OECD Science, Technology and Innovation Outlook 2021

TIMES OF CRISIS AND OPPORTUNITY

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BETTER POLICIES FOR BETTER LIVES

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Foreword

The *OECD Science, Technology and Innovation Outlook 2021* 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 the COVID-19 pandemic, which has triggered an unprecedented mobilisation of the science and innovation communities.

Science and technology offer the only exit strategy from COVID-19: they have been central in informing governments' efforts to limit the virus spread; and they have underpinned the rapid development of effective vaccines in record time. The pandemic has underscored the importance of science and innovation to being both prepared and reactive to upcoming crises.

The pandemic has also stretched research and innovation systems to their limits, revealing gaps that need filling to improve overall system preparedness for future crises. It is a wake-up call that highlights the need to recalibrate STI policies to better equip governments with the instruments and capabilities to point research and innovation efforts towards the long-term goals of sustainability, inclusivity and resiliency.

The eight chapters in this edition of the STI Outlook cover a range of topics, including research system responses to the pandemic, impacts on the research workforce, and likely implications for government support to business research and innovation. The rapid development of COVID-19 vaccines has relied on strong international STI co-operation that offers policy lessons for dealing with other global challenges. It also underscores the fact that national self-interest will most often be best served by international collaboration. Emerging technologies have important roles to play in tackling the pandemic and its impacts, and the STI Outlook considers two such technologies – engineering biology and robotics – that show promise in helping enhance the health resiliency of societies. A final chapter reviews various governance challenges, including the need for governments to renew their policy frameworks and capabilities to fulfil a more ambitious STI policy agenda.

The world is still in the midst of the COVID-19 crisis and there remain many uncertainties that will shape research and innovation systems, and the extent to which these systems can help solve societies' longer-term grand challenges. The STI Outlook provides evidence and analysis that should help policymakers when weighing their options in these times of crisis and opportunity.

This edition of the STI Outlook has a dual format, comprising both this book and a set of topic webpages with supporting content (see http://oe.cd/sti-outlook). The STI Outlook team has also built an online monitoring tool of governments' STI policy responses to COVID-19 (https://stip.oecd.org/covid) that provides evidence used in this book and beyond.

Acknowledgements

The 2021 edition of the *OECD Science, Technology and Innovation Outlook* (STI Outlook) is prepared under the aegis of the OECD Committee for Scientific and Technological Policy (CSTP), with input from its working parties. CSTP Delegates contributed significantly through their replies to the OECD Survey on STI policy responses to COVID-19 (https://stip.oecd.org/covid), and their participation in a high-level debate on 23 November 2020 where the STI Outlook's main findings were discussed.

The STI Outlook 2021 is a collective effort, co-ordinated by the Science and Technology Policy (STP) Division of the OECD Directorate for Science, Technology and Innovation (DSTI). It is produced under the guidance of Alessandra Colecchia, Head of STP Division. Michael Keenan served as overall co-ordinator and Sylvain Fraccola as the administrative co-ordinator. Blandine Serve co-ordinated statistical inputs.

Chapter 1, "COVID-19: A pivot point for science, technology and innovation?", was prepared by Caroline Paunov and Michael Keenan (DSTI). It is based on work carried out by the Working Party on Innovation and Technology Policy (TIP) on the impacts of COVID-19 on STI. This chapter benefited from contributions by Sandra Planes Satorra and Andrés Barreneche (DSTI).

Chapter 2, "Mobilising public research funding and infrastructures in times of crisis", was prepared by Frédéric Sgard (DSTI). It is based on the work of the OECD Global Science Forum (GSF), with contributions from members of the GSF expert groups on High-Risk/High-Reward research and on national research infrastructures.

Chapter 3, "Challenges and new demands on the academic research workforce", was prepared by Cláudia Sarrico and Carthage Smith (DSTI). It is based on work carried out by the OECD GSF on the research workforce.

Chapter 4, "Government support for business research and innovation in a world in crisis", was prepared by Fernando Galindo-Rueda and Silvia Appelt, with assistance from Georgia Ellis (DSTI). The chapter draws on recent work by the OECD Working Party of National Experts on Science and Technology Indicators (NESTI), and in particular the microBeRD project, conducted in collaboration with the OECD Committee on Industry, Innovation and Entrepreneurship.

Chapter 5, "Resolving global challenges and crises through international collaboration", was prepared by Mario Cervantes and Michael Keenan (DSTI). It draws on CSTP work on international STI co-operation and blended finance.

Chapter 6, "Why accelerate the development and deployment of robots?" was prepared by Alistair Nolan (DSTI). It draws in parts on the forthcoming OECD STI Working Paper, "Robotics: Recent developments and public policies". Detailed comments and valuable insights were had from Gregory Ameyugo, Justine Cassell, Johan Frisk, Chris Melhuish, Elena Messina, Alexandra Neri and José Saenz.

Chapter 7, "Engineering biology: Accelerating innovation to meet global challenges", was prepared by David Winickoff (DSTI). It is based on recent work carried out by the Working Party on Biotechnology, Nanotechnology and Converging Technologies (BNCT) on synthetic biology.

Chapter 8, “STI governance for crisis and recovery”, was prepared by Michael Keenan, Philippe Larrue, Carthage Smith and David Winickoff (DSTI). It draws on multiple CSTP and working party activities, notably the CSTP project on mission-oriented innovation policies, recent work by the BNCT on technology governance, and long-standing work by the GSF on scientific advice.

All the chapters of the 2021 STI Outlook were reviewed by Sarah Box, Alessandra Colecchia, Dirk Pilat and Andrew Wyckoff of the DSTI. The team thanks them for their valuable comments and guidance. Thanks are likewise due to those CSTP delegates who provided comments on chapter drafts.

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Acronyms and abbreviations

AI	Artificial intelligence
AMC	Advanced market commitment
ASD	Autism spectrum disorder
BEPS	Base erosion and profit shifting
BERD	Business enterprise expenditure on R&D
DBTL	Design-Build-Test-Learn
DSTI	Directorate for Science, Technology and Innovation
ERA	European Research Area
FDI	Foreign direct investment
GAVI	Global Alliance for Vaccines and Immunization
GDP	Gross domestic product
GERD	Gross domestic expenditure on research and development
GFC	Global financial crisis
GISAID	Global Initiative on Sharing Avian Influenza Data
GPG	Global public goods
GTARD	Government tax relief for R&D expenditures
GVC	Global value chains
HFEA	Human Fertilisation and Embryology Authority
HIV	Human immunodeficiency virus
IATT	Inter-agency Task Team
ICB	Industry Classification Benchmark
ICT	Information and communication technology
ICTSD	International Centre for Trade and Sustainable Development
IDRC	International Development Research Centre
IFR	International Federation of Robotics
IFRS	International Financial Reporting Standards
IMF	International Monetary Fund

IP	Intellectual property
IPR	Intellectual property rights
JEDI	Joint European Disruption Initiative
MERS	Middle East Respiratory Syndrome
MLP	Multi-level perspective
MOIP	Mission-oriented innovation policies
mRNA	Messenger ribonucleic acid
NASA	National Aeronautics Space Administration
OCTS-OEI	Observatorio Iberoamericano de la Ciencia, la Tecnología y la Sociedad (OCTS) de la Organización de Estados Iberoamericanos (OEI)
ODA	Official development assistance
PCT	Patent Cooperation Treaty
R&D	Research and development
RNA	Ribonucleic acid
SLS	Swiss Light Source
STI	Science, technology and innovation
TDR	Transdisciplinary research
TFM	Technology Facilitation Mechanism
USPTO	United States Patent and Trademark Office
UV	Ultra-violet
VC	Venture capital
WFH	Working from home
WHO	World Health Organization
WTO	World Trade Organization
SMEs	Small and medium-sized enterprises
STEM	Science, technology, engineering and mathematics

Executive summary

The STI systems’ response to COVID-19 has been decisive, rapid and significant

STI systems have responded strongly and flexibly to the COVID-19 crisis. Newly funded research initiatives worth billions of dollars have been set up in record time, and research and innovation have led to the rapid development of vaccines. However, the pandemic has stretched STI systems to their limits, revealing areas that need strengthening to improve overall STI resilience for both future and present challenges, including climate change.

The COVID-19 crisis has accelerated trends already underway in STI. It has further opened access to data and publications, increased the use of digital tools, enhanced international collaboration, spurred a variety of public-private partnerships, and encouraged the active engagement of new players. These developments could speed the transition to a more open science and innovation in the longer run.

At the same time, such widespread engagement risks diverting research efforts indiscriminately away from non-COVID-19-related topics. Governments and research funding bodies need to define and communicate quickly their capacities to support research in the coming years, as well as their strategic priorities, to allow research-performing organisations to elaborate realistic long-term plans.

The effects of the pandemic, particularly lockdowns, have also disrupted the normal functioning of innovation systems, endangering key productive and innovation capabilities, especially in hard-hit sectors. On an aggregate basis, business investments in research and innovation are pro-cyclical, and thus prone to contracting in times of crisis. This crisis may be different since some of the top global R&D players are expanding their activities during the crisis. The pandemic could exacerbate existing gaps in business research and innovation activities between “leading” and “laggard” sectors, large and small firms, and geographical areas. This distributional unevenness could widen productivity gaps, deepen the vulnerability of laggards, and reduce economic resilience, and should be the target of innovation-support policies.

Beyond their research activities, scientists continue to provide expert input on public health and other policy responses to the pandemic. They have had to communicate evidence that is incomplete and changing, and to do so in ways that promote public confidence and trust. This advice has sometimes been contested, given its policy consequences. In response, governments should carefully communicate uncertainties, provide a balanced presentation of potential scenarios, and be transparent about mistakes. Governments should also draw upon multi-disciplinary advisory mechanisms to ensure they consider different types of expertise when developing policy.

Looking forward, STI policies should be recalibrated to tackle the long-term challenges of sustainability, inclusivity and resiliency

The pandemic and its effects offer a stark reminder of the need to transition to more sustainable, equitable and resilient societies. Science and innovation will be essential to promote and deliver such transitions, but the pandemic has exposed limits in research and innovation systems that, if not addressed, will prevent this potential from being realised. Governments should rethink STI policies along several lines to deal with these limits.

First, the current crisis serves as a reminder that policy needs to be able to guide innovation efforts to where they are most needed. This has implications for how governments support research and innovation in firms, which account for about 70% of R&D expenditures in the OECD. The business R&D support policy mix has shifted in recent decades towards a greater reliance on tax compared to direct support instruments such as contracts, grants or awards. While effective for incentivising businesses to innovate, R&D tax incentives are indirect, untargeted and tend to generate incremental innovations. Well-designed direct measures for R&D are potentially better suited to supporting longer-term, high-risk research, and targeting innovations that either generate public goods (e.g. in health) or have a high potential for knowledge spillovers. Governments need to revisit their policy portfolios to ensure an appropriate balance between direct and indirect measures.

Second, the multifaceted nature of addressing complex problems like COVID-19 and sustainability transitions underscores the need for transdisciplinary research to which current science system norms and institutions are ill-adapted. Disciplinary and hierarchical structures need to be adjusted to enable and promote transdisciplinary research that engages different disciplines and sectors to address complex challenges.

Third, governments should link support for emerging technologies, such as engineering biology and robotics, to broader missions like health resilience that encapsulate responsible innovation principles. The responsible innovation approach seeks to anticipate problems in the course of innovation and steer technology to best outcomes. It also emphasises the inclusion of stakeholders early in the innovation process.

Fourth, reforming PhD and post-doctoral training to support a diversity of career paths is essential for improving the ability of societies to react to crises and to deal with future challenges like climate change that require science-based responses. Reforms could also help relieve the precarity of early-career researchers, many of whom are employed on short-term contracts with no clear prospect of a permanent academic position. The crisis has also highlighted the need for academia to train and embrace a new cohort of digitally skilled research support professionals and scientists.

Fifth, global challenges require global solutions that draw on international STI co-operation. The development of COVID-19 vaccines has benefited from nascent global R&D preparedness measures, including agile technology platforms that can be activated as new pathogens emerge. The pandemic has created momentum to establish effective and sustainable global mechanisms to support the range and scope of R&D necessary to confront a wider range of global challenges. However, governments need to build trust and define common values to ensure a level playing field for scientific co-operation and an equitable distribution of its benefits.

Finally, governments need to renew their policy frameworks and capabilities to fulfil a more ambitious STI policy agenda. Increasing policy emphasis on building resilience, which calls for policy agility, highlights the need for governments to acquire dynamic capabilities to adapt and learn in the face of rapidly changing environments. Engaging stakeholders and citizens in these efforts will expose policymakers to diverse knowledge and values, which should contribute to policy resilience. Governments should also continue to invest in evidence about their STI support policies with a view to improving them.

1 COVID-19: A pivot point for science, technology and innovation?

The COVID-19 pandemic has called for science, technology and innovation (STI) to provide solutions. At the same time it poses major challenges for STI systems, and there remains uncertainty on its near-term and long-term impacts. This chapter outlines the STI policy responses to the COVID-19 shock and the effects of the crisis on STI systems. It offers a stylised framework for governments to systematically monitor the evolution of the crisis and its consequences from an STI policy perspective. It discusses a series of "critical pivot points", where future developments could go in radically different directions. The chapter concludes by discussing how STI policy can best contribute to shaping those critical pivot points to support a transition towards more equitable, sustainable and resilient futures.

Key findings

- **Research and innovation systems have responded impressively to the pandemic**, underpinning much of the resiliency countries have shown. Both private and public actors in the STI system have provided solutions to the crisis, most visibly in the rapid development of vaccines, but also in the rollout of digital technologies that have helped lessen the pandemic's impact. COVID-19 has accelerated trends that were already underway, opening access to scientific publications, increasing the use of digital tools, enhancing international STI collaboration and spurring a variety of public-private partnerships.
- **The pandemic continues to pose major challenges for STI systems**, endangering key productive and innovation capabilities, especially in hard hit sectors. Important segments of the STI system have been severely affected, including a large share of small and medium-sized enterprises (SMEs), early-stage start-ups, young researchers still needing to make their mark, and women – who, on average, devoted more time to care duties at the expense of their STI activities during lockdown. In the short-term, governments should continue their support for science and innovation activities that aim to develop solutions to the pandemic and to mitigate its negative impacts, while paying attention to the uneven distributional effects of COVID-19.
- **Many uncertainties remain that will shape research and innovation systems, and the contributions these systems can make to solving societies' longer-term grand challenges**. The chapter discusses a series of "critical pivot points", where future developments could go in radically different directions. Monitoring these can provide an early warning system that alerts policy makers (and others) to possible future developments. It also allows decision makers to keep sight of alternative pathways and outcomes they could pursue, or want to avoid, thereby making STI policy more agile and resilient.

Introduction

The COVID-19 pandemic poses a global health threat and has resulted in the largest global economic crisis since the Second World War. In the absence of population immunity to the disease and effective treatments, extensive lockdowns and related sanitary and “social distancing” measures are needed, which involve a high socio-economic cost. In this context, much attention has been directed at science, technology and innovation (STI) to provide solutions quickly, even though the COVID-19 crisis has also severely affected STI activities. With ongoing uncertainty on the evolution of the pandemic, and massive government intervention to safeguard public health and the economy, the global economy faces several critical pivot points that will shape the longer-term impacts of the crisis. STI systems and policies have a role to play in shaping the directions of those critical pivot points.

The objective of this chapter is to synthesise the state of STI during the COVID-19 pandemic. It first presents how the STI system has engaged in finding solutions to the COVID-19 health challenge, and how the diverse actors of the STI system – industry, universities, public research institutes and the research workforce – were affected by the pandemic. Second, it provides a short overview of the types of STI policy measures implemented across the OECD area to respond to the crisis. Third, it discusses the key critical pivot points facing the global economy, their implications for STI, and how STI policy can best respond.

Both private and public actors in the STI system have engaged actively in providing solutions to the COVID-19 crisis. This has led to massive investments in research on vaccines and treatments, but also produced innovations to deal with the impacts of “social distancing” measures, such as improvements in digital tools to work remotely. A rapid surge in COVID-19-related research articles in the medical field and other disciplines was observed during the first months of the outbreak, and has been followed by a steady addition of research papers informing the scientific debate (see Chapter 2). Initiatives to facilitate data sharing and access to critical research infrastructures were also undertaken to speed up responses, along with new processes, such as hackathons, to solicit inputs and measures supporting effective collaborations. Nonetheless, as the world scrambles to find decisive solutions to COVID-19, it is debatable whether these collaborations have occurred on a sufficiently global scale, and whether funding has been sufficient and appropriately allocated.

With the sudden shock of the COVID-19 pandemic and its first wave, the operation of the STI system was severely affected, albeit with uneven impacts. Businesses, research institutes and universities saw their research and innovation activities severely disrupted by lockdowns and social distancing measures. Following the initial shock, several parts of the STI system – including venture capital (VC) funding, patenting and entrepreneurship, but also large research and development (R&D) investments by leading firms in the digital and health sectors – recovered quickly as governments lifted lockdown measures after the first wave of the pandemic. Many companies in the digital sector – already a leading R&D investor prior to the crisis – grew as the COVID-19 crisis hit, since digital tools proved essential to limit the costs of social distancing measures. The relatively quick recovery of parts of the STI system was also driven by the fact that aside from initial disruptions in global supply chains, a number of large companies were able to resume their activities and saw a return of demand after the lockdowns of the first wave of COVID-19 were lifted. Funding for innovation also kept up thanks to active government interventions and boosts to a number of firms by capital investors.

At the same time, important segments of the STI system were severely hit, including a large share of innovative small and medium-sized enterprises (SMEs), early-stage start-ups, young researchers still needing to make their mark, and women – who, on average, devoted more time to care duties at the expense of their STI activities during lockdown. The sectors most hit by the crisis – e.g. entertainment, tourism, retail and aviation – are among the smaller actors in terms of R&D-intensive technological innovation performance.

Early STI policy responses to the crisis strongly focused on providing funding for COVID-19-related research and innovation, with governments, foundations and industry raising several billion dollars to fund new vaccines and therapeutics. Governments also lent support to those STI actors most severely affected by the crisis. An impressive battery of fast-track policy measures were rolled out to mobilise the STI ecosystem to provide solutions to the pandemic, solicit inputs from diverse actors, facilitate co-operation and knowledge sharing, ease barriers that slow down innovation (e.g. through regulatory flexibilities and accelerated intellectual property examinations), and enhance international collaboration on addressing the global challenge. However, the ongoing uncertainty poses potentially longer-term challenges for STI to keep up as an engine of recovery.

The crisis also prompted government innovation, illustrated by the use of digital contact-tracing apps (though with mixed results), but also the use of real-time data analysis for policy making at levels not previously seen. Governments set up schemes to keep innovative businesses afloat (e.g. facilitating access to finance by innovative firms and start-ups), and help researchers and research institutes adapt to the new context (OECD, 2020[1]) Most countries are also preparing or have recently launched stimulus and recovery packages to boost the economy and, in particular, protect jobs that directly or indirectly support STI actors.

Looking forward, the COVID-19 pandemic presents a number of significant uncertainties for the future of STI. Besides the course of the pandemic itself, among those explored in this chapter are (1) the value society assigns to sustainability, inclusivity and resilience in shaping futures, but also to the role governments and STI should play in supporting those futures; (2) the pace and direction of the digital transformation, which influences both STI processes themselves and demands for innovation in the future; (3) social preferences on the importance of inclusive economic and societal outcomes, which may change fundamentally and affect the inclusiveness of innovation processes; and (4) changes in the international political economy – driven in part by the desire to reduce vulnerabilities in the future – which will shape the division of labour of STI systems at the national, (supranational) regional, and global levels.

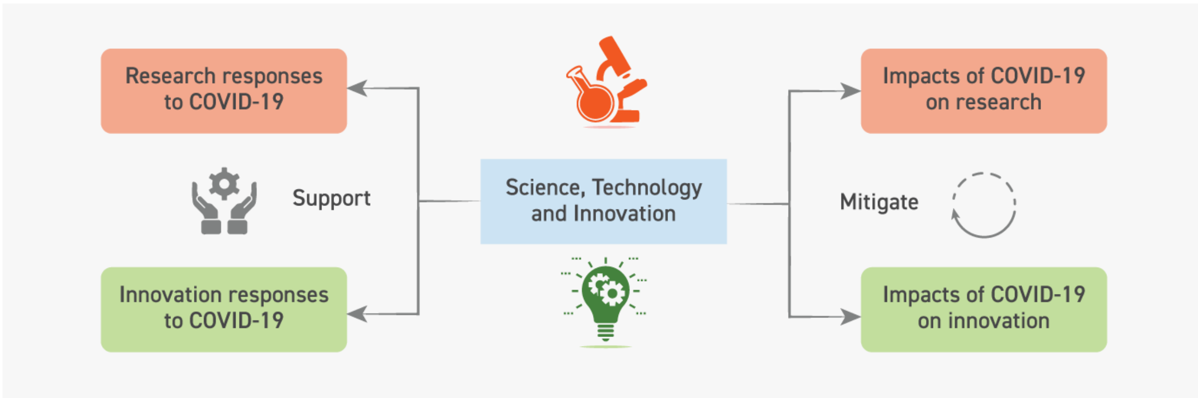
STI policies are affected by these uncertainties at the same time that they can contribute to shaping them. Policy can deploy STI to find solutions, manage effective dialogue between citizens and government bodies to handle the COVID-19 crisis (including confinement decisions and their trade-offs), deal with the potential distributional effects of COVID-19 on STI systems, and mobilise the responsiveness of STI systems. STI policies will also be influenced by the manner in which the COVID-19 crisis and these key uncertainties co-evolve, e.g. in terms of available funding for research and innovation, and the priorities governments and other actors pursue.

More extensive analysis of the issues discussed here is provided in two policy papers on the impacts on STI of the COVID-19 crisis between January 2020 and September 2020 (Paunov and Planes-Satorra, forthcoming[2]), and on its possible longer-term impacts and policy implications for STI (Paunov and Planes-Satorra, forthcoming[3])[1]. The analysis also leverages information on country policies collected through the OECD Survey on STI Policy Responses to COVID-19 (OECD, 2020[4]).

STI responses to the COVID-19 crisis and impacts on STI systems

The COVID-19 pandemic has set off a cascade of responses from – and impacts on – the STI ecosystem in many countries (Figure 1.1). This section explores the situation in public research sectors and the business community, highlighting not only the pivot to relevant research and scientific advice, but also the disruption to research activities and the asymmetric impacts on researchers and firms.

