mode 2: Communication and consultation

Mode 2 pertains to engagement techniques aiming to gather stakeholder views. While their outcomes and influence on the innovation process are often indirect, they do have capacity-building elements. For example, a UK citizen jury exercise to understand public attitudes towards ethical AI also resulted in their gaining a better understanding of automated decision systems (BEIS, 2021[63]).

Table 6.2. Engagement techniques and rationales : Mode 2

Mode 2: Communication and consultation	
Techniques and rationales	exhibitions to engage publics in "engagement spaces" such as science museums, libraries, universities, and science cafés citizen juries, citizen assembly, consensus conference, World Wide Views, citizens' dialogues foresight and gaming focus groups and surveys for public consultation to gather views lived experience council to consult with those concerned artists in residence programmes to promote exchanges between scientists and artists and engage the local community.

Mode 2 contains a wide array of mechanisms and processes for soliciting views and attitudes towards emerging technology (see Table 6.2). Processes can vary from a one-off citizen dialogue to a sequence of meetings and conversations lasting many months. An important consideration across many Mode 2 engagement techniques is the need to design engagement spaces. This includes not only the location's selection, accessibility, and institutional affiliation, but also the types of event formats and interactivity. For example, public outreach in science museums may take the form of exhibitions or room for experimentation. At Science Café events, on the other hand, scientists may engage with lay persons and discuss their research. Each form of consultation requires a different engagement space.

Mode 3: Co-constructing science and technology development

Mode 3 encompasses the wide variety of modalities for direct contribution by stakeholders and even publics to the creation of new knowledge and technology. As shown in Table 6.3, these techniques and processes promote exchanges between innovators and societal stakeholders that may explore complex and controversial questions and capture deeper underlying values and trade-offs. The exchange is bidirectional, resulting in the "co-construction" or "co-creation" of STI (König, Baumann and Coenen, 2021[64]; Kreiling and Paunov, 2021[31]).

Table 6.3. Engagement techniques and rationales : Mode 3

	Mode 3: Co-construct technology development
Techniques and rationales	• participatory agenda-setting to co-create or inform research agenda • citizen science, science shops, games to conduct community-based (participatory) research • participatory TA includes affected social actors, interest groups, consumers, and members of the public alongside professional experts and policy makers • "maker spaces" for co-creation or prototype testing (e.g., FabLabs or Living Labs) • transdisciplinary research combining knowledge from different scientific disciplines with that of public- and private-sector stakeholders and citizens • collaborative platforms using convergence spaces for technological development and diffusion • guidelines and policies to govern scientific practice.

Mode 3 engagements can occur at different stages in the innovation process.

- **Agenda-setting:** engagement typically occurs in *participatory agenda-setting* exercises, using formats like "decision theatres" or "social foresight labs". The rationale is to co-create or inform research agendas (Matschoss et al., 2020[65]) by involving, for example, patient groups (Scheufele et al., 2021[66]). It can also be to integrate the needs of rural areas and indigenous communities in research and innovation processes (Schroth et al., 2020[67]).
- **New knowledge creation:** *community-based research* strives to build equitable partnerships based on long-term commitment and applies interventions that are beneficial to all stakeholders involved (Baik, Koshy and Hardy, 2022[68]). This category also includes different forms of citizen science and transdisciplinary research (OECD, 2020[33]), both of which are premised on the power of experiential and acquired expertise in the creation of new knowledge. One example is the German funding initiative for citizen science, which is extending support to 28 projects in two phases between 2017 and 2024.[9]
- **Prototype development:** the prototype stage is an important innovation milestone, and engagement is increasingly considered critical to its success. The user-centric methods for the development and testing of prototypes have been evolving. For example, (Rodriguez-Calero et al., 2020[69]) identified 17 strategies to engage stakeholders with prototypes during front-end design activities in the area of medical devices.

- **Deployment and testing at scale:** Maker spaces have been used to engage societal stakeholders. For example, the “Lorraine Fab Living Lab”[10] tests prototypes and prospectively assesses innovative usages, combining elements of FabLabs and Living Labs (Engels, Wentland and Pfotenhauer, 2019[70]).
- **Engagement governing scientific conduct:** These occur alongside technology development processes and could result in the development of guidelines, such as on human genome editing (Iltis, Hoover and Matthews, 2021[71]). The term “open innovation” describes the opening of the innovation process. In the private sector, open innovation happens when future consumers are included in “customer co-creation” activities (Piller, Ihl and Vossen, 2010[72]), resulting in “prosumers” (Rayna and Striukova, 2015[73]). Initiatives are underway to build industry tools for engagement. One such initiative is the “Societal engagement with key enabling technologies (SOCKETS”)[11] project supported by the European Commission (2020-23), which develops and tests methods to engage citizens in the industrial development and use of key enabling technologies.

Challenges and policy considerations

Despite their importance, establishing and running engagement initiatives upstream in the innovation process can be challenging, both from a procedural and organisational standpoint. Procedural challenges relate to the context and impact of the engagement exercise. Concretely, this means using the appropriate channels to ensure that inputs from engagement reach relevant decision makers and innovators and that engagement exercises are not perceived as an additional requirement which is met with a “tick-box mentality” of innovators. Moreover, processes tend not to recognise that experts and communities have different stakes, with traditional decision makers having more to gain and marginalised communities potentially having more to lose. Hence, another issue lies in the power relations between technical experts and societal stakeholders (see Chapter 4). Implementing meaningful participation requires capacity-building and training, as well as developing formats, procedures and a framework that enable members of the public to participate in the process (Schroth et al., 2020[67]).

Organisational challenges revolve around selecting and motivating stakeholders. In this respect, both the scope of the perceived societal impact of the technology and the societal relevance of the research are key. In the case of emerging technologies, relevance and urgency for stakeholders may not be high (de Silva et al., 2022[74]). Still, some technology solutions may affect a smaller group of (local) stakeholders, while others could impact broader groups and cover a geographically larger (global) scale. Lack of relevance, expertise, trust, skills, motivation, incentives, time, and financial resources are common engagement barriers across all stakeholder groups.

As diversity, equity and inclusion become dedicated goals, stakeholder differences in terms of knowledge, ways to communicate, values, expectations, contextual understanding, and routes to forming opinions may become even more pronounced. Allowing an open yet focused debate by balancing between an overly narrow and an open framing of the issues is essential to handle differences and disagreement, facilitating deliberation without forcing consensus (Bauer, Bogner and Fuchs, 2021[75]).

Box 6.2. Policy considerations for conducting effective societal engagement

Procedural aspects

Deploy engagement techniques sequentially to bring societal stakeholders into the innovation process at different stages. This means organising a series of societal engagements so that they build on each other and inform different dimensions of the technology governance process.