Figure 1.1. The roles of STI in the immediate crisis



Public research organisations and researchers' responses and impacts

Research activities that respond to COVID-19

Rapid deployment of research on solutions to COVID-19

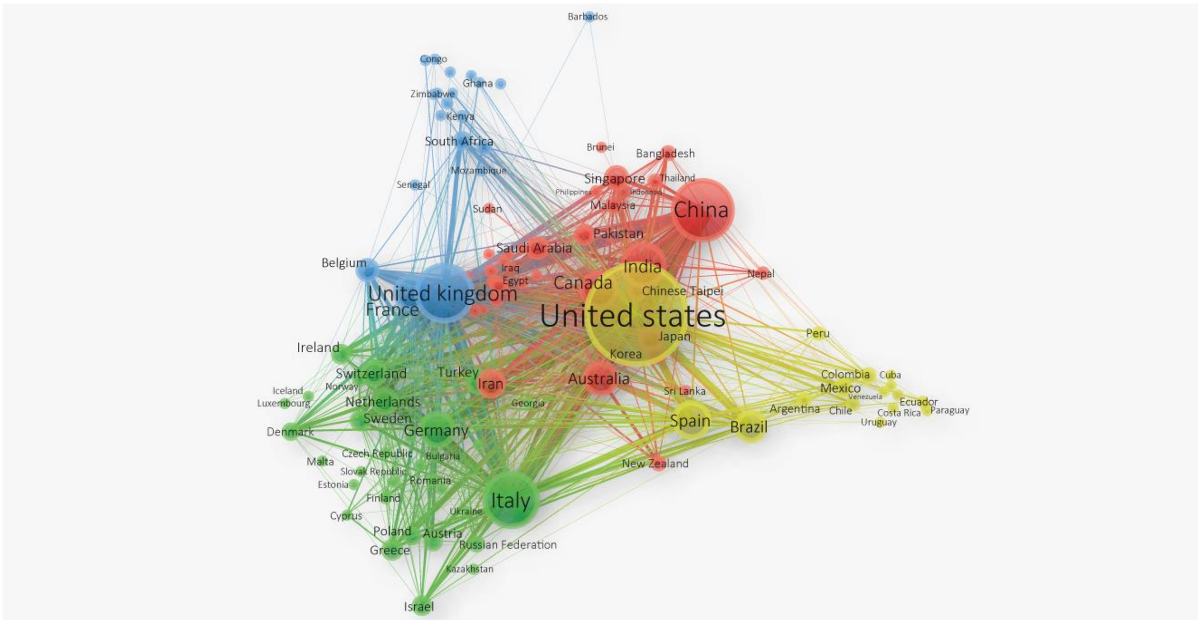
Universities, public research institutes, and pharmaceutical and biotech firms – sometimes in collaboration – have undertaken R&D to rapidly develop new treatments and vaccines for COVID-19. Several trackers provide real-time information on vaccine development, including the *New York Times* coronavirus vaccine tracker,[2] based on World Health Organization (WHO) data. Already by the end of May 2020, 131 vaccine candidates (10 in clinical evaluation) were under consideration. By early September 2020, the numbers had increased to 180 vaccine candidates, 35 of which were in clinical evaluation (WHO, 2020[5]). By mid-October 2020, the National Institute of Health's database in the United States showed that more than 3 600 trials on COVID-19 had been conducted or were still under way around the world (NIH, 2020[6]). The vast majority are clinical trials for drugs to treat COVID-19, around 30% of which are registered in the United States (Chapter 5). As 2020 drew to a close, the vaccination rollout had started in a first set of countries, providing cautious hope for an exit to the crisis, although reaching a critical mass of people will still take months and years.

The active engagement of the scientific community is also reflected in the explosion of scientific publications related to the virus. By mid-April 2020, more than 3 500 COVID-19-related articles had already been published in medical academic journals – a higher rate than for previous pandemics, according to PubMed, a free resource supporting the search and retrieval of biomedical and life sciences literature by the US National Center for Biotechnology Information (Bryan, Lemus and Marshall, 2020[7]). By the end of November 2020, articles related to COVID-19 on PubMed numbered around 75 000 (Chapter 2 provides a detailed breakdown of publications on COVID-19). Other evidence of the massive and rapid engagement comes from an international survey of researchers in different disciplines conducted by Springer Nature and Digital Science from 24 May to 18 June, which found that 43% of the 3 436 surveyed had already or were likely to repurpose their grants for COVID-19 research (Baynes and Hahnel, 2020[8]).

Figure 1.2 maps the country of origin of research on COVID-19 and shows that the United States and the People's Republic of China (hereafter, China) are among the two major contributors to COVID-19 publications on PubMed. They are also each other's main collaborating partner (see Chapter 5). Other research confirms this pattern, showing that the United States and China increased their levels of collaboration following the outbreak (compared to coronavirus research conducted prior to the COVID-19 pandemic) (Fry et al., 2020[9]). Other countries with high engagement in international research collaborations on COVID-19 include the United Kingdom, Germany, France, Italy, Australia, Canada and India.

Figure 1.2. International scientific collaboration on COVID-19 biomedical research

Whole counts, January to 30 November 2020



Note: A map with four clusters, also known as communities, was created based on economy affiliation bibliographic data. Economies are assigned to clusters based on their interconnection. The colour of an item is determined by the cluster to which it belongs. The higher the weight of an item, the larger its label and circle. Lines between items represent links. In general, the closer two economies are located to each other, the stronger their relatedness. The strongest co-authorship links between economies are also represented by lines. Note that the territory attribution for these indicators is entirely based on country affiliation information reported by the authors and publishers as registered on PubMed. Please refer to https://doi.org/10.1787/888934223099 for more methodological information.
Source: OECD and OCTS-OEI calculations, based on U.S. National Institutes of Health PubMed data, https://pubmed.ncbi.nlm.nih.gov/ (accessed 30 November 2020).

StatLink https://doi.org/10.1787/888934223099

Provision of scientific advice to policy makers and the public

Countries have different standing systems for providing science advice to policy makers, supplemented by additional ad hoc mechanisms in times of crisis. While most OECD countries have relied on national expertise, many lesser-developed economies have been more reliant on international sources of advice, for example from the WHO. As the pandemic has evolved, the requirements for scientific advice have expanded across ministries and geographic scales – local, national and international.

Scientific evidence that is informing the policy response to COVID-19 remains incomplete and conditional; as more data are collected, the scientific understanding of COVID-19 changes. This dynamic situation has represented a challenge for the scientific community at a time when policy makers and the public have sought assurance and certainty. Scientific consensus continues to be difficult to achieve, and yet communicating uncertainties and alternative views can undermine trust in scientific advice and related policies (see Chapter 8).

In many countries, scientific experts have become national spokespersons, who are expected not only to provide scientific evidence, but also to justify policy actions. This has sometimes blurred the distinction between advisor and policy maker. With the second wave of COVID-19 infections, there exists intense public debate about the scientific data and information that help determine policy. Trust is critical to ensuring support and compliance with policy measures, such as obligatory wearing of masks and social distancing. In the longer term, trust will be important in ensuring solidarity and broad public support for interventions to ensure socio-economic recovery.

Open access to journal articles has reached unprecedented levels

An important change effected by the pandemic has been the greater speed in which scientific research results have been released, highlighting the role of open science. Many journals have accelerated their peer-review processes to ensure rapid dissemination. Based on data from 669 articles published in 14 medical journals during and prior to the current pandemic, a study finds that the time to publish had decreased by 49% on average, from 117 days to 60 days (Horbach, 2020[10]). Pre-prints (i.e. academic papers that have not yet been peer-reviewed or published) have become more common in the medical research field in a matter of weeks. Pre-prints allow increased speed of diffusion (also across scientific fields) and reaching a wider range of potential peers. Their rapid adoption is also illustrated by the high proportion of open-access documents published: OECD analysis of PubMed finds that the share of open-access research on COVID-19 was 76% (compared, for example, to 43% for Diabetes and 40% for Dementia publications over the same period – see Chapter 2).

Impacts of the COVID-19 crisis on the public research sector

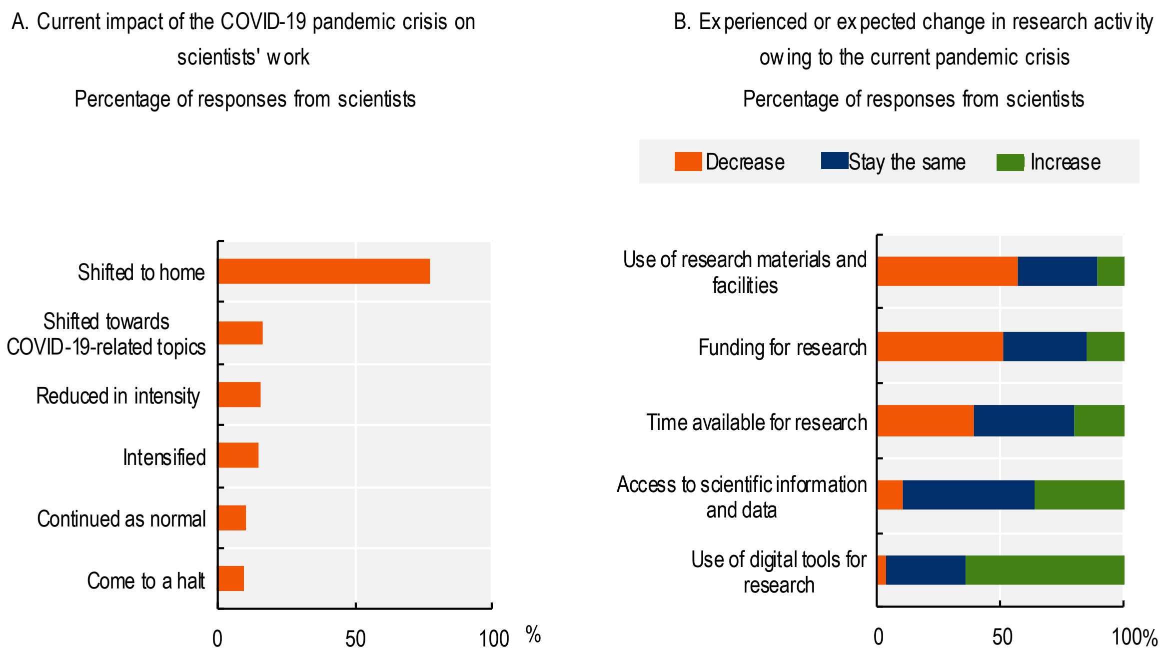
Limited access to research infrastructures and tools during lockdown

With the exception of activities directly addressing the COVID-19 health emergency and others considered essential to protect the public, research and innovation activities requiring physical access to laboratories and other research facilities, as well as those involving field work or clinical trials, were strongly disrupted by lockdown measures (World Bank, 2020[11]). This included activities where interruptions severely impede research delivery (e.g. long-term experiments where time-frequency observation is critical) and those requiring ongoing supervision for regulatory, safety or health requirements (e.g. caring for living specimens or research that uses hazardous materials)[3].

Where access restrictions applied, many researchers shifted to research activities that can be conducted from home (Stenvot, 2020[12]). A ResearchGate survey using data from 3 000 international researchers across academic fields suggested that nearly half of them replaced on-site activities with more focused writing, analysis, publishing and planning for future research during the first wave of the lockdown. In the absence of new research data, some also spent more time analysing older data sets that had not been explored previously (Research Gate, 2020[13]; Baynes and Hahnel, 2020[8]). Others donated their time and expertise to fight the coronavirus, repurposing their facilities and equipment to serve COVID-19 needs. For example, the Francis Crick Institute in London, a cancer research centre, has partly turned into a coronavirus-testing facility (Viglione, 2020[14]; Baker, 2020[15]).

Results from the OECD Science Flash Survey 2020[4] echo these findings, with more than three-quarters of scientists indicating they had shifted to working from home (Figure 1.3, Panel A). More than half experienced or expect a decrease in the use of research materials and facilities, and around 40% a fall in the time available for research. More than half also experienced or expect a decline in research funding (Figure 1.3, Panel B).

Figure 1.3. Impact of the COVID-19 crisis on scientists' work



Note: Panel A shows the percentage of responses from scientists to the statement, "In recent weeks and days, as the COVID-19 emergency intensified, your work has (i) Come to a halt; (ii) Continued as normal; (iii) Intensified; (iv) Reduced in intensity; (v) Shifted towards COVID-19-related topics; and (vi) Shifted to home". Panel B shows the percentage of responses from scientists to the question, "As a result of the current crisis, have you personally experienced or do you expect to experience a change in (i) Use of digital tools for research; (ii) Access to scientific information and data; (iii) Time available for research; (iv) Funding for research; and (v) Use of research materials and facilities?"
Source: OECD Science Flash Survey 2020, https://oecdsciencesurveys.github.io/2020flashsciencecovid/ (accessed 12 October 2020).

StatLink https://doi.org/10.1787/888934223118

The "COVID-isation" of research

The lockdown measures affected scientific disciplines unevenly by diverting research efforts towards COVID-19. Based on responses from 3 436 researchers, an international survey conducted by Springer Nature and Digital Science from 24 May to 18 June 2020 found that the disciplines most disrupted, e.g. due to lab closures, were chemistry, biology, medicine and materials science, while the humanities and social sciences reported the lowest impact (Baynes and Hahnel, 2020[8]). Based on responses from nearly 1 300 researchers, the OECD Science Flash Survey, launched in April 2020, found the lockdown had the highest disruption on immunology and microbiology, health professions, and pharmaceuticals, while physics and astronomy, and earth and planetary sciences, reported the least disruption.

The flip side to widespread engagement of the research community in designing solutions to COVID-19 is the risk of diverting research efforts away from non-COVID-19-related topics. The Cancer Research Institute, for instance, registered 958 stopped clinical trials due to COVID-19 from March to September 2020 (Cancer Research Institute, 2020[16]). This applies to the medical field, but also to other science fields (see Chapter 2). Madhukar Pai, Director of the McGill Global Health Programs, referred to this threat as the "COVID-isation" of research, which is leading researchers across disciplines to engage in such activities (Pai, 2020[17]).

Decline in income from research and tuition fees

Universities also face important short-term financial challenges resulting from the pandemic. Some students may defer or abandon their plans to engage in higher education programmes in 2020/21 (Jaschik, 2020[18]). Some may also abandon or postpone their plans to study abroad. Consequently, universities that rely heavily on student tuition fees, particularly those with an important share of international students, will suffer from reductions in income. This could also have an impact on research spending, as teaching income often cross-subsidises research activities. This could be accompanied by reductions in research funding (e.g. contract research income from firms) and other income-generating activities, such as accommodation and conferencing.

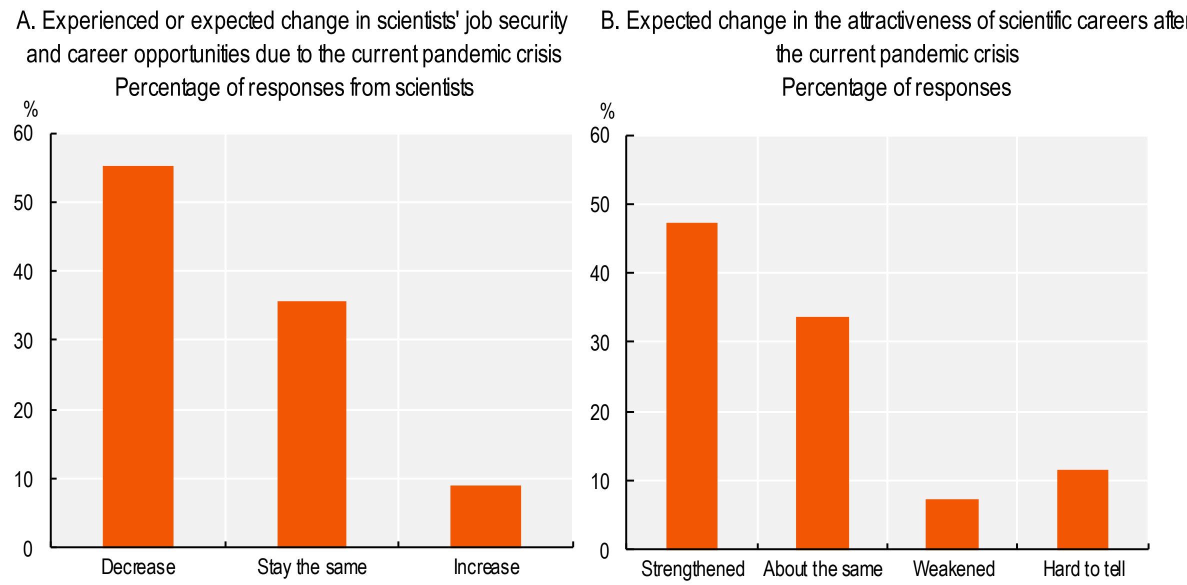
Effect of lockdown measures on researchers and successful adoption of digital substitutes

Severe restrictions to travel imposed by lockdown measures have interrupted the mobility of human resources in STI (e.g. visiting researchers, staff exchanges with industry). During the first months of the pandemic, many scientific events and conferences were postponed or cancelled, and uncertainty still prevails as to when they will fully resume. As substitutes, some of these conferences and events (including large flagship conferences) are increasingly organised digitally, sometimes registering very high attendance. For instance, the American Physical Society had over 7 000 registered participants for its April 2020 meeting held online, a significantly higher number than the 1 700 participants on average who would normally attend the in-person meeting (Castelvecchi, 2020[19]). Such a move has emphasised the advantages of digital conferences, particularly in terms of improved accessibility, reaching more diverse audiences, lower costs and reduction in the carbon footprint of travel. Nevertheless, virtual exchanges are not perfect substitutes for in-person conferences, which often result in collaborations and long-term trusted relationships, and also represent an opportunity for early-career researchers to find jobs and enhance the visibility of their work.

Negative impacts on young and female researchers

The limitations of virtual environments have favoured ongoing connections, but not the creation of new connections. They have also disadvantaged job starters, including early-career researchers with fixed-term contracts, who need to connect and share their work. More than half of the scientists who had responded to the OECD Science Flash Survey 2020 by October 2020 expected the crisis to negatively affect their job security and career opportunities (Figure 1.4, Panel A). Getting a foot in the door of industry research was also more difficult in the early phase of COVID-19. Evidence from the United States suggests that firms significantly cut back on postings for high-skill jobs in March and April 2020 (Campello, Kankanhalli and Muthukrishnan, 2020[20]). The COVID-19 shock has generally helped well-known researchers, but challenged early-career researchers to position themselves in the field. The need for swift solutions, and the ability of virtual events to draw more "star power", have led to fewer opportunities for less well-known researchers to express their views, culminating in more dominance for those singled out as superstars in their respective networks (see Chapter 2).

Figure 1.4. Scientists' expectations for a research career in light of the COVID-19 crisis



Note: Panel A shows the percentage of responses by scientists to the question, "As a result of the current crisis, have you personally experienced or do you expect to experience a change in your job security and career opportunities?" Panel B shows the percentage of all responses to the question, "How do you expect the world of science to emerge out of the current crisis, in terms of attractiveness of scientific careers?"
Source: OECD Science Flash Survey 2020, https://oecdsciencesurveys.github.io/2020flashsciencecovid/ (accessed 1 October 2020).

StatLink https://doi.org/10.1787/888934223137

Women were also particularly affected, as they spent more time on childcare and elderly care during the lockdown of the first COVID-19 wave (OECD, 2020[21]; Minello, 2020[22]). An analysis of more than 300 000 pre-prints and registered reports finds that women's research production significantly declined in March and April 2020 compared to both the two preceding months and the same two months of 2019, with a disproportionate impact on early-career researchers (Vincent-Lamarre, Sugimoto and Larivière, 2020[23]). Another analysis based on publication data for working papers finds that although COVID-19 has spurred research in economics, the average share of female researchers (particularly in early and mid-career positions) engaged in research related to the pandemic is significantly lower (12% of the total number of authors) than their average engagement in other topics (21%). However, the study also finds that women have continued to work on their ongoing research, suggesting they have contributed less to the new literature on the economics of pandemics (Amano-Patiño et al., 2020[24]).

Despite this gloomy picture, respondents to the OECD Science Flash Survey 2020 were more sanguine about the attractiveness of scientific careers in the long run, with nearly half expecting it to increase (Figure 1.4, Panel B).

Mobilising business innovation

Business innovation activities in response to COVID-19

Aside from research conducted by the health industry – often in connection with public research organisations – industry has also moved to respond to COVID-19 challenges. A survey of R&D professionals and decision makers at 247 patenting companies showed that close to one-quarter (23%) of companies had repurposed their innovations in markets, such as internet services, communications, sanitation and healthcare/hospital services, even if this was not their primary industry (Kanesarajah and White, 2020[25]). An illustrative example of industry engagement is the strong increase in United States Patent and Trademark Office (USPTO) patent applications on technologies supporting working from home (WFH) between January and May 2020 (Bloom, Davis, and Zhestkova, 2020[26]).

Another phenomenon observed during the first months of the pandemic was the quick development of frugal innovations to remedy supply shortages in medical equipment and other emergency products (Harris et al., 2020[27]). In mid-March 2020, an Italian start-up reverse-engineered a 3D-printed version of a respirator valve and supplied 100 of those to Chiari hospital within a few days. Soon afterwards, the team engineered an emergency ventilator mask, modifying a snorkelling mask already available on the market from the French sporting goods retailer Decathlon (Isinnova, 2020[28]). Some firms in the automotive, aviation or consumer-goods sectors repurposed (part of) their production lines to manufacture urgently needed medical equipment, such as ventilators and respirator equipment, masks, protective face shields and hand sanitiser.

Academic start-up companies also played an important role in answering the immediate needs posed by the COVID-19 health challenge. Zentech,[5] a biotechnology company founded in 2001 as a spin-off of the University of Liege, developed "QuickZen", an antibody testing kit intended for use by healthcare professionals. AdaptVac,[6] a joint venture between ExpreS2ion Biotech and the University of Copenhagen spinout NextGen, is currently focused on developing a vaccine against COVID-19. In the technology sector, the Indian start-up Azimov Robotics[7] has developed robots to serve COVID-19 patients (e.g. bringing them food and medicines, performing disinfection, and enabling video calls between the doctor and the patient).

Impact of the COVID-19 crisis on business research and innovation

Innovative companies were hit by lockdowns

Many businesses scaled back on innovation activities at the height of the lockdown. According to an April 2020 survey of innovative companies conducted by the German Federal Ministry for Economic Affairs and Energy, which received 1 800 responses (86% from SMEs), 54% of companies had suspended ongoing research and innovation projects, and 24% were planning to terminate one or more projects (BMWi, 2020[29]). An international survey and subsequent interviews of over 200 executives across industries conducted by McKinsey in April 2020 found that the focus on innovation as a core business priority had decreased across most industries – except the pharmaceutical and medical supply sectors – as companies sought to address immediate COVID-19-related challenges (McKinsey, 2020[30]).

Sharp decreases in demand during the first-wave lockdown period and reduced access to research infrastructures affected innovation. As is the case elsewhere, lockdown measures led to the closure of most innovation and testing facilities, labs and science parks. This had a direct impact on many firms' ability to progress with their planned research, product development and commercialisation activity, as set out in business plans and investor agreements. More broadly, early estimates for the OECD area suggested that in the absence of government intervention, 30% of firms would run out of liquidity after two months of confinement (OECD, 2020[31]). A survey of 414 technology firms conducted in Israel in May 2020 found that 54% of firms (and 65% of firms with under ten employees) would not be able to maintain operations for more than six months (Solomon, 2020[32]).

Innovation performance persisted and recovered

The evidence from patent data to date suggests moderate and short-lived impacts of the pandemic's first wave. Comparing trends in Patent Cooperation Treaty (PCT) patent applications between November 2019 and June 2020 with the same period year on year, OECD countries experienced on average a slowdown in patent filings following the COVID-19 outbreak. However, the pandemic itself has not resulted in a dramatic break in patenting trends. In the case of China, PCT patent filings in March 2020 even returned to the levels registered in March 2019, and in the OECD as a whole, the gap with the previous year seemed to be narrowing as of June 2020. Instead, reductions in innovation activities owing to COVID-19 may be reflected in patent applications in the coming months or years. Evidence from the 2008-09 financial crisis showed this pattern across many countries. The demand for digital innovations may, however, produce different trends for such inventions. For example, the finding that patenting in WFH in USPTO patent filings increased at the onset of the first COVID-19 wave (Bloom, Davis, and Zhestkova, 2020[26]) points to a different pattern. Interview evidence from 247 leading patenting firms also shows they have maintained their innovation activities, often by responding to new demands during the first wave of the COVID-19 pandemic (Kanesarajah and White, 2020[25]).

Asymmetric impacts of the COVID-19 crisis across sectors

The COVID-19 crisis has had unequal effects across economies. Some firms and sectors have been particularly hard hit, particularly those characterised by comparatively lower levels of innovation. Within the service sectors, the tourism, travel and leisure industries, as well as activities requiring contact between consumers and service providers (e.g. hairdressers and retailers), businesses were highly affected by restrictions on movement and social distancing. The same services are mostly being directly impacted by the re-confinement measures adopted to respond to the second wave of COVID-19 infections. The overall impact on business R&D is likely to be minor, since the average company's R&D investment in these sectors is low. However, more R&D-intensive activities were also impacted, including manufacturing sectors with long global supply chains (e.g. automotive and electronics), as demand for durables momentarily dropped. Demand gradually increased again as lockdown measures were lifted, except in those manufacturing industries that are directly linked to the tourism and transportation sectors.

Some businesses, particularly in the digital sector (e.g. cloud services, videoconferencing and digital collaboration tools, video streaming, online shopping, online learning and telemedicine), are thriving in this context and continue to innovate, with increased demand for their products. Figure 1.5 shows corresponding R&D investments in the digital sector as well as the pharmaceutical sectors, compared to a reduction in expenses among major companies in the automotive, aerospace and defence sectors.

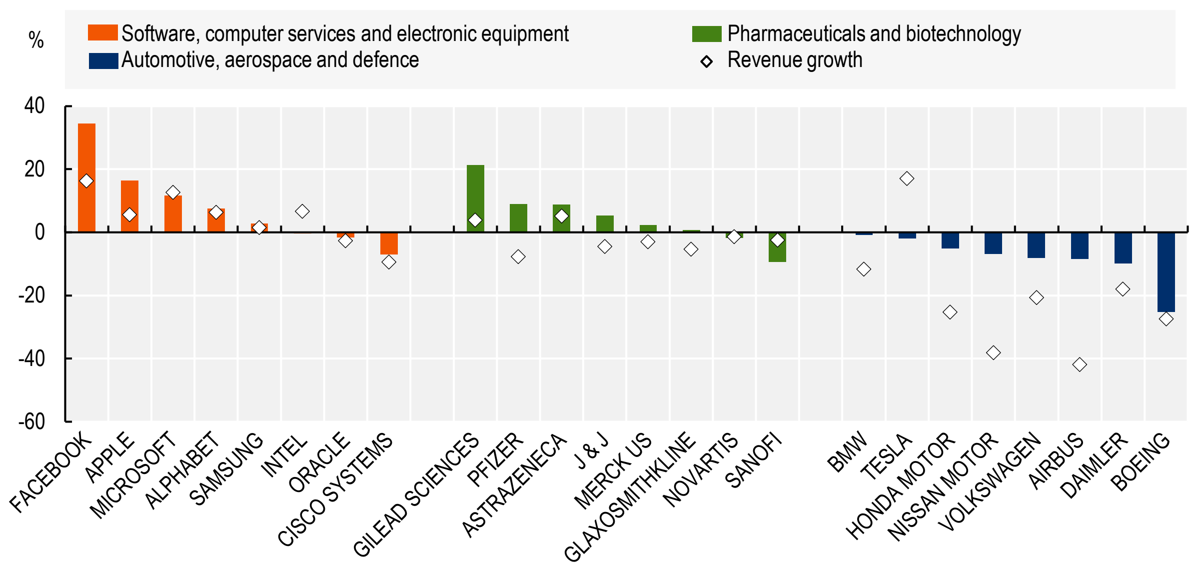
Business creation during the first wave of COVID-19

As is common in periods of crisis, lower new-business registrations and increased bankruptcies were observed in the first semester of 2020 compared to 2019 (Figure 1.6). Business registrations were down in Germany, France, Belgium and Iceland, but not in Norway, Japan, Sweden and the Netherlands, where enterprise creation was higher than during the first semester of 2019.

Early evidence for the United States shows that the initial shock of the first COVID-19 wave was short-lived, with a rapid rebound and surge in business applications (Dinlersoz et al., forthcoming[33]). The United Kingdom's Office of National Statistics also reported that the number of business creations in the United Kingdom in the third quarter of 2020 was slightly higher than during the same period in 2019, following a small fall in the second quarter of 2020 (Office for National Statistics, 2020[34]). While this is a positive phenomenon, it may only be temporary given future uncertainties. Moreover, some of the business creation may stem from individuals affected by unemployment temporarily opting for private business activities.

Figure 1.5. Reported R&D expense and revenue growth in selected R&D-intensive companies

Percentage change between April-September 2019 and April-September 2020

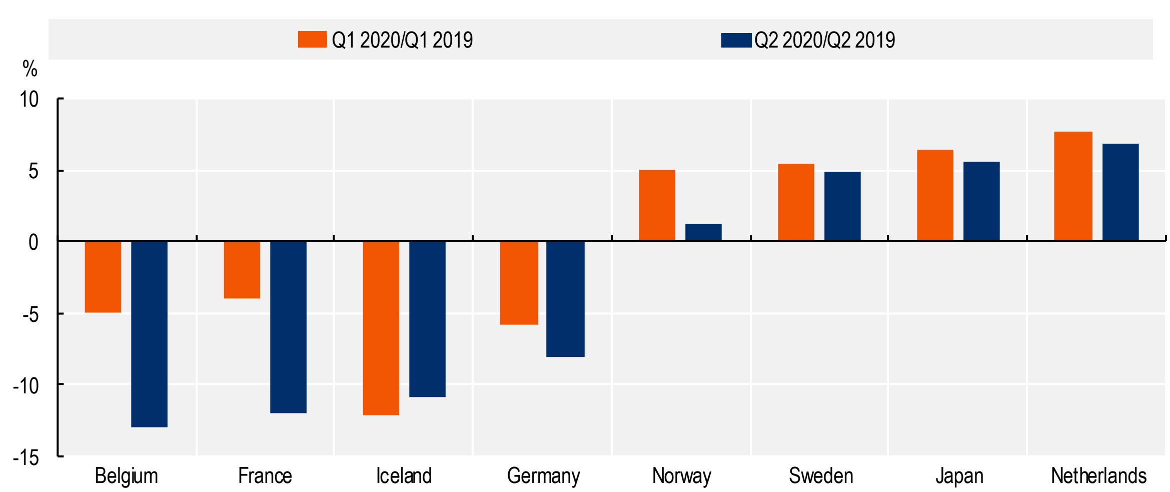


Note: R&D growth rates are in nominal terms and measured between April to September 2019 and April to September 2020. Data refer to the 6-month period from the beginning of April to the end of September, except for Cisco (May to October) and Oracle (March to August). Company reports of R&D expense need not coincide with R&D expenditures as covered in official R&D statistics compiled according to the Frascati Manual. Methodological information can be found in the StatLink below.
Source: OECD calculations, based on published quarterly business financial reports, December 2020.

StatLink https://doi.org/10.1787/888934223156

Figure 1.6. Growth rates in enterprise creation

Q1 2020/Q1 2019 and Q2 2020/Q2 2019 for a selection of countries



Note: The concept of enterprise "creation" reflected in the data series differs across countries. The OECD Timely Indicators of Entrepreneurship Database uses data based on national definitions only. An enterprise creation refers to the emergence of a new production unit. This can be either due to a real birth of the unit, or creations by mergers, break-ups, splitoffs or through the re-activation of dormant enterprises.
Source: OECD (2021[35]), "Timely indicators of entrepreneurship", Structural and Demographic Business Statistics (database), https://doi.org/10.1787/b1bfd8c5-en (accessed on 19 October 2020).

StatLink https://doi.org/10.1787/888934223175

Venture-capital funding for innovative entrepreneurship

Early evidence suggests that the COVID-19 shock affected VC and angel/seed investment, a key source of funding for innovative start-ups (OECD, 2020[1]). According to analyses by Ipsos MORI, the number of VC deals at the global scale declined between January and August 2020, reaching its lowest level since February 2013 (Ipsos MORI, 2020[36]). A survey of 1 000 mostly US-based institutional and corporate venture capitalists also found they slowed their investment pace (71% of normal) during the first half of 2020 (Gompers et al., 2020[37]). Evidence from many countries suggest that early-stage companies were hit harder by investment declines, including in China (Brown and Rocha, 2020[38]), Ireland (ICVA, 2020[39]), the United Kingdom (Ipsos MORI, 2020[36]) and the United States (Howell et al., 2020[40]).

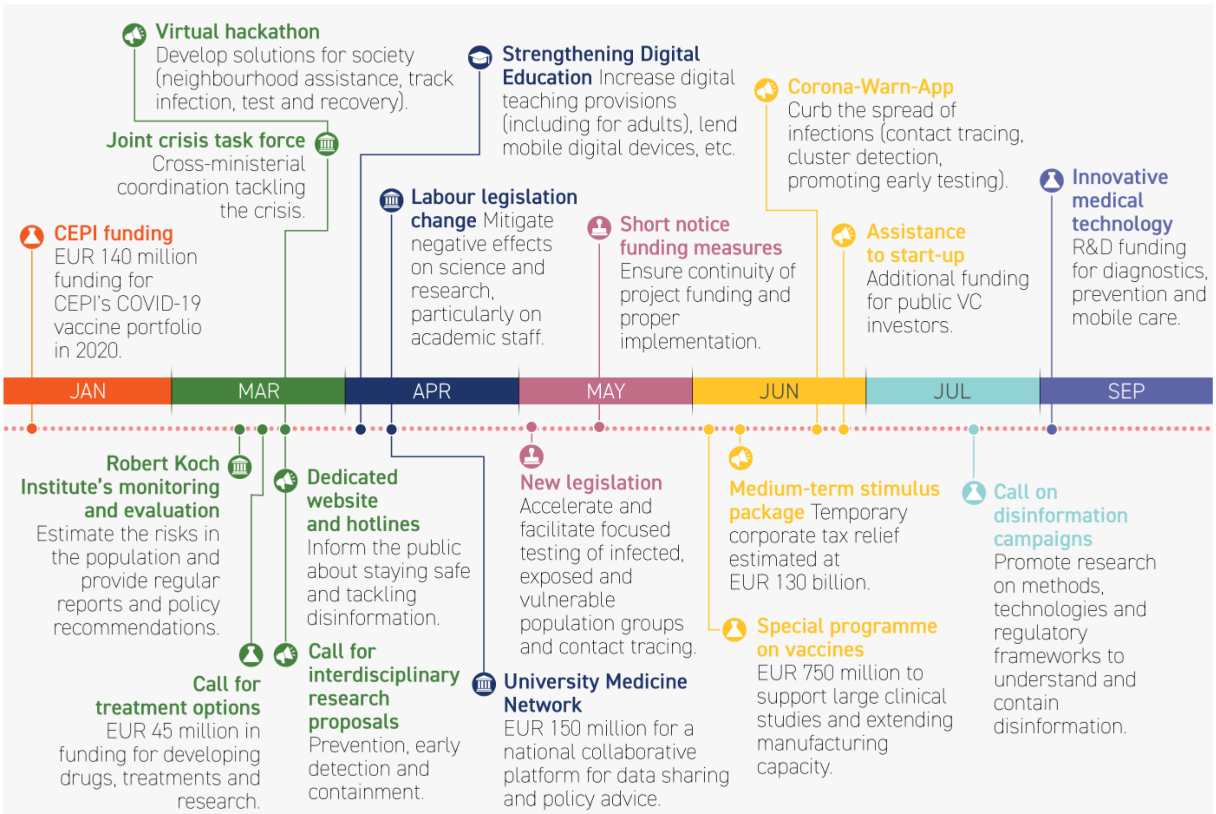
However, the aggregate shock to VC was much weaker than during the 2008-09 financial crisis, and VC activity had recovered relatively swiftly by July 2020. Indeed, the analysis by Ipsos MORI shows that the value of deals was already back to high levels by that date, although based on fewer large deals (Ipsos MORI, 2020[36]). The study by Gompers et al. (Gompers et al., 2020[37]) also notes that the slowdown in investments was more modest than during the 2001-02 dotcom bust (where investments declined more than 50%) and the 2008-09 global financial crisis (when investments declined by 30%). There exist, however, important asymmetries in funding, with more financing allotted to established larger firms and companies operating in sectors that benefited from the COVID-19 pandemic. This change in the distribution of VC funding may still challenge future innovation dynamics across different sectors and actors, notably early-stage companies.

Mobilising STI policies to combat the COVID-19 pandemic

STI policy responses to the COVID-19 pandemic

STI policy makers rapidly stepped up their responses to the COVID-19 pandemic, seeking to both mobilise and protect STI systems. Initial efforts directed resources at finding medical solutions (i.e. vaccines and treatments), and supporting innovation actors in research and industry hit by the pandemic shock. To address the socio-economic costs of the crisis, governments invested in STI, including through initiatives to boost digital services, enhance the capacity of public and private organisations to use these across education and industry, and tackle the spread of misinformation. Governments also established co-ordination mechanisms to ensure efficient STI responses and implementation of measures at different levels of government (see Chapter 8). For example, Ireland established a cross-governmental National Action Plan on COVID-19, and South Africa set up a National Command Council. Countries have implemented a wide range of measures. Figure 1.7 illustrates the measures implemented by Germany's federal government from January to September 2020.

Figure 1.7. Germany's federal level STI policy response to COVID-19, January-September 2020



Source: OECD (2020[4]), STIP COVID-19 Watch (https://stip.oecd.org/Covid.html).

Fast-tracking of research initiatives

Governments, firms and foundations have committed large amounts of funding for R&D activities aimed at developing vaccines, therapeutics and diagnostics for COVID-19. In the United States, the National Institutes of Health (NIH) alone had devoted USD 1.8 billion to research on COVID-19 as of April 2020 (Lauer, 2020[41]). The European Commission had mobilised EUR 1 billion (i.e. USD 1.2 billion) as of May 2020 under Horizon 2020, the EU framework programme for research and innovation (European Union, 2020[42]). Several R&D funding trackers provide regularly updated estimates of the total amounts of funding allocated to COVID-19 R&D projects. According to the tracker developed by Policy Cures Research,[8] a global health think tank, more than USD 9.1 billion had been committed by government, industry and philanthropic organisations as of 18 September 2020 to COVID-19 R&D projects. Nearly 60% of such funding has been allocated to R&D on vaccines, and around half of the funds have come from organisations located in the United States (Policy Cures Research, 2020[43]). The COVID-19 Research Project Tracker[9] jointly maintained by the UK Collaborative on Development Research and the Global Research Collaboration for Infectious Disease Preparedness shows a remarkable number of projects dedicated to studying societal responses to the COVID-19 crisis (see Chapter 2). As of September 2020, data from the OECD collection of COVID-19-related R&D funding show total public and philanthropic investments in R&D projects amounting to USD 6.6 billion (see Chapter 2) (OECD, 2020[4]).

As described in Chapter 2, many governments have fast-tracked competitive research-funding initiatives to support the development of COVID-19 vaccines, diagnostics and treatments. In March 2020, the French National Agency for Research launched a Flash COVID-19 call[10] for EUR 3 million (soon increased to EUR 14.5 million) allowing the evaluation, selection and funding of research proposals within a short period of time. In some cases, support is channelled through existing funding mechanisms to accelerate responses. In Canada, one of the measures of the Mobilize Industry[11] plan is to refocus existing industrial and innovation programmes (e.g. the Strategic Innovation Fund and Innovation Superclusters) on the fight against COVID-19. Some government calls also encourage existing grant holders to repurpose their research and innovation activities. The UK Research and Innovation (UKRI) grants programme for ideas related to COVID-19[12] invites researchers holding existing UKRI standard grants to switch the funding to COVID-19 priority areas (UKRI, 2020[44]).

Governments have also invested in improving the visibility of research-funding opportunities, often by creating online platforms that list all relevant information on STI activities related to COVID-19, such as the European Commission's European Research Area (ERA) corona platform[13] and Portugal's Science 4 COVID-19 portal[14] (OECD, 2020[45]).

Accelerating innovation to respond to COVID-19

Most countries have also implemented measures to stimulate quick innovative responses to the wide range of challenges posed by COVID-19 – from preventing virus transmission, to producing essential supplies, combatting misinformation and handling effects of the lockdown. Country approaches include:

- **Launching fast-track open competitions**. These seek to stimulate out-of-the box thinking by aiming for inputs from all parts of STI systems, including from firms, research teams and individual inventors. Ireland's COVID-19 Rapid Response Call and the United Kingdom fast-track competition for business-led innovation in response to global disruption are fairly open, and ask applicants to demonstrate the relevance of the COVID-19-related challenge they address with their innovations.
- **Organising or supporting virtual hackathons**. Hackathons are typically 24- to 48-hour events during which participants are provided with data they must use to create an innovative product. Winners are compensated with funding to develop and scale their ideas. In late April 2020, over 30 000 participants from across the European Union joined the EUvsVirus hackathon hosted by the European Commission and the European Innovation Council to address around 20 COVID-19-related challenges. More than 2 100 solutions were submitted across different challenge categories, with the highest contributions on health and life (898), business continuity (381), remote working and education (270), social and political cohesion (452), and digital finance (75). A total of 117 innovative solutions were identified, including a highly scalable patient monitoring system that minimises the need for physical contact between nurses and patients (European Commission, 2020[46]). The winners were invited to a "Matchathon" (and a Demo Day) in May 2020 to help winning teams match with corporations, investors and accelerators around the world to put their innovative solutions into production. This matching exercise generated more than 2 000 new partnerships (European Commission, 2020[47]).
- **Promoting research collaborations**. Governments are also launching initiatives to encourage research and innovation collaboration. In Canada, for example, the National Research Council Pandemic Response Challenge programme15 aims to mobilise Canadian and international researchers from universities, business and government to work together on specific COVID-19 challenges identified by Canadian health experts (Government of Canada, 2020[48]).
- **Supporting data and knowledge sharing**. Data-sharing initiatives have been launched to share epidemiological, clinical and genomics data, as well as related studies (see Chapter 5). Protocols and standards used to collect data are also being shared. The COVID-19 Open Research Dataset (CORD-19),16 created by the Allen Institute for artificial intelligence (AI) in collaboration with the US government and several firms, foundations and publishers, contains17 over 200 000 machine-readable scholarly articles on COVID-19 and related coronaviruses (including over 100 000 with full text), and serves as a basis for applying machine learning techniques to generate new insights for COVID-19 research. Other initiatives include repositories of genome data (e.g. Nextstrain18

and Gisaid),19 chemical-structure data (e.g. CAS COVID-19 data set on antiviral candidate compounds),20 clinical studies (e.g. ClinicalTrials.org) and data for modelling research (e.g. MIDAS).21

- **Introducing regulatory flexibilities where needed** to ensure rapid responses while maintaining safeguards. In the COVID-19 emergency context, regulatory flexibilities were introduced where feasible. In Australia, the Therapeutic Goods Administration, part of the Department of Health, has been prioritising regulatory assessment of applications for therapeutic goods related to COVID-19. In the United Kingdom, the Medicines and Healthcare Products Regulatory Agency published a package of regulatory flexibilities to support the healthcare response to COVID-19, including through expedited scientific advice and rapid reviews of clinical-trial applications, and expedited clinical investigations of medical devices.22
- **Initiatives to facilitate access to research infrastructures**, such as laboratories, databases and tools, have been launched to help researchers accelerate their activities (see Chapter 2). For instance, the public-private COVID-19 High Performance Computing Consortium in the United States provides COVID-19 researchers worldwide with access to high-performance computing,23 while the European Research Infrastructure on Highly Pathogenic Agents offers access to in-vitro and in-vivo research capacities to researchers conducting studies on COVID-19.24
- **Setting incentive systems for intellectual property rights (IPR) to address the COVID-19 pandemic**. In May 2020, the USPTO launched a COVID-19 prioritised examination pilot programme to accelerate the examination of patent applications related to COVID-19 submitted by small and micro entities, without charging additional fees (USPTO, 2020[49]). An ongoing debate regarding the search for solutions to COVID-19 is how to harness IPR incentives in order to develop solutions without restricting access to those solutions.

Support for STI systems to withstand the pandemic shock

Aside from STI policy action to underpin research and innovation as it responds to COVID-19 challenges, the immediate STI policy response has focused on keeping innovative businesses afloat, and helping researchers and public research organisations adapt quickly to the new context. Such measures are often part of broader stimulus packages designed to boost the economy (e.g. the Coronavirus Aid, Relief, and Economic Security (CARES) Act in the United States),[25] which also directly or indirectly bolster STI actors. Compared to the 2008-09 financial crisis, the scale and speed of fiscal support provided by many countries during the COVID-19 crisis has been exceptional (IMF, 2020[50]). However, it is important to note that middle- and low-income countries have much more limited financial capacities to provide such support, and some countries are likely to need international assistance to weather the crises they are facing.

Immediate policy measures to address the negative impacts of COVID-19 on STI have included the following:[26]

- **Closely monitoring impacts of the crisis on different STI actors**. For example, Israel is conducting monthly surveys and has organised roundtables with essential stakeholders to obtain a comprehensive picture of the main challenges facing innovative businesses, and how these are evolving over time.
- **Introducing flexibilities for current beneficiaries of research and innovation programmes**. Most research-funding bodies have introduced flexibilities, as well as postponing application deadlines.
- **Supporting higher education institutes and researchers** – including early-career researchers – as they cope with short-term challenges. Measures have included helping higher education institutions provide academic staff with tools and training to effectively deliver their teaching activities online. Several measures aim to support PhD students: for example, UKRI is providing

grant extensions of up to six months to funded PhD students in their final year whose studies have been disrupted by the pandemic (see Chapter 3). In Germany, the Erasmus+ programme and German scholarship providers have flexibly revised their conditions for national and international students.

- **Supporting higher education and research institutes in protecting research jobs and research projects impacted by the pandemic**. Given the expected income loss from a decline in international students, the United Kingdom has launched a GBP 280 million (USD 361 million) scheme providing low-interest loans to universities to cover researchers' salaries and other costs, such as laboratory equipment and fieldwork, and to fund ongoing R&D projects.27
- **Facilitating access to funding for entrepreneurs and innovative firms**. Such support can take different forms, such as loans, grants and repayable advances. France launched a EUR 4 billion (USD 4.75 billion) Emergency Start-up Relief Plan, which provides state-guaranteed cash-flow loans; cash advances through the fast-tracked repayment of corporate tax claims that are refundable in 2020 (including the 2019 R&D tax credit); and early payments of innovation grants under the Investments for the Future Programme.28
- **Helping businesses** – particularly SMEs and start-ups – adapt to the COVID-19 context. Enterprise Ireland provides Lean Business Continuity Vouchers up to EUR 2 500 (USD 3 200) to companies so that they can acquire training or advice on how to continue operating their businesses during the pandemic.
- **Using digital tools to design and implement research and innovation policy**. Such tools promote quicker and more effective decision-making, based on stronger evidence. The Italian Ministry of Universities and Research launched a mapping activity to collect information about all ongoing and planned research projects on COVID-19, with the objective of reducing fragmentation and preventing unnecessary duplications.

Key uncertainties, critical pivot points, and their implications for STI systems and policy choices

The response to the pandemic raises several key issues where future developments are highly uncertain. Figure 1.8 sets out the key issues related to public research organisations and researchers, while Figure 1.9 does the same for key issues related to business research and innovation. In addition to these domain-specific issues, there exist broader "key uncertainties", e.g. related to societal and economic dynamics, technological change, and international relations, which will shape STI activities and policies over the coming months and years. "Going broad" is essential when thinking strategically about future developments, as changes emanating from outside one's own field of specialisation can often be the greatest source of surprise and disruption. The effects of a disruptive change like COVID-19 will be felt far and wide. Many impacts in other sectors will spill over and cascade through STI landscapes, with implications for STI policy. Some of these broader key uncertainties are particularly acute in the context of the pandemic and present "critical pivot points", where future developments could go in radically different directions. Mapping these pivot points, and outlining plausible yet sufficiently divergent visions of the future that capture a wide range of possible future developments, can make STI policy more agile and resilient.

Figure 1.8. Key issues emerging for public research organisations and researchers

Will public research funding shift towards new priority areas?
Public funding for research has an important influence on the type of research conducted and consequently the fields of scientific discoveries. The level of research funding for COVID-19 and other health research will depend on the course of the pandemic, but also on future policy orientations (e.g. an emphasis on essential goods and related research). In the absence of increased research budgets, additional spending on one issue will reduce funding elsewhere.

Will COVID-19 research dissemination practices accelerate the time needed to publish high-quality research?
The pandemic emergency has led to new ways of operating in science, notably by accelerating the speed at which research findings are published. This was achieved through a mix of methods, including new types of peer review and alternative publication formats. The obvious advantages from quicker publication have raised questions about possible downsides, particularly in terms of quality, but also the feasibility of faster publication processes if applied to all disciplines. Yet the pandemic experience may result in new debates on alternative publishing arrangements. Much will depend on whether it will be possible to guarantee the quality of the research published under such arrangements, in which case quicker dissemination may accelerate scientific exchange and ultimately progress.

Will the pandemic lead to a stronger push for open science?
To accelerate research, a vast amount of research data were made publicly available, along with investments to facilitate working with these data. A prominent example is the COVID-19 Open Research Dataset, discussed below. Other initiatives were also implemented and may generate new impetus for more open science. Nonetheless, several structural factors complicate expanding open science, which are neither obvious nor easy to resolve.