Frame engagement around societal missions and goals, as early-stage emerging technology may appear abstract to societal stakeholders. Effective engagement uses narratives that focus on anchors to which stakeholders can relate.

Provide training and incentives to innovators to nurture a culture of engagement and inclusion, so that engagement outcomes are linked with decision-making processes and embedded in innovators' core activities.

Organisational aspects

Identify and select relevant stakeholders depending on the scope of the engagement exercise and the technology's societal impact. Consider mobilising civil society or advocacy groups that represent societal members with high personal stakes in the R&D process, as well as positively seeking out diversity.

Make diversity, equity, and inclusion key design goals for engagement in Mode 1, Mode 2, and Mode 3. This means involving various types of expertise and creating an environment that allows an open yet focused debate, facilitating deliberation without forcing consensus. Funding structures can motivate innovators to engage with broad and diverse communities.

Build capacity and minimise barriers to entry for societal stakeholders to participate in engagement exercises. Suitable formats and effective procedures are essential to attract and retain committed participation.

Adaptivity: Co-developing principles, standards, guidelines, and codes of practice

Compared to strategic intelligence and societal engagement, norms and institutions are the more typical tools of technology governance through, for example, regulation, rules, and standards by authoritative bodies. However, while they will be necessary in certain situations, formal regulatory approaches that use norms to define permissible and impermissible activities, along with sanction or incentives to ensure compliance, may present disadvantages in more upstream contexts. First, the speed of technological advances makes it difficult for regulation to keep up. Second, novel ethical, social, and economic issues can operate outside or across regulatory jurisdiction and expertise. Third, applications across multiple industries and government agencies can create interagency co-ordination problems. For all these reasons, formal regulatory approaches may be ill-suited to govern emerging technology, at least in the earlier stages of development (Marchant and Wallach, 2015[76]; Hernández and Amaral, 2022[77]; OECD, 2019[78]). Further, attempts to govern emerging technology could derail innovative approaches, prompting concerns that companies and technologies may simply move across borders (Pfotenhauer et al., 2021[79]).

The OECD is rethinking regulatory policy to document and encourage more agile regulatory governance using a wide array of approaches (OECD, 2021[15]). One such approach might be to use principles, standards, guidelines, and codes with moral or political force but without formal legal enforceability. These "soft law" approaches may provide a number of advantages in terms of multisector co-operation and cross-jurisdictional flexibility (García and Winickoff, 2022[80]). For instance, (Gutierrez, Marchant and Michael, 2021[81]) have pointed to the adaptivity of soft law in governing AI, noting that "AI's dynamic and rapidly evolving nature … make it challenging to keep in place. In these scenarios, soft law…can transcend the boundaries that typically limit hard law and, by being non-binding, serve as a precursor or as a complement or substitute to regulation." Nevertheless, its effective deployment has both opportunities and challenges. Indeed, soft law is an increasingly important mode of governance for emerging technology (Hagemann, Huddleston and Thierer, 2019[82]). In the current context, soft law – in all its different forms -- should be considered an important tool for achieving an emerging technology governance system that is more anticipatory, inclusive, and adaptive.

Rationale

Guidelines, standards and codes of practice feature different types and rationales. Organisations create high-level principles that communicate a joint commitment to ideals and values-based operations. Standard-setting bodies – such as the Institute of Electrical and Electronics Engineers (IEEE) and the International Organization for Standardization (ISO) develop technical norms to guide communities of practice. Professional groups and firms also often ask their members to follow certain rules and codes of conduct. Governments can publish guidelines while threatening to pass enforceable laws as a backstop in the event of insufficient adherence. Finally, voluntary programmes, labels or certification schemes may drive markets, and ultimately the adoption of best practices.

Trends and examples

Public international principles: OECD recommendations

In situations where new international legal treaties are rarely achieved, principles 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. Principles can operate at the international level through a number of organisational sources, from the United Nations to the Council of Europe and the OECD. The OECD offers salient examples of public international recommendations that present principles in the field of technology governance. OECD recommendations feature regular reporting requirements by Adherents, to promote progress in their implementation as well as transparency. Recent recommendations and implementation work include:

- May 2019: the Recommendation of the Council on Artificial Intelligence (OECD, 2019[17]), under which the OECD convened a multi-stakeholder group, developed a practical toolkit, created an "observatory" of existing policies to promote mutual learning, and led to the establishment of a new OECD Working Party on AI Governance
- December 2019: the Recommendation on Responsible Innovation in Neurotechnology (OECD, 2019[11]), which seeks to anticipate problems during the course of innovation, steer technology towards the best outcomes, and include many stakeholders in the innovation process.
- October 2021: the Recommendation for Agile Regulatory Governance to Harness Innovation (OECD, 2021[15]), which provides guidance for policy makers to design agile regulations that can address the regulatory challenges and opportunities arising from emerging technologies.

Public-private international standards

Other important technology governance mechanisms arise at the public and private interface. As a case in point, ISO is an independent, non-governmental international organisation with a membership of 167 national standards bodies. Among other things, ISO sets many technical standards in the arena of emerging technology, which are developed through a stakeholder-driven process at a fairly high level of technical detail. ISO/TR 12885:2018 on health and safety practices in occupational settings of nanotechnologies is a good example of a technical governance standard.[12] This standard focuses on the occupational manufacture and use of manufactured nano-objects, and their aggregates and agglomerates greater than 100 nanometres.

Codes of practice

Codes of scientific and engineering practice

Novel and specialised codes of practice in science and engineering are sometimes deployed before new technologies hit the market, when their potential risks and harms are anticipated but not well-known, or the work has significant ethical implications. These can cross over into public funding agencies through policy. A good example of guidelines that have influenced both the public and private sectors are those developed by the International Society of Stem Cell Research (ISSCR) (Box 6.3).

Box 6.3. Guidelines on the ethics of stem cell research as a self-regulatory approach

ISSCR is an independent global non-profit organisation that promotes excellence in stem cell science and therapies. Founded in 2002, the ISSCR consists of 4 500 scientists, educators, ethicists, and business leaders across 80 countries. ISSCR members make a commitment to uphold the ISSCR Guidelines for Stem Cell Research and Clinical Translation (ISSCR Guidelines), an "international benchmark for ethics, rigor, and transparency in all areas of practice." [1]

Although not directly enforceable, the guidelines provide regulators and research funders with a framework for the regulatory oversight of stem cell research and clinical translation, including recent advances related to embryo models, chimeric embryos and mitochondrial replacement (Anthony, Lovell-Badge and Morrison, 2021[83]). The guidelines can be indirectly enforced by research institutions, funding agencies and scientific journals that require scientists to comply (Marchant and Allenby, 2017[34]).

In 2021, the ISSCR updated its guidelines to address advances in stem cell science and other relevant fields since the previous update in 2016. These advances included human embryo culture, organoids, mitochondrial replacement, human genome editing and prospects for obtaining *in vitro*-derived gametes. The guidelines directly address new ethical, social and policy issues that have arisen, and recommendations for oversight.

1. https://www.isscr.org/guidelines (accessed 22 September 2022).

Industrial codes of practice

Many companies find it advantageous to work at the industry-wide level to design joint solutions to governance in the form of self-regulation. For example, the biopharmaceutical industry is experiencing intense changes, with a number of frontier technologies impacting the way it does research, commercialises its products, and collaborates with partners and stakeholders across the world. At the industry level, the International Federation of Pharmaceutical Manufacturers and Associations has responded by creating new bodies, like global future health technologies and bioethics working groups, to consider the next generation of risks, benefits, and standards, with a view to updating its "Code of Practice".[13] Another example is the International Gene Synthesis Consortium (Box 6.4), which has developed a strong network and commitment to biosecurity measures in the industry.

Box 6.4. International Gene Synthesis Consortium

Synthetic biology, also known as “engineering biology”, is a multidisciplinary field that “integrates systems biology, engineering, computer science, and other disciplines to achieve the ’modification of life’ or even the ’creation of life’ via the redesign of existing natural systems or the development of new biological components and devices” (Sun et al., 2022[84]). Several major breakthroughs have occurred over the last two decades, including the development of the first synthetic cell at the James Craig Venter Institute in 2010 (Trump et al., 2020[85]), advances in DNA synthesis and assembly (Sun et al., 2022[84]) and the adoption of the Clustered Regularly Interspaced Short Palindromic Repeats-associated protein system (CRISPR/Cas) for genome editing in eukaryotic cells (Cong et al., 2013[86]). Like other emerging technologies, synthetic biology is a rapidly advancing field that has outpaced its current regulatory framework and is likely to have disruptive impacts.

The power to design organisms carries risks in terms of biosecurity. Formed in 2009, the International Gene Synthesis Consortium (IGSC) is an industry-led group of gene synthesis companies and organisations. Currently, IGSC members represent approximately 80% of commercial gene synthesis capacity worldwide. IGSC was created to develop the Harmonised Screening Protocol, now in its second version. Under the protocol, IGSC members test the complete DNA and translated amino acid sequences of every double-stranded gene order against a curated regulated pathogen database derived from international pathogen and toxin sequence databases.[1]

The current version of the Harmonised Screening Protocol, which amounts to a private standard enacted to protect the public, was launched in 2017.[2] More recently, in the context of the rapid pace of technological change in the field, some industry and academic actors have publicly called for a process to update the protocol that should include the synthesis companies themselves, policy makers, science and technology funders (both public and private), and the broader synthetic biology community (Diggans and Leproust, 2019[87]).

1. https://genesynthesisconsortium.org (accessed 23 September 2022).
2. https://genesynthesisconsortium.org/wp-content/uploads/IGSCHarmonizedProtocol11-21-17.pdf (accessed 20 September 2022).

Self-regulatory product or process standards

Technology-based standards determine the specific characteristics (size, shape, design, or functionality) of a product, process, or production method. These standards are an important form of governance that can emanate from both the private sector (e.g., de facto standards in the form of dominant designs) and the public sector (e.g., government-regulated vehicle safety standards or mobile phone frequency bands). Environmental non-governmental organisations (NGOs) are partnering with industry on the development of product standards for new food products driven by new and emerging technologies. These partnerships can help generate standards or certification schemes that may command premiums in the market.

Co-developed product standards have potential utility for “upstream governance” because retailers can leverage their market power to influence how technology developers are considering unanticipated consequences throughout the supply chain, from design and sourcing to disposal. Companies are accountable as they have a duty to report on their activities to their investors. They have the power to “bake in” these concerns as the new technologies, chemicals and innovations develop.

Recently, the Environmental Defense Fund, a US-based NGO, worked with the private sector to develop principles and standards to ensure the environmental sustainability of cell-based meat and seafood. This information allows companies to assess these products’ potential impacts on human health, the environment and society, and to communicate the implications to stakeholders clearly and transparently

(Environmental Defense Fund, 2021[88]). An important question was how to translate the mechanisms and principles of co-design and upstream engagement into practice. Involving multiple stakeholders was key to ensuring the quality and legitimacy of the guidance.

“By-design” approaches

With the “ethics-by-design” or “sustainability-by-design” approach to governance, some firms and regulatory agencies assess and build in the sustainability or ethical implications of new technologies at different stages of technology development. The “Safe(r)-by-Design” concept, for instance, encourages industry to reduce uncertainties and risks to human and environmental safety, starting at an early phase of the innovation process and covering the whole innovation value chain (or life cycle for product development) (OECD, 2022[89]).

This ethics-by-design approach seeks to embed ethics and societal values – such as privacy, diversity, and inclusion – through clear protocols (e.g., search protocols in AI). Analytical tools can serve to assess privacy impacts, safety impacts, diversity, inclusion, and human rights impacts, and avoid bias. At the December 2021 Summit for Democracy, the United States announced new international technology initiatives including International Grand Challenges on Democracy-Affirming Technologies to drive global innovation on technologies that embed democratic values and principles (Matthews, 2021[90]). In July 2022, the United States, and the United Kingdom co-launched “a set of prize challenges to unleash the potential of privacy-enhancing technologies (PETs) to combat global societal challenges”, making sure privacy and trust are at the heart of the design process” (The White House, 2022[91]).

Challenges and policy considerations

Principles, guidelines, standards, and codes of practice face some challenges. First, they may lack the formal legitimacy of regulations, which are derived from governments’ legislative authority. This means that they may escape some of the formal procedures required to enact regulations, such as transparent and accountable public comment periods, and structured stakeholder engagement.

Second, the efficacy of these systems must be better addressed should “soft law” become an even more important tool (Hagemann, Huddleston and Thierer, 2019[82]). Third, the existence of too many non-binding sets of norms in a particular terrain may cause overlaps, impeding efficacy across the complex system of actors and institutions that make up global governance (Black, 2008[92]).

Box 6.5. Policy considerations for co-developing principles, guidelines, standards, and codes

Perform empirical analysis of diverse mechanisms and tools, recognising its interplay with regulation to optimise their use, further increasing the credibility and effectiveness of technology governance.

Co-design

Ensure “meaningful” participatory mechanisms where concerned stakeholders (both citizens and SMEs) are invited into the design of both technologies and governance systems. Principles, standards, guidelines, and codes of practice should be transparent and built on evidence, so that they are accountable not only to industry, but to the public.