How diverse will the research workforce be?
The first wave of the COVID-19 pandemic has had an impact on research, especially challenging early-career researchers and women. With the second wave of the pandemic and continued social distancing measures, the question of possibly permanent effects on the diversity of the research workforce is pertinent. This directly relates to the discussion below on critical pivot points for inclusion and exclusion. The future workforce will also be affected by the impacts of the COVID-19 pandemic on the diversity of students choosing to engage in science, technology, engineering and mathematics disciplines, and more broadly in innovation activities.

Figure 1.9. Key issues emerging for the future of business research and innovation

How will business research and innovation respond to ongoing uncertainties?
Market uncertainties are known to limit business innovation. However, industry may identify fields of safe future demand – such as for environmentally sustainable technologies – if recovery packages feature large public funding commitments.

How inclusive will innovation be in the future?
This depends on whether sectoral innovation dynamics will create large imbalances in investment, whether certain regions will be further disconnected, and whether small-sized firms will keep up with their larger counterparts, favouring wider diffusion of STI. Changes in market concentration, driven by inequalities in the impacts of the pandemic, will also shape the future inclusiveness of innovation.

How will industrial research and innovation evolve in a context of countries seeking wider resilience to shocks?
The COVID-19 crisis led to shortages in "essential goods" stemming from a massive global demand shock, sometimes leading to production capacities being reassigned to meet requests for personal protective equipment, ventilators, etc. A potential shortening of global value chains, combined with changes in industrial patterns aimed at increasing resilience, might induce changes in business research and innovation performance in specific sectors. The extent of the changes will also depend on which items are included in the list of "essential goods".

How will entrepreneurship flourish in a context of ongoing uncertainties?
The future evolution of entrepreneurship will depend on how uncertainties will be interpreted, and to what extent opportunities arising from the pandemic (such as the demand for new digital ways of interacting, despite social distancing) will be seized by start-ups rather than established businesses (including large players in the field).

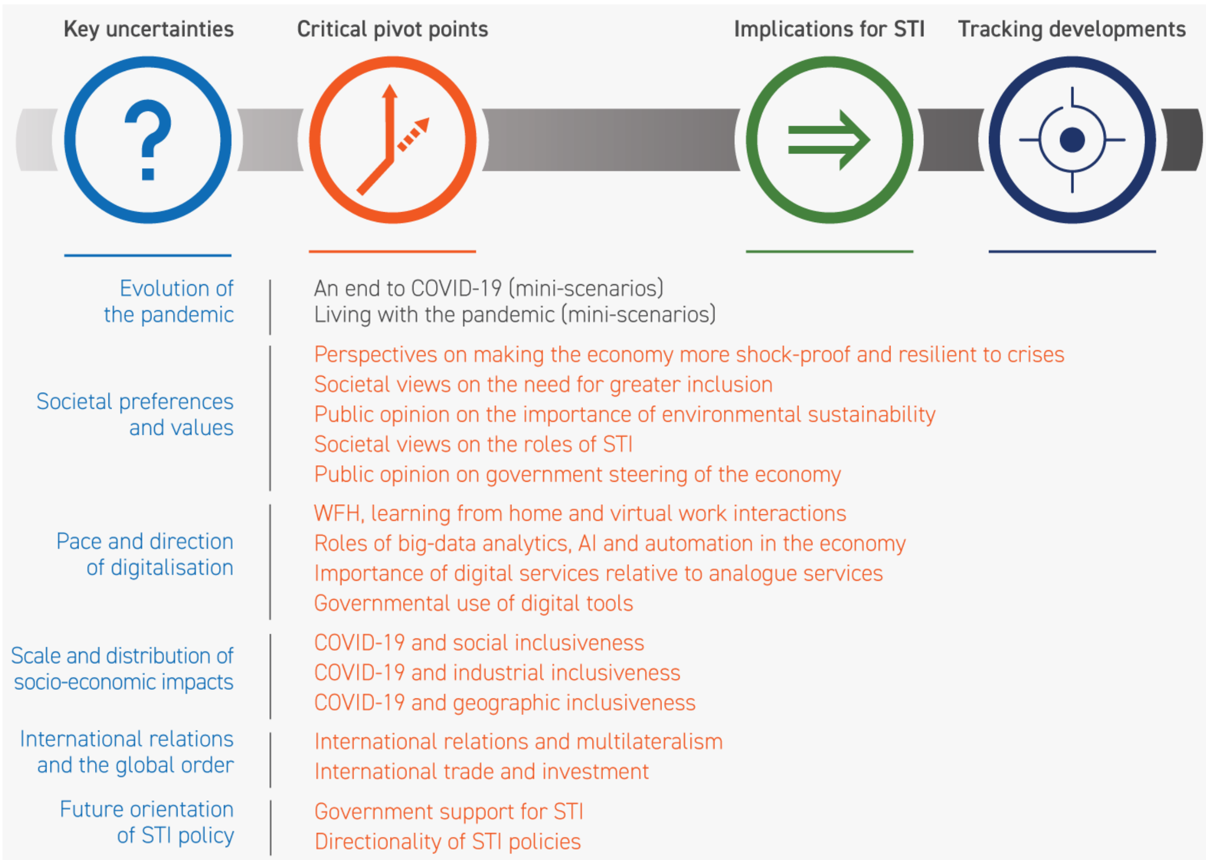
This section offers a stylised framework for systematically monitoring the evolution of the crisis and its impacts from an STI policy perspective (Figure 1.10). Given the fast pace of change during the crisis, providing such a framework, rather than just an ad hoc set of forecasts, can be useful. When combined with regular monitoring using indicators, it can operate as an early warning system that alerts policy makers (and others) to possible future developments. It also allows decision makers to keep sight of alternative pathways and outcomes they could pursue – or want to avoid. Indeed, the course of uncertainty is shaped by choices on the direction to be taken to avoid some obviously bad choices and pursue more promising ones.

The framework has four main elements:

1. **Key uncertainties**: the first step is to start with a limited set of high-level key uncertainties related to the pandemic crisis that are expected to have significant implications, including for STI and STI policy, as shown in Figure 1.10. How these key uncertainties unfold can be influenced by STI and STI policy, but is also somewhat influenced by exogenous factors. Other key uncertainties could be added later as users deploy the framework. In the version below, other crises and challenges, such as the climate emergency, are introduced as part of economic stability and recovery packages, but they could be included as standalone elements.
2. **Critical pivot points**: most of the key uncertainties covered here comprise critical pivot points, which refer to aspects of uncertainty where radically different development paths remain open. For the time being, each critical pivot point has just two opposing “mini-scenarios”, typically just a few sentences in length, to convey the main idea. Further mini-scenarios could be developed for each critical pivot point in a more comprehensive exercise.
3. **Implications for STI**: this element presents very briefly some of the implications of the critical pivot points’ opposing mini-scenarios for STI and STI policy. These are pitched at a high level and are somewhat speculative, as is typical of such exercises. Developing these implications further would be an important part of a more comprehensive and deliberative process.
4. **Tracking developments**: if the framework is to be used to track emerging developments, it should identify “leading indicators” at the level of the key uncertainty itself, but also covering the more specific effects on STI. As far as possible, these indicators should also be quantitative, but they could also be qualitative (e.g. news stories about the impacts of the crisis on firms or their activities and new policy announcements), signalling directions of future development. Given the lag times both in the appearance of effects and their measurement, nowcasts and short-term forecasts would be useful, although they are not especially well-developed in the STI policy field. On the other hand, STI-related activities tend to react slowly, particularly on the public research and innovation side, where long-term commitments, sunk costs and lock-ins are common. The section below briefly discusses some of the indicator options. It includes quantitative leading indicator charts for a few key uncertainties, both to draw attention to particular phenomena and demonstrate the framework in action.

The following sections explore six key uncertainties, as shown in Figure 1.10. The first key uncertainty is the evolution of the pandemic. Two main scenarios are outlined; they are presented here more as a backdrop to the other key uncertainties, and their implications for STI policy are not explored. The next four key uncertainties – on societal preferences, the pace and direction of digitalisation, inclusiveness and global relations – and their critical pivot points are set out in tables that also briefly outline the implications for STI and suggest possible leading indicators to track future developments. The tables are accompanied by an introduction of the issues at stake and their implications for STI, followed by a short summary of developments to date. The final key uncertainty – on the future orientation of STI policy – is treated differently than the others, in a more discursive style, as it is more endogenous to the STI field and a central concern of many STI policy makers. Even here, considerable uncertainty remains on the extent of future government support for STI given the worsening economic conditions, and the degree to which government support will be directed at challenges, such as the “green transition” that is encapsulated in several national recovery packages (OECD, 2020[51]).

Figure 1.10. Framework for considering the key uncertainties around COVID-19 and critical pivot points, with implications for STI



This framework is likely to evolve as it is used and as the crisis unfolds. This first version is therefore highly provisional, subject to further development through adoption and use. Policy makers and STI system stakeholders could use the framework to engage in an exercise that provides an international perspective on key uncertainties and critical pivot points, mapping their evolution to complement national efforts. These elements could also be building blocks for developing exploratory scenarios of future STI systems, which would help governments systematically appraise a wide range of policy options to shape the future state and dynamics of STI landscapes.[29]

The uncertain evolution of the COVID-19 pandemic

The course of the COVID-19 pandemic remains unknown, even with the regulatory approval of the first vaccines. Governments are tackling the “second wave” of the pandemic through containment measures that weigh on socio-economic activities, including the forced closure of restaurants and bars, the issuance of travel warnings and constraints, and lockdown measures of various severity. Uncertainty on the spread of the virus, the potential duration and form of restrictions, and the possibility of future new restrictions have prevented a full return to pre-crisis activities, particularly those involving social interactions and travel.

This uncertainty has had a negative impact on societal and economic optimism, despite the relatively good performance of STI across several dimensions in the early months of the pandemic, and the steady recovery of trade and economic activity as demand resumed. Massive stimulus packages implemented across the developed world have reduced even more substantive shocks, at least in the initial period.

Whether effective vaccines or treatments will remove the threat of COVID-19 (signifying “an end to COVID-19”), or whether the virus will remain a threat for years to come (“living with the pandemic”), various changes to future social and economic life are possible. Multiple scenarios on the course of the pandemic can also be envisaged (Scudellari, 2020[52]). Two are briefly outlined below:

- A quick solution bringing an end to COVID-19, either through effective vaccines and/or treatments, could mean a return to more-or-less business-as-usual. Practices that grew out of necessity during the pandemic, such as WFH, limited or no business travel, and use of online health and education services, would largely be reversed. However, successful experiences with some of these practices may lead to their continuation, even after the pandemic crisis has passed. Moreover, a shorter-lasting pandemic would offer a quicker economic recovery. Industry and governments would have the means to make the necessary investments to improve the technologies allowing such practices to flourish. They could also take measures to prepare against future shocks and disruptions, including those that will likely arise from the climate emergency.
- Living with the pandemic could lead to forced long-term changes. It may also result in a return to previous practices, despite ongoing pandemic risks, on account of the huge economic costs and reduced public acceptance of containment measures. In the context of the second wave of the pandemic, many governments are attempting to implement efficient social distancing to reduce COVID-19 cases while reducing economic damage as much as possible. If “living with the pandemic” results in a prolonged period of economic downturn, this would affect investments in socio-technical sustainability transitions.

Working out what scenarios like these might mean for STI activities is far from easy. The following section discusses various key uncertainties related to the pandemic and the critical pivot points they pose for the global economy, as well as their implications and significance for STI.

Key uncertainties and critical pivot points presented by COVID-19

Societal preferences and values

The issues at stake and their implications for STI

The COVID-19 pandemic and the resulting lockdown measures – leading in April 2020 to the confinement in their homes of more than 3.9 billion people – have affected the lives of most of the world’s population. In such a context, social preferences and their translation into future policy priorities may change. For instance, the experience of collective action during the crisis could spur new forms of solidarity, while collective narratives about the COVID-19 crisis could bring the link between environmental sustainability and societal resilience to the fore, leading societies to seek more balance in environmental, economic and social priorities (OECD, 2020[53]). At the same time, public opinion and societal views are far from being monolithic in democratic societies. There are varieties of opinions, values and interests at play, often competing with but also complementing one another. Recent years have seen greater polarisation of societies in many OECD countries, sometimes manifest as “culture wars” or inter-generational conflicts, which have been driven in part by growing inequalities, and the rise of identity politics and “populist” political parties.

Public opinion and societal preferences are shaped by numerous factors that are largely impossible to disentangle, though this does not make them any less important as influences on public policy. The management of the COVID-19 pandemic (e.g. the restrictions implemented and their effectiveness in controlling the spread of the virus, and the communication of scientific advice to the public), as well as the socio-economic impacts of the crisis (e.g. the level of reliance of the economy on sectors largely unaffected by the crisis, and the impacts on inclusiveness) are likely to have implications on how societies view government intervention in general, the roles of science in society, and the need for greater attention to sustainability, inclusivity and resiliency. Table 1.1 outlines several critical pivot points related to the impacts of COVID-19 on societal preferences and possible implications for STI.

Table 1.1. Critical pivot points in societal preferences and values

Impacts of the COVID-19 crisis: Critical pivot points
Perspectives on making the economy more shock-proof and resilient to crises *Factors favouring resilience as a key policy goal*: the COVID-19 crisis raises social awareness of the vulnerabilities of the real economy to shocks, favouring policy action to create more resilient economies. *Factors against resilience as a key policy goal*: the crisis is seen as an exceptional occurrence, which will not be repeated, and the changes needed to make economies more resilient are viewed as too costly. Consequently, there is little demand from society for more shock-proofing of the economy
Societal views on the need for greater inclusion *Factors favouring inclusion as a key policy goal*: problems of social and economic exclusion were exposed and exacerbated during the crisis. Inclusiveness as a goal gains ground in policy agendas as social movements like #MeToo and Black Lives Matter permeate political and social spheres. In the economic sphere, the dominance of big companies is seen as detrimental to socio-economic well-being and leads to a wider call to support SMEs. *Factors against inclusion as a policy goal*: the need to recover after the extensive economic shock relegates inclusiveness to a lesser priority. Movements such as nationalist groups advocating exclusion gain greater traction. Big companies provide products consumers demand and use their resources/capacities to respond to COVID-19 challenges, leading to implicit public endorsement of their dominance.
Public opinion on the relative importance of environmental sustainability *Factors favouring sustainability as a key policy goal*: the COVID-19 shock raises public awareness of the need to tackle climate change and environmental degradation as a key policy priority, as they pose risks of future shocks at an unprecedented scale. *Factors favouring less public support*: public opinion downplays the climate challenge as health matters and economic recovery (including preserving jobs at any cost) gain in importance.
Societal views on the roles of STI *Factors favouring STI*: public support for STI increases as it is seen to provide the only long-lasting solutions to the COVID-19 crisis, e.g. through the rapid development of an effective vaccine. *Factors against STI*: public opinion turns negative towards STI, e.g. because scientific advice is seen as a “culprit” for unpopular confinement measures and other restrictions.
Public opinion on government steering of the economy *Factors promoting more government “steering”*: the experience of the shock results in the perception that government needs to help “steer” markets to protect vulnerable crisis-prone economies. Trust in government interventions increases thanks to the perceived usefulness and effectiveness of actions taken to offset the negative impacts of COVID-19. *Factors against public opinion favouring government steering*: unpopular lockdowns and high death tolls mean public perceptions of government responses to the COVID-19 shock are unfavourable, which reduces public support for government to play key roles in steering the economy.
Examples of implications for STI
Transformative STI policies: societal perspectives on the importance of transforming socio-technical systems to be more resilient, inclusive and sustainable in the recovery would influence the objectives of STI policies and the policy instruments they use. For example, STI policies would be more directed towards social goals if society places greater value on issues of sustainability and inclusivity. **Scale of STI policy support**: societal opinion on the intensity of government intervention and the roles of STI would shape support for STI in stability and recovery packages. For example, if society views both STI and government intervention positively, STI would play prominent roles in ambitious recovery packages. **Reach of STI systems**: beyond influencing politics, changes in societal perceptions of STI will affect the influence of STI on society (e.g. people’s trust in scientific advice and their resulting actions), as well as the ability of STI to draw on new talent (e.g. more students engaging in scientific careers).
Tracking developments – indicator examples
Key uncertainties: public opinion surveys on priorities; public opinion surveys on trust in government and trust in science advice; analysis of media, social media and online searches; mapping of government policies and legislation; and analysis of civil society activities (social movements, demonstrations, responses to surveys). **Implications for STI:** mapping R&D expenditures by socio-economic objectives, the SDGs, etc.; mapping the prominence of STI in government stability and recovery packages, and associated strategic orientations, as well as industry/labour association statements on directing innovations at sustainability, resilience and inclusiveness goals.

Tracking developments on public perceptions of the roles of STI and governments

Perceptions of the roles of STI in the first phases of the crisis appear to be positive. For example, findings based on a survey of 2 651 people across England, Wales and Scotland, carried out between 30 March and 26 April 2020 show that 72% of respondents trusted health scientists and researchers completely or to a great extent to deal with the crisis (Craig et al., 2020[54]). Responses to questions in the OECD Science Flash Survey 2020 on scientific advice and trust suggest that researchers expect an increase in the use of scientific evidence, enhanced reputation of science, and a wider use of scientific advice after the crisis (see Chapter 8). They also expect scientific careers to become more attractive.

However, these positive perceptions may not necessarily last. New social distancing measures to counter the second wave of COVID-19 infections, drawing on scientific advice, have resulted in public demonstrations in a number of countries. More debate has raged about the proportionality of confinement measures given the state of infections, and more active resistance has taken place among those most affected by confinement decisions.

As for public opinion on governments' handling of the pandemic, the EU annual Regional and Local Barometer, a survey conducted in September 2020 showed a 44% average share of EU citizens (based on 26 381 responses from all EU countries) trusting their national governments to take the right decisions to overcome the socio-economic impacts of the COVID-19 crisis. This compared to 48% who said they do not trust their national governments in this regard. Levels of trust vary substantially across countries, however, being typically higher in the Nordic region and lower in Central and Eastern Europe. Trust levels are likely to evolve over time as the crisis unfolds.

Pace and direction of digitalisation

The issues at stake and their implications for STI

The role played by digital technologies, big-data analytics and AI in the economy and society during the crisis also represent a critical pivot point. Changes in the organisation of work (with increased remote working and virtual interactions); the rapid expansion of digital services (e.g. digital health and education tools); and the increased use of big data analytics, AI and digital tools by industry and government are putting those technologies to the test.

These developments also have important impacts on STI, both because they mark new processes that may change the productivity of STI systems, and because they are changing demands for STI (e.g. in terms of better WFH technologies and progress in virtual reality), potentially spurring new waves of technological innovation in these fields.

Whether digital technologies, big-data analytics and AI will take on more important roles in society and the economy will depend on several factors, including their contributions to addressing the COVID-19 crisis. The success of WFH, virtual conferencing, robotics (see Chapter 6), and virtual services in health, education and entertainment will also play a role. Experience in managing the crisis using digital tools will also influence governments' future use of such tools. Table 1.2outlines several critical pivot points related to the impacts of COVID-19 on the socio-economic role of digital technologies, and their possible implications for STI.

Table 1.2. Critical pivot points in the socio-economic role of digital technologies, big-data analytics and AI

Impacts of the COVID-19 crisis: Critical pivot points
WFH and virtual work interactions *Factors for an increase in WFH and virtual work*: the confinement experience stemming from the pandemic leads to widespread experimentation with WFH and virtual exchanges. Many professional workers prefer at least part-time WFH. Firms see their cost structures shift as office space is reduced and becomes more flexible to accommodate fewer staff on-site at any one time. *Factors against more digital work and consumption patterns*: negative experiences with WFH, particularly shortcomings of virtual conferencing in promoting effective exchanges, reduce interest in WFH and lead to limited development and uptake. Infrastructure constraints and security fears also raise concerns, slowing the wide uptake of these technologies.
Roles of big-data analytics, AI and automation in the economy *Factors for increased uptake of digital technologies in the economy*: the shock to the labour supply – caused by the confinement measures enforced to reduce the spread of the first wave of the COVID-19 pandemic – leads to more automation of factories. The possible reshoring of economic activities may also result in more automation, to reduce labour costs from reshoring to locations where labour is expensive. At the same time, positive business experiences with big-data analytics and AI lead to more widespread interest and adoption. *Factors for less uptake of digital technologies*: a perceived lack of impact of AI and digital technologies in addressing the COVID-19 crisis may weaken their wide adoption. Emphasis on other priorities – for example, investments in health innovation – diverts attention away from AI and automation. Abuses of privacy; the dominance of big players; digital threats; the misuse of high-quality language models for misinformation, spam and, phishing; and abuse of legal and governmental processes may reduce their application, as could biases in AI-based applications.
The importance of digital relative to analogue services *Factors for a surge in digital services*: the widespread experience of digital services in education, health, and retail is positive and leads to their wider application. *Factors against an increased rollout of digital services*: experiences of digital services were generally unsatisfactory during the pandemic and lead to a return to previous services. This may be reinforced by concerns over privacy (especially with regard to health data) and the increased market concentration in the delivery of these services.
Governmental use of digital tools *Factors for increased use of digital tools in government*: the COVID-19 crisis showed the benefits of real-time data to feed agile policymaking. This leads to increased use of new real-time and digital applications across governments, drawing on a mix of data sources. *Factors hampering the uptake of digital tools in government*: negative experiences with digital tools, e.g. owing to technical problems, data quality, privacy concerns, lack of digital skills among officials, and concerns over private-sector involvement, lead to weak uptake across government until such challenges are resolved.
Examples of implications for STI
Increased demand for digital innovations: if digital technology use intensifies, there will be demand pressure for improved digital tools, which would generate new waves of technological innovation. **Changes to operations and performance of STI systems**: any changes to WFH and virtual interactions would affect the operations of STI systems. For example, they could lead to greater automation in science. Progress in STI critically depends on connections: while digital technologies could open these up further, they could reduce in-person exchanges, which could be detrimental. **Changes in the innovation intensity of services:** digitalisation may increase the innovation intensity of this traditionally less innovation-intensive set of industries, as well as the types of businesses operating in services. **Changes in STI policies' focus**: STI policy itself would gain in agility and responsiveness by applying new digital tools, and improvements in its effectiveness could in turn affect the performance of STI systems' performance.
Tracking developments – indicator examples
Key uncertainties: survey evidence on the uptake of WFH, big data, cloud services and AI application; diffusion of digital technologies in businesses of various sizes, in households/by individuals and in government/by industry. **Implications for STI**: indicators of digital and AI-driven innovation, as well as WFH and online education tools technologies (e.g. software applications and patents), geographic distribution of research collaborations (e.g. international and national, etc.).

Tracking developments on the uptake of digital technologies

COVID-19 has been called the "great accelerator", particularly when it comes to digital technologies[30] enabling e-commerce, teleworking, telepresence and automation. Early evidence points to actors in the STI system having adopted more digital tools during the crisis. For example, a survey by the Centre for Economic Performance-Confederation of British Industry survey of 375 UK businesses in July 2020 found that from late March 2020 to July 2020, over 60% of firms adopted new digital technologies and management practices, and around one-third invested in new digital capabilities (Riom and Valero, 2020[55]). Digitalisation has also had an impact on research. Over half of the respondents to a survey of professionals and decision makers at 247 patenting companies cited digitisation as the most significant change (Kanesarajah and White, 2020[25]). AI tools have also been used to help accelerate drug and vaccine development, identify virus-transmission chains, rapidly diagnose COVID-19 cases, monitor broader economic impacts and tackle misinformation (OECD, 2020[56]). For example, based on a data set comprising 1.8 million papers from three pre-print repositories (arXiv, bioRxiv and medRxiv) gathered at the end of May 2020, Mateos-Garcia, Klinger and Stathoulopoulos (Mateos-Garcia, Klinger and Stathoulopoulos, 2020[57]) found that more than one-third of AI publications related to COVID-19 involved predictive analyses of patient data, particularly medical scans. These papers, however, received fewer citations than comparable papers on the same topic.

Digital services in education, health, entertainment, retail and restaurants were much used concurrently with confinement measures, and have led to an unprecedented demand that continued even as the strict confinement measures were lifted. Whether all of these services remain in the event the COVID-19 challenge is resolved currently seems unlikely: some reduction in demand would be expected where virtual services are judged an imperfect substitute for their in-person alternatives.

Governments themselves have shown unprecedented agility in their use of digital tools, most exemplified by the contact-tracing applications introduced as a way to control the spread of the disease. The COVID-19 crisis has also shown how policy making has also changed compared to the 2008-09 financial crisis, as illustrated by the use of real-time data (such as Google's mobility statistics) and other tools to better monitor and respond to the crisis. A series of pulse surveys have also been informing STI policies. The open release of COVID-19 papers by initiatives such as CORD-19 has not only supported scientific activities, but also helped identify the nature of scientific collaboration on COVID-19. Early analysis of such data has pointed to a drop in female research activities and high reliance on existing networks for research collaborations, for example. These types of tools could be more systematically used in the future to support the responsiveness and agility of STI policies. For example, the Portuguese Foundation for Science and Technology launched AI 4 COVID19, a competition endowed with a budget of EUR 3 million (USD 3.6 million) for R&D projects on data science and AI that help improve public administration bodies' response to the impact of COVID-19 and future pandemics.

Scale and distribution of socio-economic impacts

The issues at stake and their implications for STI

The extent to which policy measures help avoid strong negative distributional effects will be an important critical pivot point shaping STI systems and policy. This will depend on several factors, including the intensity of the COVID-19 shock and the related confinement measures, and the availability and uptake of digital technologies and practices by different actors. Socio-economic exclusion influences the operation of STI systems and the diffusion of new technologies. A combination of more limited means to invest in leading technologies and a more limited ability to retain qualified staff to operate those technologies in difficult times explain why exclusion negatively affects diffusion. Table 1.3 outlines several critical pivot points related to the impacts of COVID-19 on inclusion and exclusion, and their possible implications for STI.

Tracking developments on the scale and distribution of socio-economic impacts related to COVID-19

As discussed earlier in the chapter, the asymmetric impacts of the COVID-19 shock on innovative businesses, universities and public research institutes, the research workforce and entrepreneurs highlight the different distributional challenges of the COVID-19 shock. One risk is that existing gaps in the uptake and use of digital technologies are exacerbated, in particular between large firms and SMEs, but also between sectors. If not addressed, such uneven diffusion may have important implications for firms' productivity performance as the pandemic continues to accelerate digitalisation. It could potentially widen the productivity gap between digital adopters and digital laggards, enhance the vulnerability of laggards, and reduce economic resilience. Greater policy efforts will therefore be needed to boost adoption and diffusion of digital tools, in particular for SMEs.

An additional dimension concerns the geographic impacts of the COVID-19 shock. Differences in effects across sectors have influenced the intensity of the shock at regional levels (Bailey et al., 2020[58]). For example, regions highly specialised in the tourism sector are among the hardest hit by the crisis (Gössling, Scott and Hall, 2021[59]; OECD, 2020[60]). These sectors were also most affected by "social distancing" measures aiming to reduce international and national travel, as well as social gatherings. As the crisis unfolds and other sectors are hit hard in the resulting recession, further regions are likely to suffer more than others.

Table 1.3. Critical pivot points regarding the distribution of socio-economic impacts

Impacts of the COVID-19 crisis: Critical pivot points
COVID-19 and social inclusiveness *Factors pointing to more exclusion*: the pandemic provides fewer opportunities for new connections for recent graduates, job seekers and people with precarious contracts (often including younger workers and people in contract-based professions) and has a negative effect on the female workforce, taken up by dependent (children or elderly) care. The demand for a constant online presence may also exacerbate the hurdles for those providing more dependent care. *Factors pointing to more inclusion*: the shock leads to even more awareness of inclusiveness challenges, which were somewhat hidden prior to the COVID-19 pandemic. Accordingly, stability packages and related policy action highlight greater inclusion as an explicit goal. Changes in practices owing to COVID-19, such as WFH and digital services, offer opportunities for more inclusion. The goal of achieving greater resilience also aligns with promoting inclusive economic processes across firms, regions and individuals.
COVID-19 and industrial inclusiveness *Factors pointing to less inclusiveness*: government recovery packages primarily focus on the big employers (airlines, large manufacturers, etc.). Big tech companies, but also other large firms, benefited from large demand for their products during lockdowns, possibly reducing opportunities for smaller firms in the digital and other sectors to compete. *Factors pointing to more inclusiveness*: policy responses aimed at shielding the economy from the crisis have successfully targeted the financial fragilities of SMEs, particularly young innovative firms, which emerge as catalysts for radical innovation. The pandemic provides new opportunities for entrepreneurship, where start-ups help address the constraints created by difficult health and economic conditions, and respond to changing preferences and needs.
COVID-19 and geographic inclusiveness *Factors pointing to less inclusiveness*: the COVID-19 crisis was geographically unequal as outbreaks differed across and within countries, the effects across sectors (e.g. tourism vs. digital tech) and regions varied, confinement measures were more or less severe, and countries' capacities to respond differed (e.g. depending on the level of government debt/ability to borrow). *Factors pointing to more inclusiveness*: policy efforts to support the regions and sectors most affected, and regional measures to control outbreaks and mitigate the negative effects of the pandemic were implemented. New ways of providing goods and services (such as online entertainment offers) helped reduce unequal sectoral effects. The urban-rural divide may also be lessened as rural areas become more popular by virtue of the higher exposure to the pandemic in cities and the reduced cost of participating in professional activities remotely through digital tools, rather than engaging in time-consuming commuting
Examples of implications for STI
Impacts on STI system performance: the crisis presents different innovation opportunities for different players across firms, regions, countries and social groupings. More diversity is conducive to more innovation, while concentration has mixed effects on innovation outcomes. Greater inclusivity can increase market competition, which may raise the rate of innovation (albeit in non-linear ways). **Impacts on STI policy**: if inclusiveness is taken seriously, STI policies will pay greater attention than in the past to those that are more excluded, including women and minorities, and innovation in low- and medium-tech sectors and in 'laggard' regions. This would mean a greater focus on technology diffusion policies and STI policies to support inclusiveness more generally.
Tracking developments – indicator examples
Key uncertainties: Gini indices and distributional measures at regional, firm and individual levels in response to COVID-19. **Implications for STI**: various STI performance indicators (e.g. scale and scope of publications, graduates, IP, etc.) by region (incl. rural-urban divide), firms (by size, sector, age), and individuals (profiles of entrepreneurs and researchers).

The issues at stake and their implications for STI

There exist considerable uncertainties about the future of the current multilateral system, and what this could mean for international STI co-operation and mobility. On the one hand, there are signals that “peak” globalisation has passed, and that a new fragmented global order – marked by a rise in ethno-nationalism, more managed trade and investment, and greater strategic competition between “great powers” – is emerging. Furthermore, the current crisis may contribute to undermining trust in global governance solutions, fuelling the already growing pre-crisis discontent and ultimately driving a shift towards national approaches as countries – especially larger economies – seek to become more self-reliant. These tendencies could be augmented by multinational enterprises seeking to rely less on global value chains to reduce uncertainty and enhance their resilience, leading to further “reshoring” of production.

On the other hand, multilateral frameworks could be reinforced as a result of a greater appreciation of risks and challenges that transcend national boundaries and require co-ordinated responses, especially if transnational actors in the public and private sectors are successful in leading the fight against the pandemic. Table 1.4 outlines critical pivot points related to the impacts of COVID-19 on the international political economy.

Table 1.4. Critical pivot points on international relations and the global order

Impacts of the COVID-19 crisis: Critical pivot points[31]
International relations and multilateralism *Factors pointing to strong multilateralism*: the cascading systematic effects of the pandemic as well as its indiscriminate nature serve as a strong argument for renewed endorsement of multilateral co-operation. It illustrates that global responses are needed to global crises, spurring countries to engage in greater international collaboration. The global health emergency and economic aftermath trigger a major new commitment to development co-operation that moves beyond a traditional North-South approach to focus on multi-directional mutual learning and solidarity. The SDGs’ holistic vision of development is reinforced as there is a new appreciation of interconnectedness and interdependence of human development outcomes and human security. *Factors pointing to faltering multilateralism*: The multilateral system begins to break down due to lost credibility and resources, and unilateral or bilateral actions and decisions prevail, making way for new but competing institutions, power players and alliances. Emerging and developing economies see a rise in regional multilateralism, while the ‘old powers’ are preoccupied with internal issues and divisions and abdicate leadership internationally
International trade and investment *Factors pointing to sustained international trade and investment*: the COVID-19 crisis catalyses new global trade and investment links to address localised supply shocks. Accelerated digitalisation enables a new wave of globalisation that is more transparent and efficient. The efficiency gains from international collaboration and the international division of labour in production introduce a large cost to autarchic behaviour, particularly in a period where rebuilding economic growth is essential. *Factors pointing to preferences for national or supranational regional approaches*: the COVID-19 crisis has already elicited international competition to secure scarce global resources. Wider geopolitical tensions increase national or supranational efforts to safeguard against future shocks, including in the provision of essential goods. The shock created by the pandemic and the shortage of key products during the crisis may amplify demands for access to key technology fields, such as 5G communications and AI, in light of concerns over national security, the risk of future dependencies on foreign technology suppliers, and concerns over global monopolies and their potentially detrimental impact on technological progress.
Examples of implications for STI
Impacts on STI systems: disruptions in international scientific collaboration and the international division of labour in production would affect the performance of STI systems, as well as shift the orientations of national STI (as a substitute or complement to global efforts). **Impacts on STI policies***:* STI policies may focus on existing national specialisations and support international scientific collaborations to optimise the global STI system. Alternatively, STI policies may be technology- or product-specific in order to ensure national access to core technologies or products. Strategic STI alliances with chosen countries may also be sought to exploit shared values and the reciprocal benefits and costs of such collaborations
Tracking developments – indicator examples
Key uncertainties: measures of the evolution of barriers to international collaboration and economic exchanges, e.g. trade and investment data, data on global value chains, government funding of multilateral organisations, etc. **Implications for STI**: measures of the nature and extent of international STI collaboration, e.g. patent and publication data, research funding data.

Tracking developments on international relations and the global order

In co-operation with national governments, a diverse range of foundations and international organisations are actively engaged in STI actions to respond to COVID-19. The WHO, the Coalition for Epidemic Preparedness and Innovation, and the Global Research Collaboration for Infectious Disease Preparedness (to name just a few) are playing prominent roles co-ordinating the development of vaccines and therapeutics (see Chapter 5). The foundations involved in this endeavour include the Bill and Melinda Gates Foundation, the Wellcome Trust and the Novo Nordisk Foundation. Among other objectives, these globally operating foundations seek to harness science and innovation to address infectious diseases. In the context of COVID-19, they have not only provided research funding, but also promoted STI responses to COVID-19 at the global level, with special emphasis on the challenges faced by developing countries.

Several bilateral and supranational regional approaches have also supported research collaborations. For example, the National Research Foundation of Korea and the Swedish Research Council launched a grant programme for joint research collaborations between Swedish and South Korean researchers on the control and prevention of COVID-19, while the Nordic Health Data Research Projects on COVID-19 is a collaborative call for proposals for funding to promote research co-operation and sharing of health data across Sweden, Finland, Denmark, Norway, Iceland, Estonia and Latvia.[32]

A large number of research outputs have also been international. Analysis of research papers published on COVID-19 from January 2020 to September 2020 shows that around half of UK-based authors, one-quarter of US-based authors and one-quarter of China-based authors co-published their papers with an international co-author. Chinese collaborators represent by far the largest share of co-authors in the United States, and vice versa (see Chapter 5).

At the same time, the COVID-19 crisis has also shown that an important component of the scientific response has occurred at the national level. National institutes working on infectious diseases, such as the Institut Pasteur in France and the Robert Koch Institute in Germany, have played central roles in advising domestic policy makers on the means to address the national COVID-19 situation.

The future orientation of STI policies

STI policy is shaped by the key uncertainties above, but it also influences them. Compared to the situation during the 2008-09 global financial crisis, STI lies at the heart of solutions to the COVID-19 crisis and has a highly visible part in shaping policies to contain the virus's spread. The role played by STI in this context is therefore likely to influence the positioning of STI policy in the future. However, there are also uncertainties on the future goals and practices of STI policies and the resources they will have at their disposal. This section considers future levels of government support for STI, in light of the highly visible contributions STI is making to solve the pandemic, but also the public sectors' growing indebtedness. It also considers whether STI policy will become more directional to enact sustainability and digital transitions over the medium and longer term.

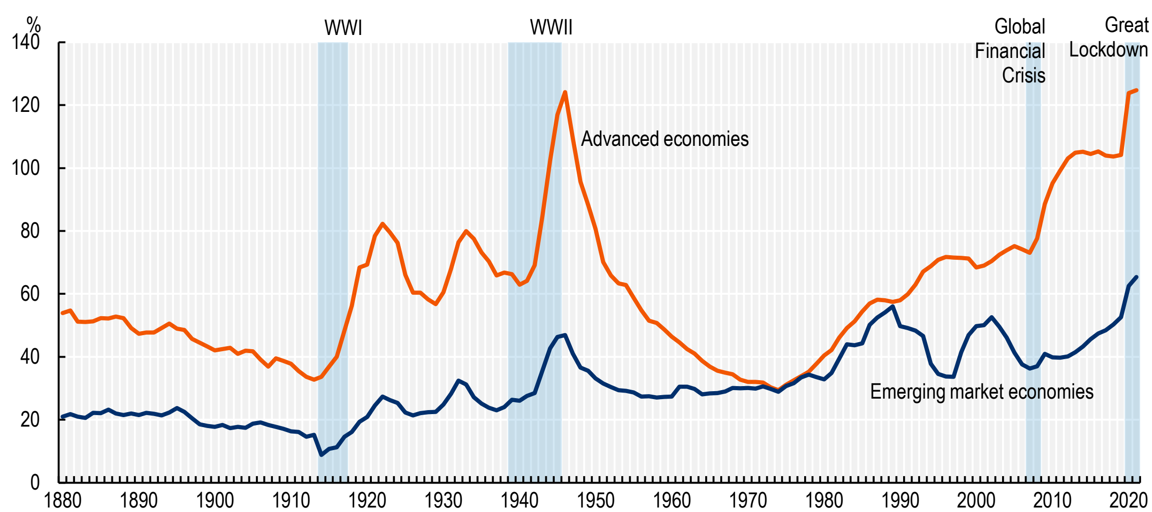
Government support for STI

Future levels of government support will be determined by societal preferences and the recognition of STI as an essential actor of socio-technical transitions to meet sustainability, inclusiveness and resilience goals. Strong endorsement and recognition of STI could lead to significant increases in public R&D – the equivalent, perhaps, of the West's reaction to Sputnik, which ushered in the US-Soviet space race (Subbaraman, 2020[61]). This could become a reality as the United States, China, other Asian industrialised countries and Europe chase leadership positions in AI, quantum computing, supercomputing, robotics (see Chapter 6) and other technologies, particularly health-related (see Chapter 7 on engineering biology). Most OECD governments are launching recovery packages to help overcome the longer-term fallout of the pandemic crisis. Many have lofty ambitions to modernise national economies, particularly through digitalisation, and drive a green transition towards more sustainable production and consumption. Some also proclaim greater "technology sovereignty" as a goal.

However, the extent to which ambitions like these translate into actions that drive structural change remains uncertain. Government intervention also needs to be affordable, which will be a major concern for many countries as the pandemic raises the costs to the economy. Following the first wave of COVID-19 infections, government debt for all countries was already at an unprecedented high, far above the levels reached during the global financial crisis (Figure 1.11). The current level of support for research and innovation emulates behaviour in 2008-09, when funding was impressive in the immediate aftermath but dropped-off in a number of countries because of unsustainable levels of public debt. While some countries will have few difficulties obtaining credit, others will not be so fortunate. The impacts of COVID-19 are already substantive, and not all countries have been in a position to support those most adversely affected by COVID-19. This applies notably to developing countries, which have left a number of their industries unsupported. This has implications for STI, as the scale and focus of recovery packages will affect the goals and types of measures supporting research and innovation that governments choose to implement, as well as the level of funding.

Figure 1.11. Historical patterns of general government debt

Percentage of GDP



Note: The aggregate public-debt-to-GDP series for advanced economies and emerging market economies is based on a constant sample of 25 and 27 countries, respectively, weighted by GDP in purchasing power parity terms.
Source: International Monetary Fund (IMF). 2020. Fiscal Monitor: Policies for the Recovery. Washington, October.

StatLink https://doi.org/10.1787/888934223213

At the same time, the amount of public funding is not necessarily synonymous with support for STI systems, as industry and civil society also play a role. As a possible remedy to funding constraints, industry and civil society actors – notably foundations – working jointly with public research and innovation-funding agencies can amplify the impacts of public support.

Directionality of STI policies

Public preferences on the need to build more resilient, sustainable and inclusive societies, as well as perspectives on the limits of government intervention, will shape the goals and toolboxes of STI policy.

The move towards a more proactive “systems transformation” model, compared to a model mainly focused on eliminating market failures, could accelerate. This could be reflected in ambitious mission-oriented projects aiming to engage a wide range of stakeholders from across the STI system (see Chapter 8). Such projects may feature prominently in government recovery and stimulus packages, particularly those that emphasise green and digital transformations. STI policy has well-established roles to play in supporting the development of sustainable technologies (e.g. by investing in environmentally sustainable technologies) and responding to the need for greater inclusiveness (e.g. by enabling the participation of excluded groups in STI) (OECD, 2011[62]; Planes-Satorra and Paunov, 2017[63]; Borowiecki et al., 2019[64]). OECD countries have been increasing their support programmes along these lines over the last decade or more, and could now expand them. While STI policy may need to adjust to the new emphasis on building greater socio-economic resilience, STI already makes important contributions in this regard, as outlined in Box 1.1.

Box 1.1. The contributions of STI to building resilience

STI systems can contribute to building resilience in the following ways:

- An agile STI system that operates effectively can help find responses and solutions to unexpected challenges. In the context of the COVID-19 crisis, the STI system has the capacity to develop vaccines and treatments quickly (e.g. through novel technology platforms) and ways of dealing with the virus (e.g. through tracking apps and finding alternative ways to reduce infection rates while keeping the economy operating). It has also developed a range of digital technologies that have helped much of the economy and society continue its operations through remote working and electronic business. However, STI systems need to remain agile, as future crises – including health crises and other shocks – will likely require very different responses than those that apply to COVID-19.
- STI plays an important role in ramping up the production of goods and services that can help address a crisis. During the initial onslaught of the COVID-19 pandemic, several countries were able to bolster critical production quickly, thanks to their strong technological and industrial base, and using new tools and technologies such as 3D printing and open-source designs and software. More widely, technological strengths in core fields – such as biotechnology, the digital sector and AI – provide the means to respond to shocks to global production.
- While the exact timing and type of future shock cannot be predicted, a number of crises are foreseeable. Preparedness measures can benefit from STI efforts aiming to avert crises before they emerge and build resilience to their consequences. Future shocks may emerge from climate change, including its impacts on health, biodiversity and food production. Dealing with such contingencies means that STI must contribute to sustainability.
- Scientific advice is also essential to helping develop effective responses to future crises. Scientific advice can contribute to the preparedness of research systems, anticipating likely knowledge and infrastructure requirements needed to support socio-economic systems in times of crisis. Multi-disciplinary advice structures that simulate future crises can contribute to national contingency planning efforts in case of emergencies.

Conclusions

Science is the only exit strategy from COVID-19, and the chapter shows that the pandemic has triggered an unprecedented mobilisation of the scientific community. Science and innovation have played essential roles in providing a better understanding of the virus and its transmission, and in developing hundreds of candidate therapeutics and vaccines over a very short period. The pandemic has underscored more than in other recent crises the importance of science and innovation to being both prepared and reactive to upcoming crises. It has also stretched research and innovation systems to their limits, revealing gaps that need filling to improve overall system resilience and preparedness for future crises. It is a wake-up call for all and highlights the need to recalibrate STI policies to better equip governments with the instruments and capabilities to point innovation efforts towards the goals of sustainability, inclusivity and resiliency.

A range of relevant STI policy goals and actions will help implement this orientation for the recovery and meet the challenges of the current crisis, as shown in Table 1.5.

Table 1.5. Broad STI policy goals and actions for crisis and recovery

STI policy goals	Examples of STI policy actions
Direct STI to identify solutions to the COVID-19 pandemic	• provide research and innovation funding for diagnostics, as well as vaccine and treatment development • support areas of research and innovation, including social sciences, that contribute solutions to COVID-19 and mitigate the negative effects of measures taken to contain the spread of the pandemic • support international collaboration on STI solutions to the shared global challenge of COVID-19.
Mitigate the negative impacts on STI systems, including the uneven distributional effects of COVID-19	• offer support to public research institutes in light of potentially reduced funding resulting from the pandemic (e.g. because of lower student intake) • support early-career researchers and women researchers who are more affected by the disruptions caused by the crisis • support innovative SMEs and entrepreneurs affected by the COVID-19 crisis • invest in the diffusion of digital technologies to help companies deal with confinement measures • support the agility of the STI system by providing grant extensions to innovators affected by COVID-19, including innovative SMEs.
Provide scientific advice to policy makers and the public on appropriate responses to COVID-19	• manage the trusted communication of scientific evidence on COVID-19, including its limitations as more is learnt (including dealing with misinformation) • offer transparent perspectives on the trade-offs of decisions and the role of science in informing (but not deciding on) policy decisions • communicate the contributions of STI to dealing with the impacts of COVID-19 (paying close attention to social media and possible echo chambers) • tackle disinformation on scientific evidence regarding COVID-19.
Raise the agility and responsiveness of STI systems	• set policy directions that meet societal goals, including inclusiveness, sustainability and resilience • use such directionality, e.g. in recovery packages, to reduce uncertainties for businesses and other non-governmental actors, by signalling intended investments and future demand commitments in support of transition goals • revisit the policy mix, e.g. in support of business innovation, if more direct measures are necessary to meet ambitious transition goals • use the crisis an as opportunity to reform those parts of research systems that operate sub-optimally, e.g. the research-career pipeline • use new policy tools for optimal and agile support of STI to address COVID-19 problems, leveraging new digital technologies for policy making (e.g. real-time data, digital apps and interconnected databases) • use deliberative and anticipatory approaches to policy that systematically consider broader dynamics and the longer-term.

The need remains for medical research and innovation to contribute solutions to the pandemic, and support for these should continue – including international collaboration, given the global scale of the challenge. Collaborative partnerships provide STI systems with greater agility to respond to future challenges. Policy support for other areas of science and innovation that mitigate the effects of the crisis should also continue, paying close attention to the uneven distributional effects of COVID-19. With the onset of the second wave of the pandemic, scientific advice to policy makers and citizens is increasingly contested. This calls for renewed emphasis on transparency and a multidisciplinary approach, and a clear presentation of scientific advice as just one – albeit important – input to the policy-making process. Finally, if the post-crisis recovery is to promote the structural reforms required to meet an agenda focused on a transition to sustainability, then STI policies will need to reform research and innovation systems. Governments will also need to prepare more effectively against future shocks, assessing developments around key uncertainties and their implications for STI. Policy makers and STI system stakeholders could use this chapter's key uncertainties framework to appraise a wide range of policy options to shape the future state and dynamics of STI landscapes.

Outline of the book

The remainder of the book dives more deeply into several topics covered in this chapter. Chapter 2 takes a closer look at the intense pressure of COVID-19 on research systems, revealing their inherent response capacity and flexibility. Scientific production, in terms of academic publications, has been impressive. Research databases and scientific publishers have removed traditional barriers, so that the scientific community can quickly share COVID-19-related data and publications. Digital tools and open-data infrastructures have allowed many scientists to continue to function effectively outside their usual laboratory or field environments. COVID-19 has also shed light on areas needing strengthening to increase research systems' overall preparedness for (and resilience to) future crises, bringing to the fore pre-existing concerns about risk-taking in research and research quality. In the rush to understand and find solutions to COVID-19, the tendency has understandably been to support "safe" mainstream research, but there also exists a need to take calculated risks and explore new ideas that might lead to breakthroughs. The intense pressure to release data and results rapidly has cut short or circumvented normal peer-review publication processes, though the sharp rise in pre-prints appears to have caused relatively few problems, and experiments are under way to "speed review" such papers before they are released.