Perform outreach to ensure effective standardisation. This includes SMEs, which often do not have the resources to contribute effectively to standardisation. Include user groups (like patients), regulatory authorities, social scientists, philosophers, and civil society in standard-setting. This co-creation is critical in the early phases of development of soft law instruments for self-regulation. For instance, co-design will enhance the likelihood of public acceptance, which will facilitate the use of technology at scale to enhance and save patient lives.

Compliance

Develop oversight mechanisms for implementation and compliance, including third-party audits of technology governance as part of an effective quality control infrastructure.

Consider other mechanisms like liability regimes with contractual force, external ethics committees, insurance companies that might require compliance and performance, and government off-ramps (if conditions of governance not satisfied, government regulator will step in).

Strengthen the use of and compliance with governance tools. Tie funding, publication, and regulatory approval to compliance with safety standards; access; transparency; and ethical, legal, and social principles.

By-design

Change the incentives for researchers to promote more transparent processes for the selection, funding, and monitoring of early prototype plans for technology innovation.

Funders could require and provide adequate incentives for peer-review and community engagement during the early design phases of disruptive research.

Towards international co-operation on anticipatory governance

Technological sovereignty as a concept is becoming more pronounced, and more countries are striving for technological sufficiency – if not clear advantages – in specific domains (see Chapter 2). Yet this movement towards *national* or *regional* approaches might be out of step with current demands. The *global* nature of the challenges facing the world today requires greater technological (or other) co-operation. The question is whether – and how – the technological governance framework addresses these dynamics.

The section above pitched the use of such design criteria and tools at the national level. This framework could also encourage technological co-operation at the international level – first, by reinforcing commitment to common values such as human rights, responsibility, economic co-operation, and democratic governance; and second, by paving the way for the development of international approaches, such as good strategic intelligence, stakeholder and societal engagement, and mechanisms like OECD recommendations. As stated previously, international co-operation is a consideration for good emerging technology governance that spans the gamut of values, design criteria and tools.

International co-operation on TA and strategic intelligence

As explored in the above section, anticipatory tools can enhance the capacity to spot issues, understand a given technological and governance landscape, and ultimately make better governance decisions. Across the world, TA, strategic foresight, and other forms of strategic intelligence (such as horizon-scanning) are being applied at the national level to inform national STI policies and technology governance.

One clear gap in the landscape of strategic intelligence lies in the international arena. International technology decision-making on the possible limits on geoengineering,[14] human augmentation[15] and AI will require strategic intelligence sources that are trusted across countries and sectors. Commonly recognised evidence can serve as the foundation of agreement on different forms of governance. The Intergovernmental Panel on Climate Change, which has supported climate co-ordination and co-operation under the Paris Agreement/COP21, is a case in point. Such global forward-looking analysis could be informed by and link to so-called “global observatories”, which aggregate policy approaches and technology developments. The AI Observatory at the OECD is a good model, with its searchable database of AI policies and normative instruments throughout the world, and its hub for expert blog posts and articles. Some have proposed a Global Observatory for Gene Editing which would serve a broader set of functions, notably to enrich ethical, legal, and cultural understandings, and encourage debate among the global citizenry (Jasanoff and Hurlbut, 2018[93]). Collaboration around such efforts at the international level could pool insights on the development and potential impacts of technology, as well as build best practices for collective strategic intelligence.

International stakeholder and public engagement

In this vein, the development of emerging technologies has ramifications for the nature of citizen engagement. For example, geoengineering techniques could affect weather patterns or water supply, with impacts that are not restricted to national borders. AI applications exert profound impacts not only on national, but global, economies. Growing calls for international public deliberation exercises, such as a global citizens' assembly on genome editing (Dryzek et al., 2020[94]), evince the co-emergence of technology and new kinds of global citizenship. Going from the traditionally local or national level to the global scale will require adapting engagement techniques, for example by using formats like World Wide Views.[16] However, deciding which stakeholder groups should be involved in global efforts raises questions related to the nature of international publics and the identification of relevant stakeholders.

International co-operation on principles, standards, guidelines, and codes of practice

Addressing governance challenges at the country level runs the risk of being ineffective at best and counter-productive at worst, as particular jurisdictions could exploit the governance gaps to gain advantage. Several of the governance modalities (such as the OECD recommendations) discussed in this chapter operate at an international level, offering an opportunity to co-ordinate and even harmonise different jurisdictions’ approaches. Further, standards emanating from industry groups or public-private partnerships can work transnationally, across and through jurisdictions linked by supply chains, markets, and border-crossing actors.

Conclusion

Technology is driving economies, political systems, and cultures. It promises great advances for human well-being, supporting solutions to grand challenges such as green transitions and pandemics. However, technology developers and users, as well as policy makers, must be mindful of a fine balance between enabling innovation for societal benefit while reducing potential risks to democratic values, e.g., equity, transparency, accountability, that may undermine human rights or have other undesirable societal, political, or economic consequences. While important thinking and tools to regulate technology continue to develop, it is important to note that a co-evolutionary process is taking place between technological development and today’s societal structures. The social and political shaping of technology happens through a myriad of ways and policies, including intellectual property laws, science agenda-setting and funding, and regulatory policy. Here, an *anticipatory* framework featuring generalisable design criteria and tools can help guide the innovation process to embed values more purposefully into the technology development process.

Anticipation, the inclusion and integration of stakeholders, and adaptability are key design criteria allowing more explicit consideration of values in the technological development process. International co-operation grows out of shared values and informs design criteria and policy tools. But these design criteria must be optimised, using a variety of tools and activities that can drive the embedding process. Forward-looking

TA both depends on and supports the expression of key values, which underpin the analysis of potential benefits and harms, and the trajectories of emerging technology. Societal and stakeholder engagement can bring a democratic element to the governance of emerging technology, enabling deliberation on the values that should support and guide technological development. Finally, co-developed standards can endow the governance system with the necessary adaptivity and utility as it sets a normative stance towards technology through standards and guidelines. This framework will not define core human rights and values, but it could clear the way for a more reflective stance towards emerging technologies and the values they embody. As actioned through this pragmatic framework, this stance might ground a more co-operative approach to developing technologies in, for and with societies.