Even in the absence of COVID-19, many early-career researchers were in precarious positions, employed on short-term contracts with no clear perspective of a permanent academic position (Chapter 3). For women in particular, the hyper-competitive environment and lack of security have been an active disincentive to continuing in research. Most early-career researchers now expect to have even fewer academic career opportunities, a situation compounded by the radically disrupted international mobility of researchers. New and more attractive career paths that provide greater security and alternative options for mobility in and out of academia and other research sectors are required.

Regarding business research and innovation, the COVID-19 crisis is not just a key threat to the ability of innovation systems to fulfil their normal functions, but also a call for mobilising these systems to provide new solutions to the immediate health, societal and economic challenges posed by the pandemic (Chapter 4). On an aggregate basis, business investments in research and innovation are pro-cyclical, and thus prone to contracting in times of crisis. It is difficult to imagine the current crisis being any different, given its deep – although uneven – economic impacts so far. Nevertheless, governments cannot act alone to drive ambitious policy programmes (such as sustainability transitions): they require strong partnerships with business and civil society to succeed. Recovery packages will need to include a mix of measures incentivising the private sector to invest in appropriate research and innovation. An important policy goal will be to reduce uncertainties by signalling intended public-sector investments and future demand commitments supporting transition goals. The current crisis also serves as a reminder that innovation-support policies need to be able to guide innovation efforts where they are most needed. Governments need to build innovation-support portfolios that equip them with the mechanisms, instruments and capabilities allowing them to orient innovation efforts, particularly to areas where government is a primary user or customer of innovations. In this regard, tax incentives are an insufficient means of guiding innovation to broader societal needs, and are suboptimal for encouraging investment in knowledge at the interface between basic research and actual product or process development. Direct grants can support longer-term, high-risk research, as well as target specific areas that either generate public goods (e.g. health and defence) or have a particularly high potential for spillovers. Governments should revisit their policy mix in support of business research and innovation to ensure an appropriate balance between direct and indirect measures.

Just as the pandemic is a global problem, it requires global solutions involving international co-operation and collaboration (Chapter 5). No single country can beat COVID-19 on its own. Research collaboration, both between public research and businesses, and internationally, is perhaps unparalleled as the global scientific enterprise has pulled together to find solutions to the pandemic. The speed with which research groups and biopharmaceutical firms are developing COVID-19 vaccines builds on years of basic research investment, as well as the recent institutionalisation of international co-ordination efforts to develop agile technology platforms that can be activated as new pathogens emerge. These relatively new arrangements are performing well, but are underfunded and dependent on a handful of countries and philanthropic institutions for financing. Governments should consider scaling them up and extending them to other global challenges where R&D preparedness is important, capitalising on the momentum from the response to COVID-19. R&D preparedness measures include technology platforms, infrastructures, and collaborative networks that will improve countries' abilities to respond effectively to a diverse range of risks. Governments also need to work together on new financing and governance mechanisms, wherein business and private-finance actors work with multilateral and national development banks to co-finance STI solutions for global challenges. The rapid and unprecedented mobilisation of public and private R&D funding for COVID-19 vaccines and their global distribution has demonstrated that new innovative funding models can be deployed to address global challenges through international STI co-operation.

Digital and biomedical technologies are playing essential and highly visible roles in combatting the pandemic's impacts and in finding medical solutions, particularly with regards to rapid vaccine development. Two emerging technologies, engineering biology and robotics, have shown promise in helping enhance the health resiliency of societies. Engineering biology (Chapter 7) is an attempt to turn biotechnology into a discipline more reminiscent of engineering than biology, and is focused on industrial production. A recent technological breakthrough, the biofoundry, can greatly reduce the time from idea to product, and improve the reliability and reproducibility of bio-manufacturing. Biofoundries are highly automated facilities that follow detailed, complex workflows through the co-ordinated use of laboratory robots. The messenger RNA vaccines for COVID-19 (e.g. the Pfizer and Moderna vaccines that have been the first to clear clinical trials) are especially amenable to this approach. Beyond their use in biofoundries, robotics can play other roles that enhance the health resiliency of societies (Chapter 6), from aiding laboratory research, surgery and physical rehabilitation, to delivering medicines, transporting waste, combating loneliness, and improving medical diagnostics and treatments. Governments possess several tools to accelerate the development and deployment of technologies like these: basic and applied research in public research organisations and firms; public private partnerships and collaborative platforms; interdisciplinary and transdisciplinary research for converging technologies; and test-beds, demonstrators, and regulatory sandboxes to help companies de-risk investments. Skills development is another important requirement, as is support for standards and technology diffusion.

Countries' governance arrangements shape their research and innovation responses to the current COVID-19 crisis and will influence the contribution of STI to the recovery (Chapter 8). These arrangements are broad in scope and include the ways governments set directions and choose priorities, their relationships with other actors in the innovation system, and the technologies they use to govern. One of the more visible – and most debated – aspects of governments' response to the pandemic is the use of scientific advice in designing policies. Previous OECD work has formulated guidelines on providing and using scientific advice in international crises like COVID-19. The chapter reviews these guidelines and considers how governments have followed them in their policy making. The effectiveness of STI policies also depends on the policy intelligence tools used, including data-management systems and information services that detect, monitor and communicate developments in STI systems. These can map system dependencies, alert decision-makers to shocks and communicate the real-time impacts of possible future shocks at a granular level. The COVID-19 crisis has led to unprecedented uses of new digital tools and data to inform policy, which could accelerate the digitalisation of science and innovation policy itself.

Governments' ongoing experiments with mission-oriented innovation policies, which have tended to target grand societal challenges, could feature more prominently in the STI policy mix, for instance, as part of recovery packages targeting green transitions. Governments will need to renew their policy frameworks and capabilities to carry out a more ambitious science and innovation policy agenda. Chapter 8 argues that governments should link support for emerging technologies to broader missions that encapsulate responsible innovation principles. This will help ensure an alignment of emerging technology development with the objectives of mission-oriented innovation policies. Building government capabilities to deliver on a more ambitious policy agenda, including capacities to use advanced analytics more effectively and across the whole of government, will be paramount. An increased policy emphasis on building resiliency, which calls for policy agility, highlights the need for governments to possess dynamic capabilities to adapt and learn in the face of rapidly changing environments.

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Notes

[1] Both policy papers are a result of work conducted on COVID-19 under the auspices of the OECD Working Party on Innovation and Technology Policy.

[2] https://www.nytimes.com/interactive/2020/science/coronavirus-vaccine-tracker.html.

[3] The impacts on research infrastructures have been multifaceted, with sometimes extensive and enduring effects. As an illustration, the ability to observe the ocean was impacted in unprecedented ways. In the second quarter of 2020, governments and oceanographic institutions recalled nearly all oceanographic research vessels to home ports, and ocean buoys and other systems could not be maintained, leading to premature failure. The observations from these systems are vital to marine, climate, and weather forecasts and warnings, and some time and extra costs will be required to bring back these capabilities (Heslop et al., 2020[65]).

[4] This OECD Science Flash Survey 2020 is implemented through an online open-link questionnaire, inviting scientists or any other individuals with an interest in science or science policy to answer questions on the impact of the COVID-19 crisis from a science perspective. The survey was initially promoted through the network of the OECD Committee for Scientific and Technological Policy and former participants of the 2018 OECD International Survey of Scientific Authors. It is being carried out in collaboration with the Inter-American Development Bank. As of 12 October 2020, over 2 600 responses from nearly 100 countries had been collected; 45% of responses came from individuals who identify themselves as scientists; the remainder correspond to science policy advisors (20%), professionals involved in science (15%), science communicators (10%) and individuals carrying out science-related administrative work (10%). The survey does not request any information that can identify the respondents. As a result, results cannot be considered representative of a well-defined population and should be considered with extreme caution, as a complementary view to other evidence.

[5] http://www.zentech.be.

[6] https://www.adaptvac.com.

[7] https://www.thehindu.com/news/national/kerala/kerala-government-hospital-deploys-robot-to-serve-covid-19-patients/article31432663.ece.

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[17] As of the end of September 2020.

[18] www.nextrain.org.

[19] www.gisaid.org.

[20] https://www.cas.org/covid-19-antiviral-compounds-dataset.

[21] https://midasnetwork.us/covid-19/.

[22] https://www.gov.uk/guidance/mhra-regulatory-flexibilities-resulting-from-coronavirus-covid-19.

[23] https://www.whitehouse.gov/briefings-statements/white-house-announces-new-partnership-unleash-u-s-supercomputing-resources-fight-covid-19/.

[24] https://www.erinha.eu/covid19-research/.

[25] https://home.treasury.gov/policy-issues/cares.

[26] A more comprehensive review is provided in (Paunov and Planes-Satorra, forthcoming[2]).

[27] https://www.gov.uk/government/news/government-to-protect-uk-research-jobs-with-major-support-package.

[28] https://lafrenchtech.com/en/covid19-french-tech-fights-back-n1/.

[29] Such an exercise would not start from scratch and would scan existing forward-looking analyses, including national foresight exercises and future scenario studies, to identify and explore key trends, forecasts and future scenarios that could usefully inform strategic long-term thinking in STI policy in a post-COVID-19 world. Using dedicated workshops conducted over the course of 2021 and 2022, the exercise would deliver a unique global perspective and provide useful resources for STI policy making and other strategic foresight studies. It would also provide a useful basis for the 2022 edition of the *OECD Science, Technology and Innovation Outlook*, which could provide compelling shared visions on the future of STI policy.

[30] Some of the issues raised in this section are explored more extensively in the latest edition of the OECD's Digital Economy Outlook (OECD, 2020[66]).

[31] These critical pivot points draw upon (Paunov and Planes-Satorra, forthcoming[3]).

[32] https://funding.nordforsk.org/portal/#call/1904.

2 Mobilising public research funding and infrastructures in times of crisis

The COVID-19 pandemic has triggered an unprecedented mobilisation of the scientific community. In record time, public research agencies and organisations, private foundations and charities, and the health industry at large have set up an array of newly funded research initiatives worth billions of dollars. Nevertheless, this exceptional response from the scientific system has also revealed many challenges. This chapter examines how the scientific community has been mobilised during the COVID-19 crisis, with a particular focus on funding and infrastructures. It explores how the lessons learned can be extrapolated to other crisis situations and the operations of science more broadly, drawing policy implications for science policy makers and administrators, such as the need for better preparedness, for flexible funding mechanisms, for new policies related to early publications of scientific results, and for strengthening the overall resilience of the research system.

Key findings

- **The research system has responded strongly and flexibly during the pandemic**. The research funding system as well as research infrastructures were able to quickly refocus towards crisis-relevant topics and streamline their procedures, although the capacity to allocate or reallocate resources quickly could be improved. Assessing the effectiveness of different mechanisms in producing useful research outputs could provide insights into what works for the future.
- **The COVID-19 crisis has spurred new practices in scientific communication as rapid sharing of data and scientific discoveries worldwide has become essential**. Many traditional constraints have been lifted or relaxed to accelerate the production, publication and dissemination of scientific results relevant to the pandemic. Pre-prints, i.e. academic papers that have not been peer reviewed, have become more common, allowing for faster diffusion of scientific findings, but also raising risks around quality assurance. This raises questions as to how peer review operates, its importance and its limitations. More than three-quarters of all COVID-19 publications are open access, compared to less than one-half in other biomedical fields. These developments could accelerate the transition to a more open science in the longer run.
- **There are considerable uncertainties regarding long-term funding for research once the immediate emergency has passed**, as significant resources have been reallocated towards research fields that are relevant to the crisis. Governments and research funding bodies should define and communicate quickly their capacities to support research in the coming years, as well as their strategic priorities, in order to foster cooperation and collaboration, avoid unnecessary duplication and identify “dark spaces” where research is needed but not being performed. This would allow research performing organisations to elaborate realistic long-term strategic plans, and enable a coordinated global approach.

Introduction

The COVID-19 pandemic has generated a series of exceptional challenges for the research system. Both governments and citizens are relying on science to come up with solutions to the crisis. Starting from limited information, research is expected to provide an understanding of the disease – its causes and transmission, its impacts on society, potential cures and preventive actions – in record time. The intense pressure has tested the research system to its limits, shedding light on its inherent response capacity and flexibility, but also revealing areas needing to be strengthened to increase its overall resilience and preparedness for existing and future crises.

This chapter examines how the scientific community has been mobilised during the COVID-19 crisis, with a particular focus on research funding and infrastructures. Research infrastructures have mobilised their resources and opened up their facilities to new projects targeting COVID-19. Research databases and scientific publishers have removed traditional barriers to access, so that COVID-19 related data and publications can be quickly shared across the whole scientific community. However, national and international co-ordination has sometimes been slow and hindered by structural hurdles. Research organisations and institutions have had to reorganise their operations, rapidly setting new priorities and considering how to balance new investments to address the pandemic with the need to maintain support for the science base as a whole. Traditional peer-review processes have been stretched, and maintaining the quality of scientific production under intense public scrutiny has emerged as a particular challenge.

The chapter explores how the lessons learned can be extrapolated to other crisis situations and the operations of science more broadly, drawing policy implications for science policy makers and administrators.

Resources unlocked for research on COVID-19

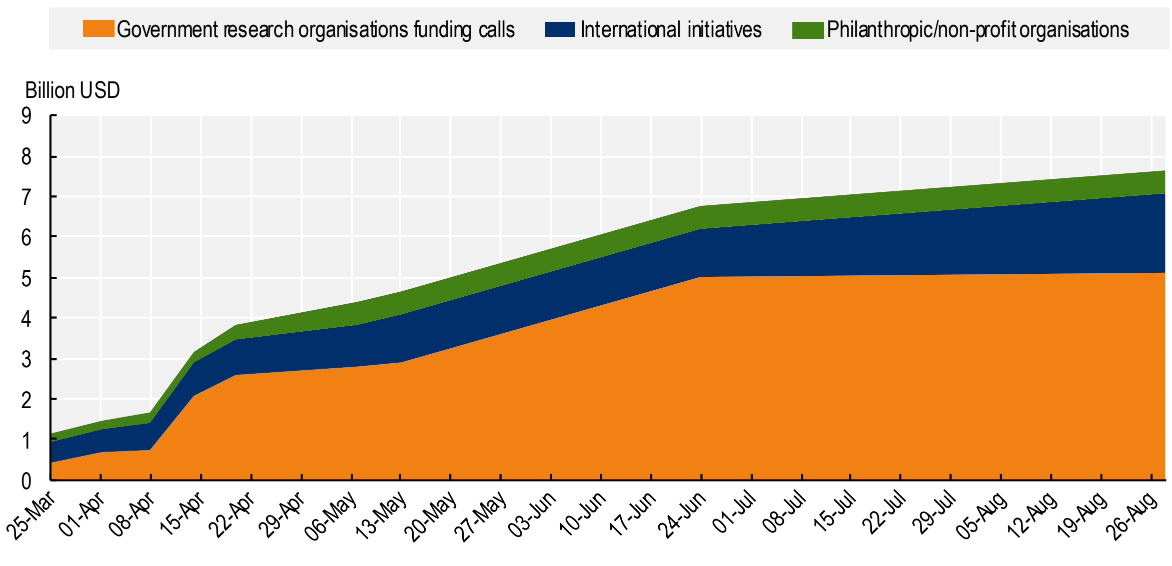
The COVID-19 pandemic has led to a worldwide mobilisation of research funders and research performing organisations. Research funders have set up numerous rapid-funding mechanisms to respond to COVID-19, and encouraged and supported researchers to redirect their efforts towards pandemic-related priorities. Philanthropic investment directed towards COVID-19 has also significantly increased, particularly to support international research efforts. While it is difficult to sum up the resources allocated by various funders to support research related to COVID-19, a preliminary analysis of the major research funding initiatives worldwide[1] (Figure 2.1) suggests that over USD 7 billion of new or redirected resources were unlocked in the first nine months of 2020.[2]

- Over USD 5 billion have been announced for public research funding schemes supported by national public research funding agencies and organisations. These include about USD 300 million for the Asia-Pacific region (excluding the People’s Republic of China, hereafter China), over USD 850 million for Europe, and over USD 3.5 billion for North America. These figures do not include internal resources that have been redirected towards COVID-19 within research performing organisations.
- About USD 2 billion (a mix of public and private money) have been pledged (mostly through the Coalition for Epidemic Preparedness Innovation [CEPI] and the Global Alliance for Vaccines and Immunization [GAVI]) for international research efforts focusing on the development of COVID-19 vaccines (see Chapter 5).
- At least USD 550 million have been allocated by philanthropic foundations to COVID-19 research in addition to their pledges to major international co-operative initiatives.

Resources pledged by industry are more difficult to ascertain, but over USD 1 billion have been allocated by private companies for public-private research initiatives. Internal research resources invested by industry in diagnostics, therapeutics and vaccines research are likely much larger.

Figure 2.1. Evolution of COVID-19 research funding programmes and pledges

March-August 2020



Note of caution: Overall investment is almost certainly underestimated: the expected level of funding is not yet fully known or validated for all funding schemes, and some funders do not publicly disclose the sums allocated. There may also be some duplication when funding commitments are redistributed among different funding programmes. These figures should therefore be treated cautiously, given the complexity of mapping funding declarations to actual investment and the absence of data from some countries. The sharp increase in funding seen in April is linked to the clarification by some major research funders of their resource allocation to major funding programmes.
Source: Data were gathered from public sources published by funders. Data on government research funding calls are available on the STIP COVID-19 Watch portal: https://stip.oecd.org/covid/.

StatLink https://doi.org/10.1787/888934223232

Countries have committed to funding research and the search for treatments at several high-level intergovernmental meetings devoted to fundraising.[3] However, these pledges were not allocated to specific funders and funding schemes, and the amounts pledged probably included those already committed by research funding agencies. More generally, reallocating funding from an existing budget during a crisis was often challenging for governments and institutions, as budgetary processes often involve complex and lengthy validation; this was sometimes circumvented by unlocking supplementary budgets, but "financial flexibility" was highly heterogeneous between countries.

Looking at the level of research projects, over 2 000 projects funded worldwide (excluding China) were registered by mid-September 2020 in a live database of funded research projects on COVID-19 maintained by the UK Collaborative on Development Research (UKCDR) and the Global Research Collaboration for Infectious Disease Preparedness (*GloPID-R*).[4] The database shows that public funding organisations had already awarded at least USD 770 million to research groups by that date. This overview of research projects, which is mapped against the priorities identified in the World Health Organization (WHO) Coordinated Global Research Roadmap (WHO, 2020[1]) illustrates the broad diversity of research being supported.

It is not easy to distinguish precisely, either at aggregate or project level, between entirely new funding and resources that have simply been reallocated. Moreover, the situation appears to be very much country-specific. In the United States, about 40% (i.e. USD 75 million) of the US National Science Foundation (NSF) resources allocated to COVID-19 as of end of October 2020 (USD 190 million) came from additional funds provided by the United States Congress. In France, the share of new resources provided by the Ministry of Research was probably even higher. By contrast, resources were mostly repurposed by the German and Norwegian research funding agencies, Deutsche Forschungsgemeinschaft (DFG) and Norges forskningsråd, respectively, at least in the first half of 2020. At DFG, available resources that had not yet been allocated to specific programmes were directed towards COVID-19 funding schemes.

Finally, while research funding on COVID-19 during the first half of 2020 was characterised by the launch of a large number of new emergency funding schemes, the situation has progressively transitioned towards integrating COVID-19-related research calls into mainstream funding mechanisms. Many research funders have now integrated calls for research proposals in various domains relevant to COVID-19 within their normal operations. Whether the integration of COVID-19 research into these mainstream funding streams is happening at the expense of funding for other disciplines – and if so, to what extent – is unclear. Researchers in the biomedical field have warned that funding and calls for proposals in their non-COVID-19-related domain may be severely cut back, both because of a potential reduction in overall funding (e.g. from medical charities, which have experienced significant drops in donations) and the new prioritisation of research related to COVID-19 (Kourie et al., 2020[2]). There are also concerns on the potential impacts of rapid response on equity, diversity and inclusion within the research funding system (Witteman, Haverfield and Tannenbaum, 2020[3]).

Research areas supported by new research funding initiatives

In response to the pandemic crisis, research funding and research performing organisations have launched a diverse range of funding projects and initiatives, covering a mix of topics and objectives (Figure 2.2). Funding schemes rarely focus on a single topic and it is difficult to assess the exact funding scale allocated to these various categories, but support for therapeutics and vaccines has been pre-eminent. The data provided by the UKCDR-GloPID-R tracker[5] show that funding agencies have issued calls and awarded significant funding in different categories, with a remarkable number of projects dedicated to studying societal responses to the COVID-19 crisis (Figure 2.3).[6]

Figure 2.2. Mix of topics targeted by funding organisations to address COVID-19 and its impacts

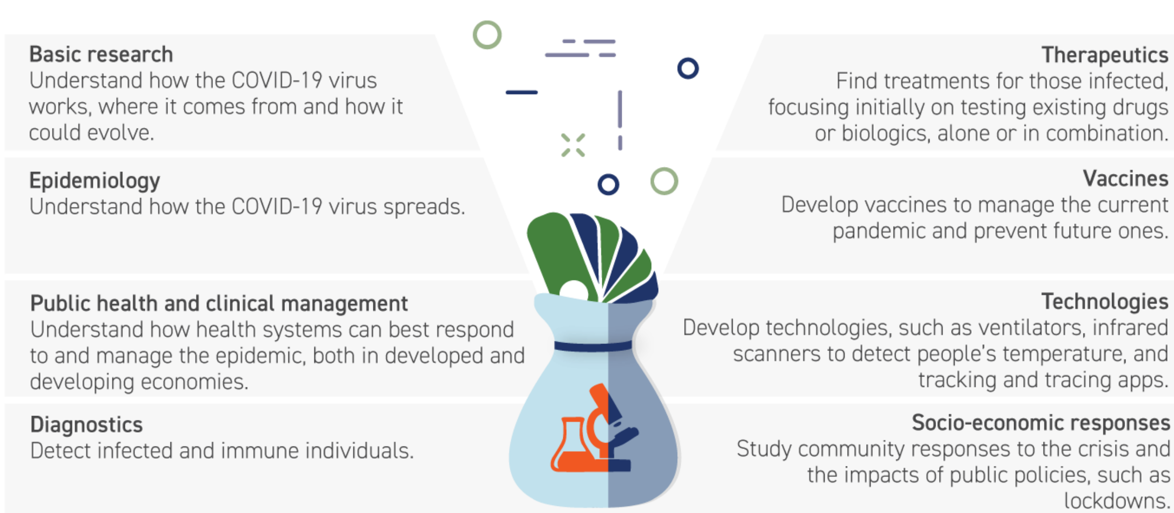
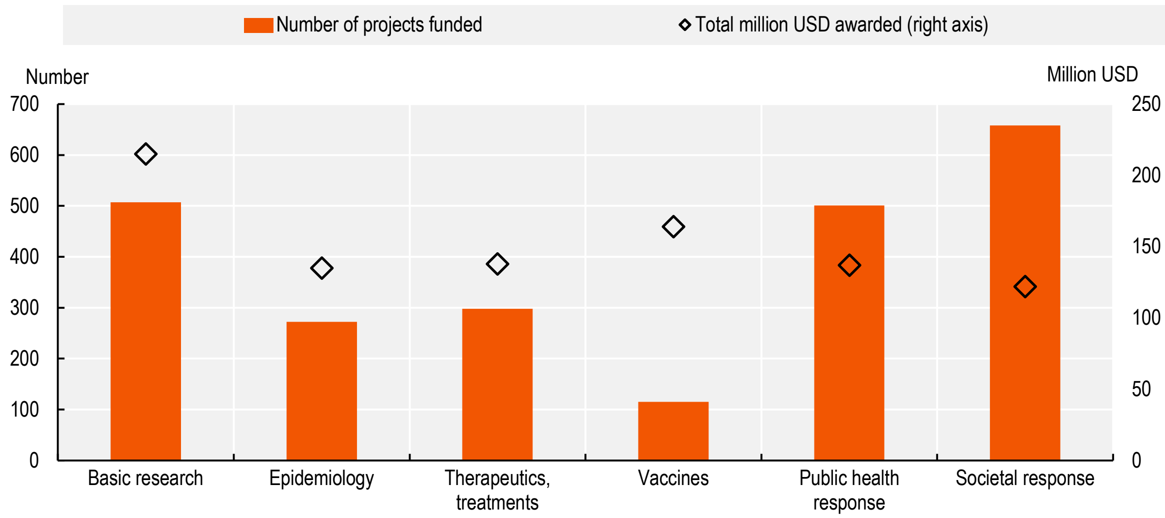


Figure 2.3. Research projects funded by public funding organisations in various research areas



Note: Large programmes on therapeutics and vaccines, such as CEPI, are not included. No disaggregated data were available on research projects on diagnostics and technologies. Some projects may be assigned to several priorities. The database currently has limited information on funding amounts for a significant number of projects. Hence, the total amount displayed significantly underestimates the actual total funding awarded.
Source: Data are derived from the UKCDR-GloPID-R tracker: https://www.glopid-r.org (accessed 15 September 2020).