References

Anthony, E., R. Lovell-Badge and S. Morrison (2021), "New guidelines for stem cell and embryo research from the ISSCR", *Cell Stem Cell*, Vol. 28/6, pp. 991-992, https://doi.org/10.1016/j.stem.2021.05.009. [83]

Baik, E., A. Koshy and B. Hardy (2022), "Communicating CRISPR: Challenges and opportunities in engaging the public", in *Progress in Molecular Biology and Translational Science, Molecular Biology and Clinical Medicine in the Age of Politicization*, Elsevier, https://doi.org/10.1016/bs.pmbts.2021.11.004. [68]

Baldwin, C. and C. Woodard (2009), *The Architecture of Platforms: A Unified View*, Edward Elgar Publishing, https://doi.org/10.4337/9781849803311.00008. [8]

Bauer, A., A. Bogner and D. Fuchs (2021), "Rethinking societal engagement under the heading of Responsible Research and Innovation: (novel) requirements and challenges", *Journal of Responsible Innovation*, Vol. 8/3, pp. 342-363, https://doi.org/10.1080/23299460.2021.1909812. [75]

BEIS (2021), "The use of public engagement for technological innovation: literature review and case studies", Department for Business, Energy and Industrial Strategy, https://www.gov.uk/government/publications/the-use-of-public-engagement-for-technological-innovation-literature-review-and-case-studies (accessed on 7 March 2023). [63]

Black, J. (2008), "Constructing and contesting legitimacy and accountability in polycentric regulatory regimes", *Regulation & Governance*, Vol. 2/2, pp. 137-164, https://doi.org/10.1111/j.1748-5991.2008.00034.x. [92]

Borrás, S. and J. Edler (2020), "The roles of the state in the governance of socio-technical systems' transformation", *Research Policy*, Vol. 49/5, p. 103971, https://doi.org/10.1016/j.respol.2020.103971. [46]

Capri, A. (2019), "Techno-Nationalism: What Is It And How Will It Change Global Commerce?", *Forbes*, https://www.forbes.com/sites/alexcapri/2019/12/20/techno-nationalism-what-is-it-and-how-will-it-change-global-commerce/?sh=62458045710f (accessed on 6 March 2023). [5]

Chilvers, J. and M. Kearnes (eds.) (2015), *Remaking Participation*, Routledge, Abingdon, Oxon ; New York, NY : Routledge is an imprint, https://doi.org/10.4324/9780203797693. [58]

Cong, L. et al. (2013), “Multiplex Genome Engineering Using CRISPR/Cas Systems”, *Science*, Vol. 339/6121, pp. 819-823, https://doi.org/10.1126/science.1231143. [86]

Council of Europe (2019), *Strategic Action Plan on Human Rights and Technologies in Biomedicine (2020-2025)*, https://rm.coe.int/strategic-action-plan-final-e/1680a2c5d2 (accessed on 6 March 2023). [19]

Crespi, F. et al. (2021), “European Technological Sovereignty: An Emerging Framework for Policy Strategy”, *Intereconomics*, Vol. 56/6, pp. 348-354, https://doi.org/10.1007/s10272-021-1013-6. [4]

de Silva, M. et al. (2022), “How did COVID-19 shape co-creation?: Insights and policy lessons from international initiatives”*, OECD Science, Technology and Industry Policy Papers*, No. 134, OECD Publishing, Paris, https://doi.org/10.1787/e11c5274-en. [74]

Delvenne, P. and B. Rosskamp (2021), “Cosmopolitan technology assessment? Lessons learned from attempts to address the deficit of technology assessment in Europe”, *Journal of Responsible Innovation*, Vol. 8/3, pp. 445-470, https://doi.org/10.1080/23299460.2021.1988433. [39]

Diggans, J. and E. Leproust (2019), “Next Steps for Access to Safe, Secure DNA Synthesis”, *Frontiers in Bioengineering and Biotechnology*, Vol. 7, https://doi.org/10.3389/fbioe.2019.00086. [87]

Dryzek, J. et al. (2020), “Global citizen deliberation on genome editing”, *Science*, Vol. 369/6510, pp. 1435-1437, https://doi.org/10.1126/science.abb5931. [94]

Engels, F., A. Wentland and S. Pfotenhauer (2019), “Testing future societies? Developing a framework for test beds and living labs as instruments of innovation governance”, *Research Policy*, Vol. 48/9, p. 103826, https://doi.org/10.1016/j.respol.2019.103826. [70]

Environmental Defense Fund (2021), “Innovative Foods: A Guide to Responsible Investment in Cell-cultured Meat and Seafood”, No. accessed on 20 September 2022, https://business.edf.org/files/InnovativeFoods-CellCulturedMeat-Brochure-LOWres-092921.pdf (accessed on 7 March 2023). [88]

Folke, C. et al. (2005), “ADAPTIVE GOVERNANCE OF SOCIAL-ECOLOGICAL SYSTEMS”, *Annual Review of Environment and Resources*, Vol. 30/1, pp. 441-473, https://doi.org/10.1146/annurev.energy.30.050504.144511. [7]

GAO (2021), “Vaccine Development: Capabilities and Challenges for Addressing Infectious Diseases”, U.S. Government Accountability Office, https://www.gao.gov/products/gao-22-104371 (accessed on 7 March 2023). [53]

GAO (2020), “Tracing the source of chemical weapons”, https://www.gao.gov/assets/gao-21-271sp.pdf (accessed on 7 March 2023). [52]

García, L. and D. Winickoff (2022), “Brain-computer interfaces and the governance system: Upstream approaches”*, OECD Science, Technology and Industry Working Papers*, No. 2022/01, OECD Publishing, Paris, https://doi.org/10.1787/18d86753-en. [80]

Guston, D. (2013), “Understanding ‘anticipatory governance’”, *Social Studies of Science*, Vol. 44/2, pp. 218-242, https://doi.org/10.1177/0306312713508669. [22]

Gutierrez, C., G. Marchant and K. Michael (2021), “Effective and Trustworthy Implementation of AI Soft Law Governance”, *IEEE Transactions on Technology and Society*, Vol. 2/4, pp. 168-170, https://doi.org/10.1109/tts.2021.3121959. [81]

Hagemann, R., J. Huddleston and A. Thierer (2019), “Soft Law for Hard Problems: The Governance of Emerging Technologies in an Uncertain Future”, Colorado Technology Law Journal, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3118539 (accessed on 7 March 2023). [82]

Hasselman, L. (2016), “Adaptive management; adaptive co-management; adaptive governance: what’s the difference?”, *Australasian Journal of Environmental Management*, Vol. 24/1, pp. 31-46, https://doi.org/10.1080/14486563.2016.1251857. [9]

Hennen, L. (2012), “Why do we still need participatory technology assessment?”, *Poiesis & Praxis*, Vol. 9/1-2, pp. 27-41, https://doi.org/10.1007/s10202-012-0122-5. [41]

Hernández, G. and M. Amaral (2022), “Case studies on agile regulatory governance to harness innovation: Civilian drones and bio-solutions”, *OECD Regulatory Policy Working Papers*, No. 18, OECD Publishing, Paris, https://doi.org/10.1787/0fa5e0e6-en. [77]