Challenges in managing emergency research funding projects

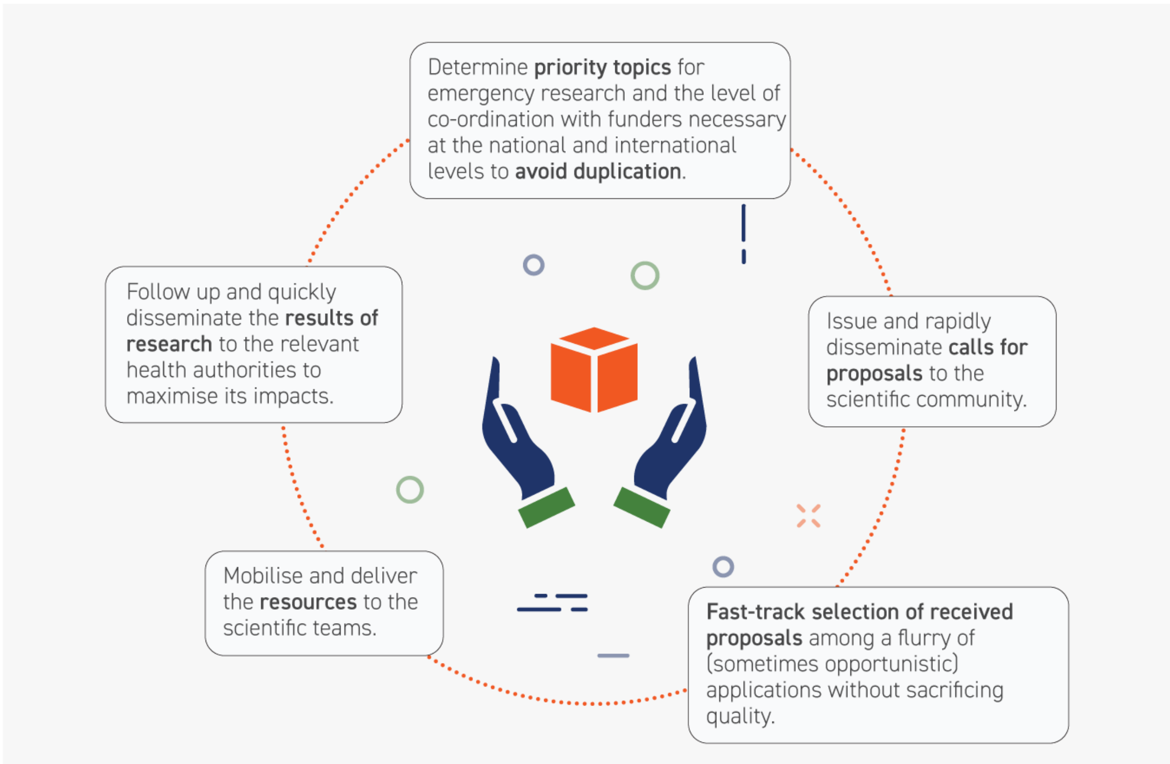
Research funders that are setting up emergency schemes for research funding face a series of specific challenges, notably around prioritisation of topics and dissemination of calls, resources and research results (Figure 2.4). Some of these are described below.

Priority-setting

Funding organisations have various ways of setting priorities. Particularly in biomedical areas, initial priorities were often defined on the basis of research gaps, as determined by the WHO, to ensure essential issues were addressed. Representatives from GloPID-R, WHO, health research funders and scientists met in February 2020 to assess the current state of COVID-19 knowledge, agreeing on key research priorities and ways to work together to accelerate and fund priority research (see Chapter 5). As an example, the Government of Canada designed its key research funding opportunities to align with the COVID-19 R&D Blueprint that came from the meeting between WHO and GloPID-R. These priorities were then often adapted to the national context, so as to take into account the relative strengths of national research performing organisations in particular domains and avoid duplication with projects (e.g. on vaccines) carried out by international consortia. In several countries, national priorities were determined by established or ad hoc advisory panels of experts set up by governments to provide a co-ordinated strategic approach. In the UK, for example, priorities were first identified by the Scientific Advisory Group for Emergencies (SAGE) in synergy with the various relevant national and international stakeholders. By contrast, priority-setting was much less prevalent in non-medical areas. For example, the NSF asked its broad research community to propose research related to the non-medical and non-clinical dimensions of COVID-19. This generated a huge and varied response, with thousands of inquiries and proposals, and over 1 000 awards granted by end of October 2020. Co-ordination was required within the NSF to avoid duplication, and extensive communication took place with other US agencies to avoid overlap and ensure projects were directed to the most appropriate agency. Similarly, in France, the Agence Nationale de la

Recherche (ANR) opened calls for proposals regarding the holistic impact (e.g. economic, societal and environmental) of the COVID-19 pandemic, extending research beyond the public-health priorities defined by the WHO.

Figure 2.4. Emergency research funding schemes face new management challenges



Fast-tracking research proposals

During the initial stages of the COVID-19 crisis, funders often assessed research proposals internally, using their own experts and project managers to fast-track awards. Research teams with a proven track record were often favoured.[7] To keep the number of applications manageable, some funders (e.g. the FWO Research Foundation in Belgium-Flanders) initially limited the number of funding slots per university and added a requirement for co-operation between research institutions within projects. In other cases, expert panels comprising both national and international researchers were established through accelerated procedures and operated virtually (for example, the Dutch Research Council funding agency reduced the proposal evaluation time to one month, compared to the average three to four months applicable in normal times). As described in a later paragraph, such accelerated procedures were also successfully implemented by research infrastructures, suggesting possible gains of efficiency in the management of research proposals in normal operational processes. However, fast-tracking very large numbers of research proposals in record time did stretch funding agencies' capacities to their limits: in the UK, for example, the number of proposals to review was twice as high as normal, and had to be done over a very short period, which led to an intense workload and fatigue of all agency personnel and reviewers involved.

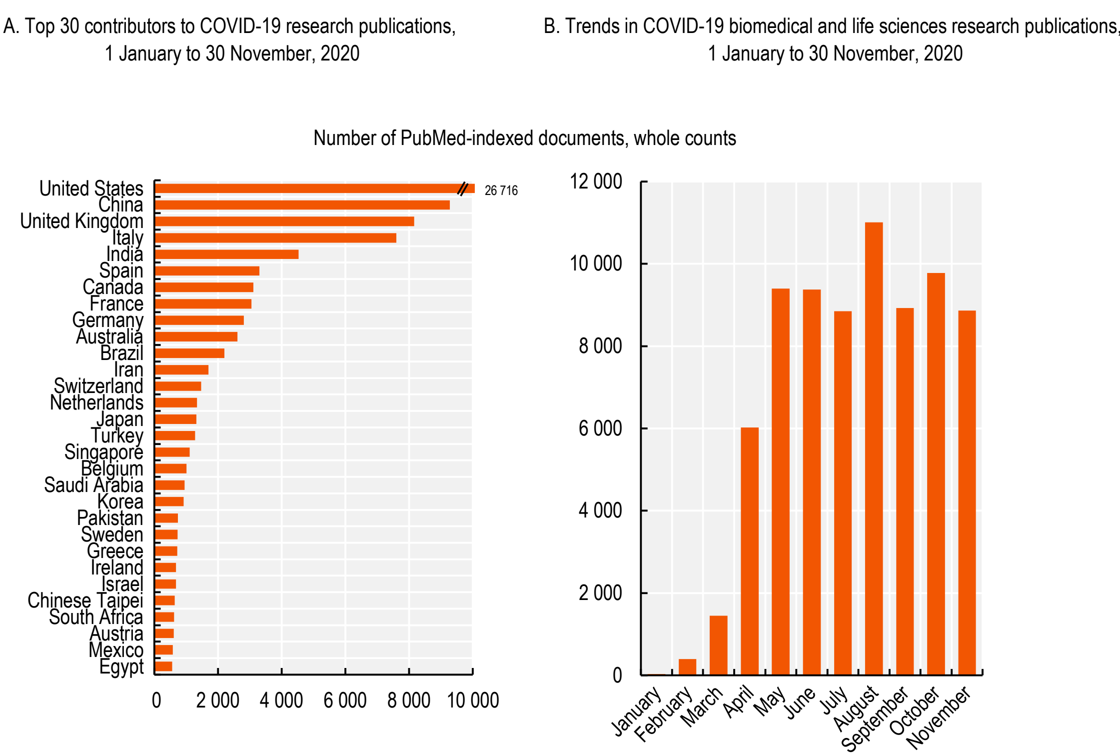
The main objective of these initial funding schemes was to deliver results that could inform solutions as soon as possible, favouring a "low-hanging fruit" approach and the funding of well-established research laboratories with a known track record. Nevertheless, some funders developed schemes that clearly prioritised the interest of the project over the reputation of the team, recognising that breakthrough research proposals could be developed by non-specialist research teams (as was the case for the Flash Covid-19 et RA-Covid-19 calls for proposals issued by France's ANR).

In most cases, funders have not set up dedicated procedures to facilitate uptake of research results. Although responsibilities are split in this matter, it is an area that probably merits greater attention. In the United States, the NSF supported the creation of the COVID Information Commons,[8] which connects projects' principal investigators, provides tools to search across NSF awards related to COVID-19, and links to other US and international research efforts. Similarly, the Canadian Institutes of Health Research (CIHR) also launched a call for a COVID-19 Knowledge Synthesis Network.[9] In France, a new centralised monitoring mechanism for research results is being set up by the national COVID-19 platform. While funding agencies have largely encouraged sharing of scientific data and results (see below), exploiting these results has been largely left to other stakeholders in the research ecosystem (i.e. researchers, institutions and private companies). There exist opportunities for funders to support and work more closely with these other actors.

Uncertainties on the long-term impacts of emergency research funding

Overall, although research funders reacted very quickly and effectively established strategies and funding schemes, many lessons can be learned from the COVID-19 crisis to improve the efficiency of these measures in future crises. While scientific production in terms of academic publications resulting from this large investment has been impressive (Figure 2.5), a number of important questions need to be addressed to inform future science policies on crisis preparedness and response.

Figure 2.5. Growth in COVID-19 related publications



Note: The period covers from 1 January to 30 November 2020 and includes 74 115 documents. Publications include the following type of peer-reviewed articles: books and documents, clinical trials, meta-analysis, randomised controlled trials, reviews and systematic reviews. Iran stands for Islamic Republic of Iran.

Source: OECD and OCTS-OEI calculations, based on US National Institutes of Health PubMed data, https://pubmed.ncbi.nlm.nih.gov/ (accessed 30 November 2020).

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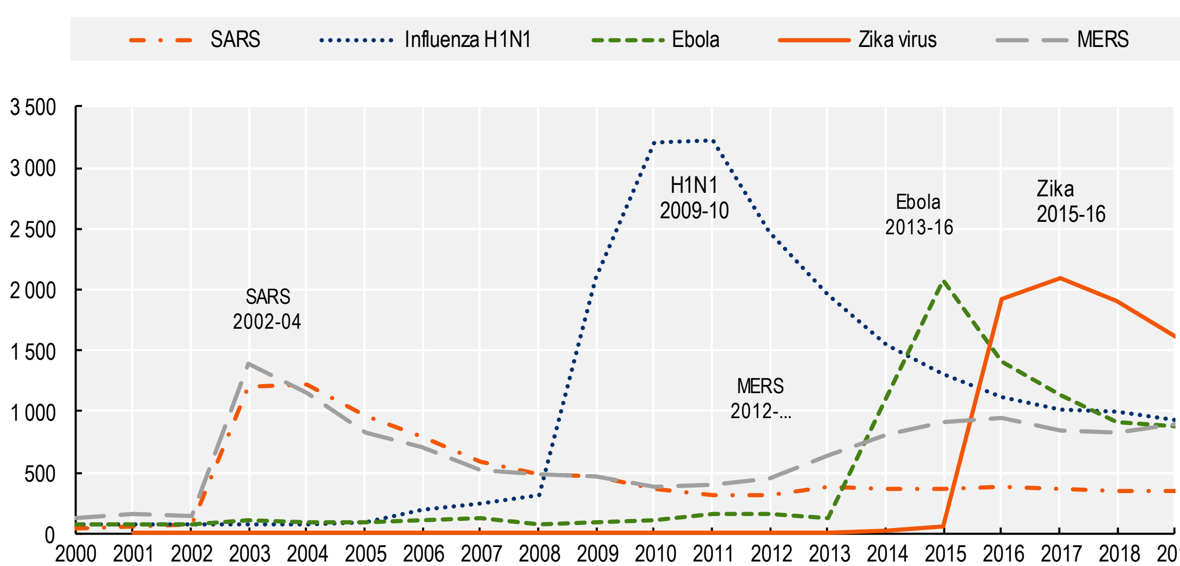
Quality and impact of the science produced

Although an abundance of research articles has already been published, it is still difficult to assess whether the scientific production was worth the public investment, and what impact it will have on informing solutions for the many problems stemming from the pandemic. It is equally important to determine whether certain types of funding mechanisms – many funders tried to innovate to respond to the emergency – have been more effective than others in producing useful research outputs (for example, did the "safe" investments based on track record and reputation yield better results than "riskier" investments?). Assessing the impacts of various funding approaches, using a range of relevant indicators, should provide useful insights on what works for the future.

Long-term impact on research domains

As previously mentioned, the COVID-19 crisis has displaced scientific funding and efforts towards specific areas of biomedical research. Even if definitive numbers are not yet available, significant resources have been reallocated towards research fields that are relevant to the crisis. Whether this will be a long-lasting shift remains unclear, but it will likely continue for some time as new waves of the pandemic take hold. How this will affect other research domains cannot be ascertained, but it does raise questions about the overall long-term research strategy both research funders and research performing organisations must put in place to ensure they have balanced research portfolios and the capacity to address new challenges, wherever they may come from. The shift in funding also has important implications for the research workforce, potentially forcing researchers to move to domains outside their real expertise. Recent examples such as the 2003 severe acute respiratory syndrome (SARS) epidemic, the 2014-16 Ebola outbreak or the 2016 Zika epidemic were associated with relatively short-term dedicated research and vaccine-development programmes that were not pursued once the urgency disappeared (Figure 2.6).

Figure 2.6. Tracking research on previous global health crises, 2000-19



Note: Publications include the following types of peer-reviewed articles: Books and Documents, Clinical Trials, Meta-Analysis, Randomized Controlled Trials, Reviews and Systematic Reviews.
Source: OECD calculations, based on US National Institutes of Health PubMed data, https://pubmed.ncbi.nlm.nih.gov/ (accessed 13 October 2020).

StatLink https://doi.org/10.1787/888934223270

This "panic and neglect cycle" had both economic and health consequences, as federal funding agencies reallocated funds that had been committed to vaccine development, leaving manufacturers with financial losses and setting back other vaccine-development programmes (Lurie et al., 2020[4]). COVID-19 is on a much larger scale and the shifts in research directions it has provoked are much more substantial. Hence, the longer-term impact on different research domains will require careful consideration.

Impact on the science-funding system

The future of research funding after the crisis is uncertain (Subbaraman, 2020[5]). On the one hand, the emerging economic crisis could trigger significant cuts in public research budgets, putting thousands of researchers out of work and reducing research capacities for many years to come. In Europe, for example, the EUR 750 billion (euros) economic recovery plan decided by the European Council will be implemented partly at the expense of the Horizon 2020 R&D budget: only EUR 80.9 billion of the reserved EUR 94.4 billion proposed in May by the European Commission remained in the final budget approved in July by the European Council, a significant EUR 13.5 billion cut (Wallace, 2020[6]), although EUR 4 billon were later recovered following discussions with the European Parliament. In parallel, research funding charities and non-governmental organisations that rely on donors are also being affected by a decrease in donations as companies and individuals face an uncertain financial future. By late June 2020, the Association of Medical Research Charities in the United Kingdom, whose members sent GBP 1.9 billion to biomedical researchers in 2019, was already reporting an average 38% drop in fundraising revenue; other countries are seeing similar situations (Cahan, 2020[7]).

On the other hand, this pandemic may underline the importance of science in preparing and reacting to upcoming crises, possibly translating into stronger and more lasting support for research. For example, the United States and the United Kingdom have pledged new funding for research for the coming years. The announced US federal R&D budget for 2021 shows a 6% increase over the fiscal year (FY) 2020 budget. Meanwhile, the United Kingdom remains committed to raising public R&D expenditure to GBP 22 billion by FY 2024/25 and increasing its total R&D expenditure to 2.4% of gross domestic product by 2027. Korea also announced a new science and technology policy initiative "post corona, science and technology policy direction for a new future" that identifies 30 promising technologies which will have high priority for government R&D funding. National strategies and funding commitments are likely to differ widely between countries, adding to future uncertainty for all the actors in research ecosystems, with important implications for the research workforce (see Chapter 3).

Effective mobilisation of research infrastructures

Research infrastructures (RIs) are facilities, resources and related services that are used by the scientific community to conduct top-level research in their respective fields. They cover major scientific equipment or sets of instruments; knowledge-based resources such as collections, archives or structures for scientific information; enabling information and communications technology-based infrastructures such as grid computing, software and communication; or any other entity of a unique nature essential to achieve excellence in research. They play a major role in modern research in all scientific domains. The COVID-19 crisis has seen an unprecedented, rapid mobilisation of RIs to support the research community. This effort covers several key aspects, as described in the following sections.

Fast-track access

To facilitate research on COVID-19, many RIs have fast-tracked access to their equipment or services without the need to undergo regular (and often lengthy) evaluation procedures. Many access requests were granted within one month of the proposal's submission. Box 2.1 provides an example of fast-track access to an RI for research related to COVID-19.

Box 2.1. Example of fast-track access to research infrastructure for COVID-19 research

The Paul Scherrer Institute (PSI) is a Swiss multi-disciplinary research institute for natural and engineering sciences that operates unique and world-leading large scientific equipment. Immediately at the onset of the crisis, PSI created a dedicated website for research related to COVID-19.[10] PSI was quickly able to contribute to various aspects of the underpinning COVID-19 science, from structural biology to pulmonary pathology and epidemiology.

In July 2020, scientists from the Goethe University in Frankfurt, Germany, published results on the papain-like protease (PLpro), an essential enzyme of SARS-CoV-2. The structural biology work was performed at the PSI electron synchrotron Swiss Light Source (SLS), following the opening of the “Priority COVID-19 call”. The crystallographic data collection happened on 9 April 2020, after the planned Easter shutdown of the SLS was cancelled to allow performing this specific experiment, along with an X-ray imaging COVID-19 experiment.

Data-sharing

The dissemination of research data on COVID-19 has been of paramount importance.[11] Many RIs provide access to data (e.g. biological, environmental and societal) that are of direct interest to COVID-19 research. Most of these data-RIs have set up dedicated portals and structures to facilitate access and use of data on COVID-19 that are relevant to the research. For example, the Korean Bioinformation Centre[12] centralises and makes available all biological information relevant to COVID-19. Some RIs have developed crowdsourcing initiatives that help open up and link COVID-19 data. The European research infrastructure ELIXIR, for instance, co-organised a virtual COVID-19 Biohackathon in April 2020[13] to develop new tools for working with COVID-19 data. In the United Kingdom, the national institute for health data science, Health Data Research UK (HDR UK), has actively championed the use of health data to address the COVID-19 challenge. Although digital infrastructure is needed to share and link data, this was not fully in place in the United Kingdom. To remedy this, HDR UK convened a number of organisations to fund the International COVID-19 Data Alliance (Health Data Research UK, 2020[8]), which focuses on sharing de-identified/population-level data. In other instances, RIs that possess substantial computing and data-analysis capacities for use in particular research fields (e.g. particle physics) have opened them up and offered their experience to facilitate data-mining on COVID-19. For example, CERN has mobilised its open-source technologies, established open-data repositories and developed a number of co-operative initiatives building on its in-house capacities.[14]

Co-ordination

A number of biomedical RIs have created co-ordinated mechanisms to facilitate research on COVID-19. For example, the German high-performance sequencing centres set up co-ordinated access to their facilities,[15] and in Canada, Genome Canada launched the Canadian COVID Genomics Network (CanCOGeN) in partnership with CGEn (Canada’s national platform for genome sequencing and analysis), national and provincial health labs, hospitals, academia and industry. At the international level, the COVID-19 Fast Response Service was established in Europe as a co-ordinated and accelerated procedure for researchers to access the academic facilities, services and resources of three medical RIs – the European Research Infrastructure for Translational Medicine,[16] the European Clinical Research Infrastructure Network[17] and the European research infrastructure for biobanking,[18] working together under the umbrella of the Alliance of Medical Research Infrastructures.

New COVID-19 dedicated research

While many RIs are service-oriented facilities geared towards external users, others also conduct internal research using their own staff. In response to the crisis, a large number of service-oriented RIs developed specific tools and programmes to facilitate COVID-19 research for their external users. They also developed additional services, such as project management tools. Many of those RIs that have conducted internal research with some relevance to the pandemic have undertaken dedicated actions to generate and provide data and information related to the crisis. For example, the European Social Survey[19] launched new modules to address pandemic-related societal issues, such as public attitudes towards government responses to the pandemic, on the support for conspiracy theories, and on the willingness to be vaccinated. In Japan, RIKEN began early operation of the new supercomputer “Fugaku” to support the search for therapeutic drug candidates for COVID-19. The initial plan was to begin sharing access to the supercomputer in 2021, but Fugaku began to exploit some of its functions as a matter of urgency in the second quarter of 2020, during the adjustment phase. In July 2020, a team of researchers from RIKEN and Kyoto University announced they had discovered dozens of substances that could be candidates for treatment of COVID-19, after performing in about ten days calculations that would normally have taken more than a year based on conventional supercomputer performance (The Japan Times, 2020[9]).