HM Government (2022), “Future Tech Forum Chair’s Report”, https://www.gov.uk/government/publications/future-tech-forum-chairs-report/future-tech-forum-chairs-report (accessed on 6 March 2023). [13]

Iltis, A., S. Hoover and K. Matthews (2021), “Public and Stakeholder Engagement in Developing Human Heritable Genome Editing Policies: What Does it Mean and What Should it Mean?”, *Frontiers in Political Science*, Vol. 3, https://doi.org/10.3389/fpos.2021.730869. [71]

Jasanoff, S. (2007), *Designs on Nature: Science and Democracy in Europe and the United States*, https://press.princeton.edu/books/paperback/9780691130422/designs-on-nature (accessed on 7 March 2023). [56]

Jasanoff, S. (2003), , *Minerva*, Vol. 41/3, pp. 223-244, https://doi.org/10.1023/a:1025557512320. [59]

Jasanoff, S. and J. Hurlbut (2018), “A global observatory for gene editing”, *Nature*, Vol. 555/7697, pp. 435-437, https://doi.org/10.1038/d41586-018-03270-w. [93]

König, H., M. Baumann and C. Coenen (2021), “Emerging Technologies and Innovation—Hopes for and Obstacles to Inclusive Societal Co-Construction”, *Sustainability*, Vol. 13/23, p. 13197, https://doi.org/10.3390/su132313197. [64]

Kreiling, L. and C. Paunov (2021), “Knowledge co-creation in the 21st century: A cross-country experience-based policy report”, *OECD Science, Technology and Industry Policy Papers*, No. 115, OECD Publishing, Paris, https://doi.org/10.1787/c067606f-en. [31]

Kuhlmann, S. (2002), “Distributed Techno-Economic Intelligence for policymaking”, https://www.urenio.org/e-innovation/stratinc/files/library/22.pdf (accessed on 6 March 2023). [37]

Kuhlmann, S. et al. (1999), “Improving Distributed Intelligence in Complex Innovations Systems”, https://www.semanticscholar.org/paper/Improving-Distributed-Intelligence-in-Complex-Kuhlmann-Boekholt/bacef7fa27b0942bce2aad3b0576cb3fa76e04ec (accessed on 6 March 2023). [40]

Larrue, P. (2021), "The design and implementation of mission-oriented innovation policies: A new systemic policy approach to address societal challenges", *OECD Science, Technology and Industry Policy Papers*, No. 100, OECD Publishing, Paris, https://doi.org/10.1787/3f6c76a4-en. [26]

Lindner, R. et al. (2021), "Mission-oriented innovation policy: From ambition to successful implementation", *Perspectives - Policy Brief*, No. No. 02 / 2021, Fraunhofer ISI, Karlsruhe, https://www.isi.fraunhofer.de/content/dam/isi/dokumente/policy-briefs/policy_brief_mission-oriented-innovation-policy.pdf (accessed on 7 March 2023). [49]

Malina, D. (ed.) (2022), "Governance of Emerging Technologies in Health and Medicine — Creating a New Framework", *New England Journal of Medicine*, Vol. 386/23, pp. 2239-2242, https://doi.org/10.1056/nejmms2200907. [27]

Marchant, G. and B. Allenby (2017), "Soft law: New tools for governing emerging technologies", *Bulletin of the Atomic Scientists*, Vol. 73/2, pp. 108-114, https://doi.org/10.1080/00963402.2017.1288447. [34]

Marchant, G. and W. Wallach (2015), "Coordinating Technology Governance", *Issues in Science and Technology 31*, No. no. 4 (Summer 2015), https://issues.org/coordinating-technology-governance/ (accessed on 7 March 2023). [76]

Matasick, C., C. Alfonsi and A. Bellantoni (2020), "Governance responses to disinformation : How open government principles can inform policy options", *OECD Working Papers on Public Governance*, No. 39, OECD Publishing, Paris, https://doi.org/10.1787/d6237c85-en. [2]

Mathews, D. (2017), *When emerging biomedical technologies converge or collide*, Oxford University Press, https://doi.org/10.1093/oso/9780198786832.003.0001. [36]

Matschoss, K. et al. (2020), "Co-creating transdisciplinary global change research agendas in Finland", *European Journal of Futures Research*, Vol. 8/1, https://doi.org/10.1186/s40309-020-0162-3. [65]

Matthews, D. (2021), "US to push 'democracy-affirming technology' with prizes and research projects", *Science Business*, https://sciencebusiness.net/news/us-push-democracy-affirming-technology-prizes-and-research-projects (accessed on 7 March 2023). [90]

Mazzucato, M. (2018), *Mission-oriented research & innovation in the European Union*, https://op.europa.eu/en/publication-detail/-/publication/5b2811d1-16be-11e8-9253-01aa75ed71a1/language-en (accessed on 7 March 2023). [48]

National Institutes of Health (2021), *Novel and Exceptional Technology and Research Advisory Committee, Gene Drives in Biomedical Research Report*, https://osp.od.nih.gov/wp-content/uploads/NExTRAC-Gene-Drives-Final-Report.pdf (accessed on 6 March 2023). [42]

National Research Council (2014), *Convergence*, National Academies Press, Washington, D.C., https://doi.org/10.17226/18722. [45]

OECD (2022), "Sustainability and Safe and Sustainable by Design: Working Descriptions for the Safer", *OECD Environment, Health and Safety Publications Series on the Safety of Manufactured Nanomaterials*, No. No. 105, https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV-CBC-MONO(2022)30%20&doclanguage=en (accessed on 7 March 2023). [89]

OECD (2022), *Towards an anticipatory innovation governance model in Finland*, https://oecd-opsi.org/wp-content/uploads/2021/09/Anticipatory-Innovation-Governance-in-Finland.pdf (accessed on 6 March 2023). [21]

OECD (2021), "Practical Guidance on Agile Regulatory Governance to Harness Innovation", https://legalinstruments.oecd.org/public/doc/669/9110a3d9-3bab-48ca-9f1f-4ab6f2201ad9.pdf (accessed on 6 March 2023). [35]

OECD (2021), *Recommendation of the Council for Agile Regulatory Governance to Harness Innovation*, https://legalinstruments.oecd.org/en/instruments/OECD-LEGAL-0464 (accessed on 5 March 2023). [15]

OECD (2021), "Trust in Global Co-operation - the vision for the OECD for the next decade", https://read.oecd-ilibrary.org/view/?ref=1110_1110970-giiac5g3aj&title=MCM-oct-2021-Trust-in-global-co-operation-Mathias-Cormann (accessed on 6 March 2023). [28]

OECD (2020), "Addressing societal challenges using transdisciplinary research"*, OECD Science, Technology and Industry Policy Papers*, No. 88, OECD Publishing, Paris, https://doi.org/10.1787/0ca0ca45-en. [33]

OECD (2019), *Recommendation of the Council on Artificial Intelligence*, https://legalinstruments.oecd.org/en/instruments/oecd-legal-0449 (accessed on 6 March 2023). [17]

OECD (2019), *Recommendation of the Council on Responsible Innovation in Neurotechnology*, https://legalinstruments.oecd.org/en/instruments/OECD-LEGAL-0457 (accessed on 6 March 2023). [11]

OECD (2019), *Regulatory effectiveness in the era of digitalisation*, https://www.oecd.org/gov/regulatory-policy/Regulatory-effectiveness-in-the-era-of-digitalisation.pdf (accessed on 7 March 2023). [78]

OECD (2018), *OECD Science, Technology and Innovation Outlook 2018: Adapting to Technological and Societal Disruption*, OECD Publishing, Paris, https://doi.org/10.1787/sti_in_outlook-2018-en. [18]

OECD (2018), "Technology governance and the innovation process", in *OECD Science, Technology and Innovation Outlook 2018: Adapting to Technological and Societal Disruption*, OECD Publishing, Paris, https://doi.org/10.1787/sti_in_outlook-2018-15-en. [6]

OECD (2016), "Public engagement in STI policy", in *OECD Science, Technology and Innovation Outlook 2016*, OECD Publishing, Paris, https://doi.org/10.1787/sti_in_outlook-2016-11-en. [61]

OECD (forthcoming), "Technology in and for society: innovating well for inclusive transitions - conference report". [30]

Owen, R., R. von Schomberg and P. Macnaghten (2021), "An unfinished journey? Reflections on a decade of responsible research and innovation", *Journal of Responsible Innovation*, Vol. 8/2, pp. 217-233, https://doi.org/10.1080/23299460.2021.1948789. [25]

Pfotenhauer, S. et al. (2021), "Mobilizing the private sector for responsible innovation in neurotechnology", *Nature Biotechnology*, Vol. 39/6, pp. 661-664, https://doi.org/10.1038/s41587-021-00947-y. [79]

Piller, F., C. Ihl and A. Vossen (2010), "A Typology of Customer Co-Creation in the Innovation Process", *SSRN Electronic Journal*, https://doi.org/10.2139/ssrn.1732127. [72]

Rayna, T. and L. Striukova (2015), "Open innovation 2.0: is co-creation the ultimate challenge?", *International Journal of Technology Management*, Vol. 69/1, p. 38, https://doi.org/10.1504/ijtm.2015.071030. [73]

Robinson, D. and M. Mazzucato (2019), "The evolution of mission-oriented policies: Exploring changing market creating policies in the US and European space sector", *Research Policy*, Vol. 48/4, pp. 936-948, https://doi.org/10.1016/j.respol.2018.10.005. [47]

Robinson, D. et al. (2021), "Policy lensing of future-oriented strategic intelligence: An experiment connecting foresight with decision making contexts", *Technological Forecasting and Social Change*, Vol. 169, p. 120803, https://doi.org/10.1016/j.techfore.2021.120803. [38]

Roco, M. and W. Bainbridge (2013), "The new world of discovery, invention, and innovation: convergence of knowledge, technology, and society", *Journal of Nanoparticle Research*, Vol. 15/9, https://doi.org/10.1007/s11051-013-1946-1. [44]

Rodriguez-Calero, I. et al. (2020), "Prototyping strategies for stakeholder engagement during front-end design: Design practitioners' approaches in the medical device industry", *Design Studies*, Vol. 71, p. 100977, https://doi.org/10.1016/j.destud.2020.100977. [69]

Ryan-Mosley, T. (2022), "The world is moving closer to a new cold war fought with authoritarian tech", *MIT Technology Review*, https://www.technologyreview.com/2022/09/22/1059823/cold-war-authoritarian-tech-china-iran-sco/ (accessed on 6 March 2023). [1]

Sambuli, N. (2021), "In my view: The promises, pitfalls and potential of global technology governance", in *Development Co-operation Report 2021: Shaping a Just Digital Transformation*, OECD Publishing, Paris, https://doi.org/10.1787/67500f38-en. [10]

Scheufele, D. et al. (2021), "What we know about effective public engagement on CRISPR and beyond", *Proceedings of the National Academy of Sciences*, Vol. 118/22, https://doi.org/10.1073/pnas.2004835117. [66]

Schroth, F. et al. (2020), "Participatory agenda setting as a process — of people, ambassadors and translation: a case study of participatory agenda setting in rural areas", *European Journal of Futures Research*, Vol. 8/1, https://doi.org/10.1186/s40309-020-00165-w. [67]

Shelley-Egan, C. et al. (2017), "Responsible Research and Innovation in the context of human cognitive enhancement: some essential features", *Journal of Responsible Innovation*, Vol. 5/1, pp. 65-85, https://doi.org/10.1080/23299460.2017.1319034. [24]

Stirling, A. (2007), ""Opening Up" and "Closing Down"", *Science, Technology, & Human Values*, Vol. 33/2, pp. 262-294, https://doi.org/10.1177/0162243907311265. [60]

STOA (2021), *Tackling deepfakes in European policy*, Panel for the Future of Science and Technology, https://www.rathenau.nl/sites/default/files/2021-08/tackling_deepfakes_in_european_policy_STOA.pdf (accessed on 7 March 2023). [50]

Sun, T. et al. (2022), "Challenges and recent progress in the governance of biosecurity risks in the era of synthetic biology", *Journal of Biosafety and Biosecurity*, Vol. 4/1, pp. 59-67, https://doi.org/10.1016/j.jobb.2022.02.002. [84]

Tech For Good Summit (2020), *Tech For Good Summit - Progress Report*, https://www.elysee.fr/admin/upload/default/0001/08/23c18d41821bd9bb2505555892fcbc19d52a3b5d.pdf (accessed on 6 March 2023). [12]

The Royal Society (2009), *Geoengineering the climate: science, governance and uncertainty*, accessed on 30 November 2022, https://royalsociety.org/-/media/Royal_Society_Content/policy/publications/2009/8693.pdf (accessed on 7 March 2023). [95]

The White House (2022), "U.S. and U.K. Launch Innovation Prize Challenges in Privacy-Enhancing Technologies to Tackle Financial Crime and Public Health Emergencies", *Press release*, https://www.whitehouse.gov/ostp/news-updates/2022/07/20/u-s-and-u-k-launch-innovation-prize-challenges-in-privacy-enhancing-technologies-to-tackle-financial-crime-and-public-health-emergencies/ (accessed on 7 March 2023). [91]

The White House (2021), *U.S. and U.K. Launch Innovation Prize Challenges in Privacy-Enhancing Technologies to Tackle Financial Crime and Public Health Emergencies*, https://www.whitehouse.gov/ostp/news-updates/2021/12/08/white-house-announces-launch-of-the-international-grand-challenges-on-democracy-affirming-technologies-for-the-summit-for-democracy/ (accessed on 6 March 2023). [16]

The White House (2021), *White House Announces Launch of the International Grand Challenges on Democracy-Affirming Technologies for the Summit for Democracy*, https://www.whitehouse.gov/ostp/news-updates/2021/12/08/white-house-announces-launch-of-the-international-grand-challenges-on-democracy-affirming-technologies-for-the-summit-for-democracy/ (accessed on 6 March 2023). [14]

Trump, B. et al. (eds.) (2020), *Synthetic Biology 2020: Frontiers in Risk Analysis and Governance*, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-030-27264-7. [85]

Tuebke, A. et al. (2001), *Strategic Policy Intelligence: Current Trends, the State of Play and Perspectives*, https://www.researchgate.net/publication/308900288_Strategic_Policy_Intelligence_Current_Trends_the_State_of_Play_and_Perspectives (accessed on 6 March 2023). [43]

UK Ministry of Defence (2021), *Human Augmentation – the Dawn of a New Paradigm*, accessed on 30 November 2022, https://www.gov.uk/government/publications/human-augmentation-the-dawn-of-a-new-paradigm (accessed on 7 March 2023). [96]

US State Department (2020), *U.S.-EU Trade and Technology Council (TTC)*, https://www.state.gov/u-s-eu-trade-and-technology-council-ttc/ (accessed on 6 March 2023). [20]

van Boheemen, P. et al. (2020), *Guidelines for foresight-based policy analysis*, https://www.rathenau.nl/sites/default/files/2020-07/REPORT%20Cyber%20resilience%20with%20new%20technology%20-%20Rathenau%20Instituut.pdf (accessed on 7 March 2023). [51]

Van Woensel, L. (2021), *Guidelines for foresight-based policy analysis*, STOA, https://data.europa.eu/doi/10.2861/39319. [54]

Van Woensel, L. (2020), *A Bias Radar for Responsible Policy-Making*, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-030-32126-0. [55]

von Schomberg, R. (2013), “A Vision of Responsible Research and Innovation”, in *Responsible Innovation*, John Wiley & Sons, Ltd, Chichester, UK, https://doi.org/10.1002/9781118551424.ch3. [23]

Wee, S. (2021), “Two Scientific Journals Retract Articles Involving Chinese DNA Research”, *The New York Times*, https://www.nytimes.com/2021/09/09/business/china-dna-retraction-uyghurs.html (accessed on 6 March 2023). [3]

Winickoff, D. et al. (2021), “Collaborative platforms for emerging technology: Creating convergence spaces”*, OECD Science, Technology and Industry Policy Papers*, No. 109, OECD Publishing, Paris, https://doi.org/10.1787/ed1e030d-en. [32]

Worthington, R. (1982), “The Social Control of Technology. By David Collingridge. (New York: St. Martin’s Press, 1980. Pp. i + 200. $22.50.)”, *American Political Science Review*, Vol. 76/1, pp. 134-135, https://doi.org/10.2307/1960465. [29]

Wynne, B. (2006), “Public Engagement as a Means of Restoring Public Trust in Science – Hitting the Notes, but Missing the Music?”, *Public Health Genomics*, Vol. 9/3, pp. 211-220, https://doi.org/10.1159/000092659. [62]

Wynne, B. (1991), “Knowledges in Context”, *Science, Technology, & Human Values*, Vol. 16/1, pp. 111-121, https://doi.org/10.1177/016224399101600108. [57]

Notes

[1] The Office for Technology Assessment was formally created in 1972 and closed in 1995.

[2] In 1994, NOTA was renamed the Rathenau Institute (www.rathenau.nl).

[3] The agenda can be found at the following link (in Portuguese): https://www.fct.pt/agendastematicas/docs/Agenda_Industria_Manufatura_Final.pdf (accessed 30 September 2022).

[4] Further information on the German Initiative “IdeenLauf” (in German) available at: https://www.wissenschaftsjahr.de/2022/ideenlauf (accessed 24 November /2022).

[5] https://ebrains.eu/ (accessed 22 September 2022).

[6] Further information on Nanocrafter (https://citizensciencegames.com/nanocrafter-playing-game-synthetic-biology/) or iGem online (https://igem.org/) (both accessed 24 September 2022).

[7] https://www.digitalskillup.eu/ (accessed 22 September 2022).
[8] https://www.aaas.org/programs/science-technology-policy-fellowships (accessed 22 September 2022).

[9] Further information on the BMBF citizen science funding programme on STIP Compass online: https://stip.oecd.org/stip/interactive-dashboards/policy-initiatives/2019%2Fdata%2FpolicyInitiatives%2F24328 (accessed 30 November 2022).

[10] Lorraine Fab Living Lab: https://lf2l.fr/ (accessed 24 September 2022).

[11] https://tekno.dk/project/sockets/?lang=en) (accessed 25 November 2022).
[12] https://www.iso.org/standard/67446.html?browse=tc (accessed 22 September 2022)

[13] https://www.ifpma.org/wp-content/uploads/2018/09/IFPMA_Code_of_Practice_2019-1.pdf (accessed 23 September 2022).

[14] The UK Royal Society provided one authoritative definition of “geoengineering” in 2009: “the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change” (The Royal Society, 2009[95]).

[15] The UK Ministry of Defence has proposed a definition of “human augmentation” as “the application of science and technologies to temporarily or permanently improve human performance”, and divides the field further into “human performance optimisation and human performance enhancement” (UK Ministry of Defence, 2021[96]).

[16] http://wwviews.org/the-world-wide-views-method/ (accessed 04 October 2022).

OECD Science, Technology and Innovation Outlook 2023

ENABLING TRANSITIONS IN TIMES OF DISRUPTION

Sociotechnical systems in areas like energy, agrifood and mobility need to transform rapidly to become more sustainable and resilient. Science, technology and innovation (STI) have essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies to meet these challenges. They should design policy portfolios that enable transformative innovation and new markets to emerge, challenge existing fossil-based systems, and create windows of opportunity for low-carbon technologies to break through. This calls for larger investments but also greater directionality in research and innovation, for example, through mission-oriented policies, to help direct and compress the innovation cycle for low-carbon technologies. International co-operation will be essential, but rising geopolitical tensions, including strategic competition in key emerging technologies, could make this difficult. *OECD Science, Technology and Innovation Outlook 2023* explores these and other key issues and trends that present STI with a new operating environment to which it must adapt.

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