In conclusion, RIs have demonstrated considerable flexibility during the crisis

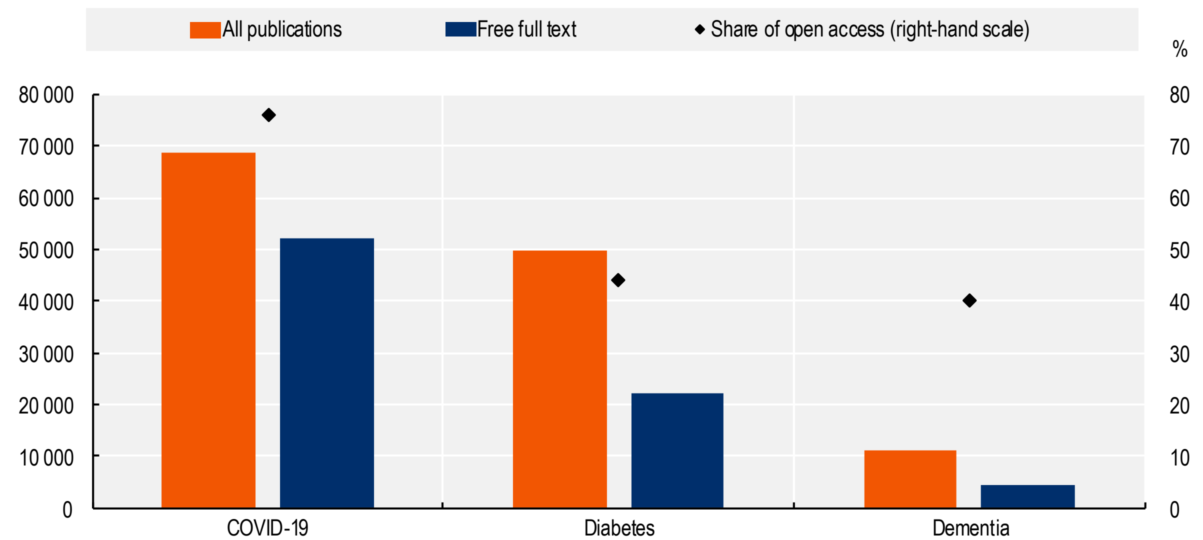
As these examples show, RIs have demonstrated considerable flexibility in adapting their facilities to meet urgent needs. Japan’s Fugaku’s computing capacities mentioned earlier were thus also used for societal-epidemiological projects to simulate and predict virus transmission indoors, and to model disease propagation under various policy containment measures. This proved to be extremely influential for health authorities (to determine the best containment policies based on scientific facts) and for the public in raising awareness about government guidelines and their acceptability. At the same time, the crisis has led many RIs to update their processes, as recommended in a recent OECD report on the operation and use of national RIs (OECD/Science Europe, 2020[10]). For example, RIs have had to both clarify and better inform potential users of their access rules, and open up their facilities to a broader community of users. Many such actions undertaken during the COVID-19 crisis were initiated by the RIs themselves, with support from their governing institutions and other stakeholders. Science policy makers may have an important role to play not only in supporting RIs financially, but also in developing the framework conditions that enable them to mobilise effectively and co-operate internationally in crises. This includes careful consideration of mandates and incentives, and a willingness to invest in RIs to maintain a degree of resilience and flexibility for reacting to future crises, balancing short-term efficiency gains with longer-term preparedness and flexibility.

The challenge of scientific dissemination in times of crisis

The COVID-19 crisis has spurred new practices in scientific communication as rapid sharing of data and scientific discoveries worldwide has become essential (OECD, 2020[11]). Many traditional constraints have been lifted or relaxed to accelerate the production, publication and dissemination of scientific results relevant to the pandemic, notably by lifting publication paywalls for a fixed period or making COVID-19 research fully open access (Nature, 2020[12]) and (Elsevier, 2020[13]). These efforts have been reinforced by various initiatives. For instance, the “COVID-19 Publishers Open Letter of Intent” aimed to speed up peer review and publication while maintaining the quality and integrity of published articles through a cross-publisher rapid-review process (OASPA, 2020[14]). Furthermore, to facilitate international access to relevant scientific results, the WHO is maintaining a global database of publications on COVID-19 research.[20] Various COVID-19 repositories and databases for articles or data were also created[21] or added to existing platforms, such as Github and Researchgate.[22] The combined effects of new funding streams, data openness and fast-track publication has had an immediate impact on scientific production. By 1 June 2020, 42 700 scholarly articles had already been published on COVID-19, 3 100 clinical trials launched, 420 datasets created, and 270 patents filed (Hook and Porter, 2020[15]). Moreover, three-quarters of COVID-19-related scientific publications are open access, compared to 43% for diabetes research and 40% for dementia research (Figure 2.7).

Figure 2.7. Open access of COVID-19, Diabetes and Dementia publications, January-October 2020

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.
Source: OECD calculations based on US National Institutes of Health PubMed data, https://pubmed.ncbi.nlm.nih.gov (accessed 30 October 2020).

StatLink https://doi.org/10.1787/888934223289

While these various initiatives have greatly facilitated the dissemination of scientific information, they have also potentially increased the likelihood of less rigorous research results entering the public domain. This issue can be exacerbated in times of crises, as any misleading information can quickly spread over social networks.[23] Preprints, i.e. articles published on the web before they have been peer-reviewed and accepted for publication by a scientific journal, accounted for around one-quarter of COVID-19 research outputs by the beginning of May 2020. While preprints can be useful in disseminating scientific information quickly, there are risks associated with the potential release of misleading or faulty information into the public domain without third-party screening (Dinis-Oliveira, 2020[16]). Owing to the speed of their release, preprints rather than peer-reviewed literature may have a disproportionate influence on policies, shaping the public discourse on the crisis (Majumder and Mandl, 2020[17]). At the same time, this widespread dissemination can also help quickly detect errors and block poor-quality research. For example, the mistaken claim that COVID-19 contained human immunodeficiency virus (HIV) "insertions" was one of the first retracted preprints, in this case withdrawn by the authors themselves (Pradhan et al., 2020[18]). It should also be noted that traditional peer review, even in the most prestigious journals, is not in itself an absolute guarantee of scientific rigour: the paper regarding the effects of hydroxychloroquine for the treatment of COVID-19 published in June 2020 in the prestigious *Lancet* journal had to be retracted after a serious international controversy (Mehra, Ruschitzka and Patel, 2020[19]). The COVID-19 pandemic has demonstrated not only the strengths and weaknesses of traditional publications and preprints, and also raises questions of how peer review works, its importance and its limitations.

What has emerged is the need for an in-depth rethinking of the way scientific information is disseminated (Taraborelli, 2020[20]):

- New best practices need to be developed to help reporters evaluate what they find in preprints and other scientific publications, and report on their findings responsibly (Khamsi, 2020[21]). The creation of rapid-response review venues (Eisen and Tibshirani, 2020[22]) could help connect reporters with independent scientists and offer on-demand expert views on new preprints of interest.
- New community mechanisms may be required to facilitate the translation of scientific publications for a more general audience.
- New technologies may be developed that would help analyse the connection between results, methods, data and resources, for example, as supported by initiatives such as ASAPbio (Accelerating Science and Publication in biology).24

These new "overlay services" could be built on top of existing repositories of scientific information, bringing value to scientists and facilitating online collaboration and peer production in a more transparent scientific publication system.

Lessons learned from the COVID-19 crisis

The mobilisation of the scientific enterprise during the COVID-19 crisis has been unprecedented. The swift response from many different fields of research will have a lasting impact on research systems and, most likely, on the relationship between science and society. While the global scientific effort towards solving climate-change issues remains much more significant than research targeting COVID-19, as illustrated by the extraordinary amount of scientific literature (about 10 000 peer-reviewed articles for physical science alone) analysed in Intergovernmental Panel on Climate Change reports, the climate emergency has not led to a dramatic readjustment of the science system itself or the rapid mobilisation of a major segment of the science community, as has happened for COVID-19.

The 2011 Fukushima disaster perhaps allows for a more direct comparison with COVID-19, albeit at a smaller scale. This major national crisis led to adjustments of the Japanese scientific system over time (Sato and Arimoto, 2016[23]; MEXT, 2012[24]). The longer-term changes were geared towards preventing similar events and mitigating their potential impact. Although the nature of the crises is very different, the Japanese experience may provide some important lessons for understanding the long-term implications of COVID-19 for science systems.

In its uniqueness, this COVID-19 crisis has revealed a number of positive and desirable characteristics of many science systems that have enabled an effective response:

- *Flexibility of research funding and the ability to allocate or reallocate resources quickly as needed*: the dedicated processes set up by research funders deserve to be analysed in depth. Not only is this relevant to future crises, but if the research projects funded through these emergency processes prove to be high quality, there may be some very useful lessons to be learned on streamlining current procedures, which are often burdensome for both researchers and funding administrations. The pandemic has also highlighted the capacity of the scientific community workforce to adapt quickly to a constrained environment while maintaining the efficiency of the R&D system.
- *A capacity for rapid sharing of data and information, which is likely to accelerate the open science agenda*: this crisis has highlighted the need for an evolution in the publication and dissemination

of scientific information and data. The lessons learned from the crisis should help develop new policies and technologies that support the validation of early publications (preprints) and data, and facilitate their use and understanding by broader user communities. On the other hand, data sharing has also sometimes been hampered, for example, by a lack of common standards for the protection of health data. The crisis should spur relevant organisations to harmonise their standards.

- *Some capacity for international co-ordination on a few objectives, often with the help of large philanthropic organisations*: the crisis has shown the need for new models for scientific research collaboration. The pandemic has triggered many valuable international scientific collaborations that produced valuable contributions to solving the crisis. However, there has been duplication of efforts (particularly in the field of clinical trials) and wasted resources. Some of the new collaborative models are being developed and tested already, offering an opportunity to build on these experiences (see Chapter 5).
- *An important role for RIs from many different domains in supporting the research community to conduct emergency research*: RIs are increasingly called upon to support research targeting societal challenges. The lessons learned during the crisis show their capacity to serve multiple research communities and to support policy decisions, but they will require support and incentives from their funders and hosts to maintain – and ideally strengthen – these capacities over the long term.

At the same time, the crisis has revealed some important future challenges:

- *Preparedness (before a crisis) is essential to accelerate the research system's response time during crisis*: Although the scientific system was able to respond quickly to the challenges raised by the pandemic, building on lessons learned from earlier epidemics, a series of unexpected issues emerged for which it was not fully ready, such as the need to overcome divergent approaches and regulations to sharing data and human samples between public and private partners. The crisis has shown the need to strengthen existing national and international structures that advise governments during emergencies.
- *It could exacerbate existing inequalities within research systems or create new ones, since the capacity to undertake research or raise funding is likely to be limited in some fields*: A full analysis of the impact and consequences of the crisis on the research system overall will be important to improve the resilience of the system to future events.
- *Ensuring the quality and rigour of scientific data, publications and communication*: this also raises questions about the current incentives driving hyper-competition and the "perish or publish" culture, with negative spill overs on researcher behaviour during crises (see Chapter 3).
- *Uncertainties regarding long-term funding for research once the immediate emergency has passed*: governments and research funding bodies should define and quickly communicate both their capacities to support research in the coming years and their strategic priorities, in order to allow research performing organisations to develop realistic long-term strategic plans.

These elements illustrate the need for a thorough analysis of the various response mechanisms implemented by different stakeholders in research systems during the COVID-19 crisis, as well as their relative efficiency and effectiveness.[25] Such an analysis could help improve the resilience and responsiveness of research systems, as well as integrate any useful practices that were successfully experimented with during the crisis.

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Notes

[1] Data were collected by the OECD either directly from funding agencies or from public sources, and pooled with data kindly provided by the NSF, which also collected similar data in parallel from other public sources. This data is not complete and does not cover all countries but can provide a minimal estimate of scale of investment in COVID-19 research. The national funding data can be accessed at the STIP COVID-19 Watch portal (https://stip.oecd.org/covid/).

[2] By way of comparison, the total amount of yearly R&D funding distributed by the European Union's Horizon 2020 programme in all disciplines is around EUR 10 billion.

[3] See, for example, the European Union-led worldwide pledging marathon planned to raise EUR 7.5 billion to end the current pandemic (https://ec.europa.eu/commission/presscorner/detail/en/ip_20_710).

[4] Note that the database is not exhaustive, and funding is unknown for many projects. Furthermore, the database registers funding already awarded and not the full amount pledged per funding programme. The database can be accessed at: https://www.ukcdr.org.uk/funding-landscape/COVID-19-research-project-tracker/.

[5] https://www.ukcdr.org.uk/covid-circle/covid-19-research-project-tracker/

[6] The focus on social countermeasures research and social science, as shown in the UKCDR tracker, also reflects patterns seen in previous crises, such as Ebola in West Africa.

[7] Feedback from expert discussion during the GSF workshop (https://www.oecd.org/sti/inno/global-science-forum.htm).

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[9] See KT FO.

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[22] https://github.com/open-coronavirus/open-coronavirus; https://www.researchgate.net/community/COVID-19

[23] https://read.oecd-ilibrary.org/view/?ref=135_135214-mpe7q0bj4d&title=Combatting-COVID-19-disinformation-on-online-platforms

[24] https://asapbio.org/ .

[25] In this regard, a project on mobilising science in times of crisis is ongoing under the aegis of the OECD Global Science Forum.

3 Challenges and new demands on the academic research workforce

Academic career structures and the allocation processes for research funding largely reflect merit-based competition among individuals, which has proven its effectiveness over time in promoting excellence in fundamental research. However, concern is growing about how these structures and processes affect the precarity and attractiveness of research careers and generate a lack of diversity in the scientific workforce. There is an expectation that science will not only produce highly-cited publications, but also rapidly translate into societal benefits and solutions to global challenges – such as the COVID-19 pandemic. The emphasis on individual disciplinary excellence and short-term outputs fits uneasily alongside the need for more transdisciplinary research, more novelty and risk-taking in research, and more data-intensive research. This chapter reviews recent OECD analysis of the challenges within science systems, many of which are accentuated by COVID-19, and what these imply for policy measures to build a diverse, appropriately skilled and motivated science workforce.

Key findings

- **The academic research workforce is leading the fight against COVID-19**, generating the new knowledge that is required to understand the pandemic and develop effective mitigation strategies. This extends far beyond medical research and the development of new diagnostics, treatments and vaccines but encompasses all research domains from mathematics to social sciences and humanities.
- **Countries need to continue to support a breadth of research**, whilst implementing measures to ensure that a new generation of researchers with inter- and trans-disciplinary skills is encouraged. The crisis has highlighted the importance of data-intensive science, in particular, propelling it forward as a critical tool. Investment in research data infrastructures needs to be matched by long-term investment in human resources, including data stewards, software engineers and data analysts.
- **The COVID-19 pandemic has severely affected researchers and shed light on the existing weaknesses in academic structures**. There has been a 25% increase in the number of people with PhDs in OECD countries over the past decade with no corresponding increase in academic posts. The current hyper-competitive system – with its focus on narrow measures of individual performance and evaluation by peers – discriminates against women and a number of social groups leading to a lack of diversity in the research workforce. Important scientific outputs, such as databases or software, policy reports or citizen engagement activities, which are critical for crisis response, are undervalued. New incentives and measures for evaluating and rewarding both individual and collective contributions to science are urgently required.
- **There is need for systemic changes in the way academic research is structured and supported** if it is to attract and retain the diversity of talent that is necessary to address current and future societal challenges. New and more attractive career paths that provide greater security and alternative options for mobility in and out of academia and other research sectors are required. National governments have a critical role to play in engaging all actors in the research ecosystem to develop co-ordinated research workforce strategies, incentives to implement these strategies and indicators and measures to monitor what is happening.

Introduction

The COVID-19 pandemic is putting enormous pressure on public science systems and those who work within them, with research being mobilised in unprecedented ways across many different disciplines. Researchers across the world are being encouraged and incentivised to quickly redirect their efforts to focus on COVID-19. There is intense pressure to release data and results rapidly, short-cutting or circumventing normal peer-review publication processes (see Chapter 2) and highlighting pre-existing concerns about quality assurance and accreditation of research findings. At the same time, scientists are being called upon as experts to provide input on public health and other policy responses to the pandemic (see Chapter 8) and they are being asked to communicate incomplete and changing evidence in a way that promotes public confidence and trust. These are activities that most scientists were not trained for and which would normally go largely unrecognised within academic structures, with their predominant focus on scientific merit and excellence.

Even in the absence of COVID-19, many researchers, particularly in the early stage of their careers, were in precarious positions and employed on short-term contracts with no clear perspective of a permanent academic position. For women in particular, the hyper-competitive environment and lack of security are an active disincentive to continuing in research (Pollitzer, Smith and Vinkenburg, 2018[1]). The COVID-19 pandemic has added to the sense of insecurity. While it has led to increased funding in some research areas, it is also threatening the future of many universities that depend on overseas students. Although some countries or institutions have taken mitigation measures, such as extending PhD grants and postdoctoral research contracts, this is not universally the case. The majority of young researchers now expect to have even more limited academic career opportunities (Woolston, 2020[2]), a sentiment compounded by the fact that COVID-19 has radically disrupted the movement of researchers between countries.

Many of the technological innovations introduced in response to COVID-19 have been driven by research and development in the private sector, particularly in the digital domain. For example, artificial intelligence (AI), which is playing a variety of roles in pandemic response and recovery (OECD, 2020[3]), is a field that is dominated by private firms, which attract many of the best science, technology, engineering and mathematics (STEM) graduates with employment packages and prospects that academia cannot match (The Royal Society, 2019[4]). At the same time, efforts to develop and test effective treatments and vaccines have been characterised by different public and private sector research actors working in tandem (see Chapter 5). The potential benefits of inter-sectoral co-operation and exchange of skills and knowledge for promoting innovation were obvious well before the current crisis and have long been a focus for STI policy. Nevertheless, the reality remains that there are substantial barriers for those who enter the academic research path and subsequently decide to make the transition from academia to other sectors and vice-versa (Vitae, 2016[5]).

Not only have digital tools and open-data infrastructures allowed many scientists to continue to function effectively outside their usual laboratory or field environments during lockdowns, they have also massively accelerated data-driven discovery and knowledge dissemination. At the same time, these developments have emphasised the digital divide between countries, institutions, disciplines and research teams, highlighting the need for more digitally skilled scientists and research professionals to conduct data-intensive research and support open science in academic settings (OECD, 2020[6]).

As the pandemic progresses, and governments move from the public health response to addressing the broader socio-economic challenges, there is a growing need not only for public-private partnerships but also for more inter- and trans-disciplinary research to produce the integrated knowledge necessary to address these issues (see Chapter 5). Many countries are seeing the "COVID moment" as an opportunity to transition to more sustainable and resilient societies, and interest is growing in co-design and co-production processes that can enable such transitions. This places greater emphasis on team working, people skills and public engagement, which are not always fully valued in an academic research setting (OECD, 2020[7]).

COVID-19 has helped reveal both the strengths and the weaknesses of existing science systems with major implications for the research workforce of the future. This chapter reviews recent OECD work on several topics related to the research workforce. It explores the policy implications for different actors in the research ecosystem, including governments, research agencies, universities and public research institutes.

The quest for research excellence

Scientific research is largely organised around disciplines. Individual career progression depends on assessment by peers, which itself is highly dependent on a researcher's publication record. The structures and processes of universities, public research institutes and funding agencies heighten this focus on disciplinary expertise and publication outputs, driven by the quest for research excellence. This arrangement has arguably been very successful, with a growing number of scientific publications being produced annually. This increase is particularly striking in the university sector (see Figure 3.1).

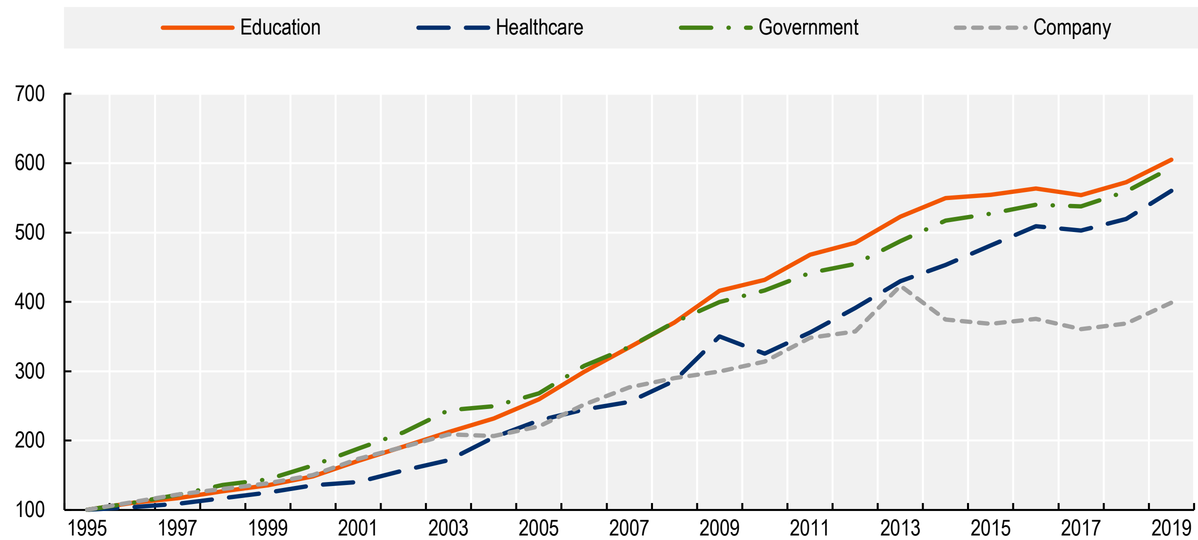
If publication numbers are an indicator of scientific performance then the system is performing well and also responding well to the COVID-19 pandemic (see Chapter 2). But numbers rarely tell the whole story. Excellence is an elusive concept, which can only be defined by peers. Hence, quantitative indicators of peer-esteem such as citation indices, journal impact factors and h-indexes have become the currency of scientific excellence or quality. Despite strong criticism (e.g. see the San Francisco Declaration on Research Assessment (DORA, 2013[8]), these proxy measures have become a major determinant of scientific behaviour. Being the lead author of a well-cited paper in a high-impact journal has become the "holy grail" for an early-career researcher, and brings with it the prospect of a secure long-term future in academia.

Hyper-competition and the "publish or perish" culture may have its merits but it is also exerting a high toll on researchers, particularly at the doctorate and postdoctoral level, where the next position depends on what the researcher publishes. It also has perverse effects on the composition of the research workforce and discriminates against certain population groups, including women (Pollitzer, Smith and Vinkenburg, 2018[1]). Even if it works in terms of triaging the truly excellent from the merely good, it discourages risk-taking and inter- or trans-disciplinary research, for which short-term outputs are less certain but which are increasingly required for science to meet societal needs. For example, bibliometric scores are of limited use for assessing public engagement activities or evaluating and rewarding the new cohorts of highly skilled research software engineers, data stewards or data analysts that are urgently required to support data-intensive research (OECD, 2020[6]).

Focusing on individual merit and disciplinary excellence has taken science a long way and should not be abandoned altogether. However, the way these qualities are assessed and measured no longer meets the broader societal expectations of science. Nor does it reflect the growing emphasis on open science (OECD, 2015[9]) and the increased tendency in many research areas to work in large, often distributed and diverse, teams (see footnote to Figure 3.1). Maintaining scientific rigour and research excellence are critical for ensuring trust in science in the current pandemic situation. However, there is a need to redefine what is meant by excellence in relation to all of the different expectations of science.

Figure 3.1. Trends in scientific publication output by type of institution, 1995-2019

Whole counts, index 100 = 1995



Note: The numbers by institutional type are not additive, as a single paper can have multiple authors with multiple affiliations with any of the types. Over the same period of time the average number of authors per paper has risen from 3.18 to 4.82 (based on separate OECD analysis using SCOPUS database) indicating an increase in the size of research teams.
Source: OECD calculations based on the Lens Database, https://www.lens.org (accessed October 1, 2020).

StatLink https://doi.org/10.1787/888934223308

Precarity of research careers

One of the issues that the COVID-19 pandemic has highlighted is the precarious employment situation of many researchers in academia. Whilst precarity is not unique to academic research, it is more prevalent than in many other sectors that depend on highly skilled professionals and it stands in striking contrast to expectations that research will attract the 'best minds' to promote long-term socio-economic development and resilience in the face of crises. The working conditions of academic researchers have been deteriorating in recent years. This is especially true for the growing number of postdoctoral researchers on fixed-term contracts and with limited continuous employment prospects. Country responses to the OECD Global Science Forum policy survey on reducing the precarity of research careers showed, for example, that in Germany, 92% of junior scholars in higher education institutions, and 83% in non-university research facilities have a fixed-term contract; in Finland, 70% of academics are on fixed-term contracts; and in Belgium, 58% of those working in universities are on fixed-term contracts.[1]

While the majority of early-career researchers display a strong intrinsic motivation and ambition for long-term academic careers, precarity can have significant negative consequences on their motivation, behaviour and well-being, affecting the nature and quality of scientific outputs (Vitae, 2016[5]; Wellcome, 2020[10]). At the same time, there is widespread concern about the capacity of countries to retain their best national talent and attract good foreign researchers. In some countries and research fields, the problem is evident even upstream of the research pipeline, as evidenced by difficulties in attracting the best candidates to doctoral training.

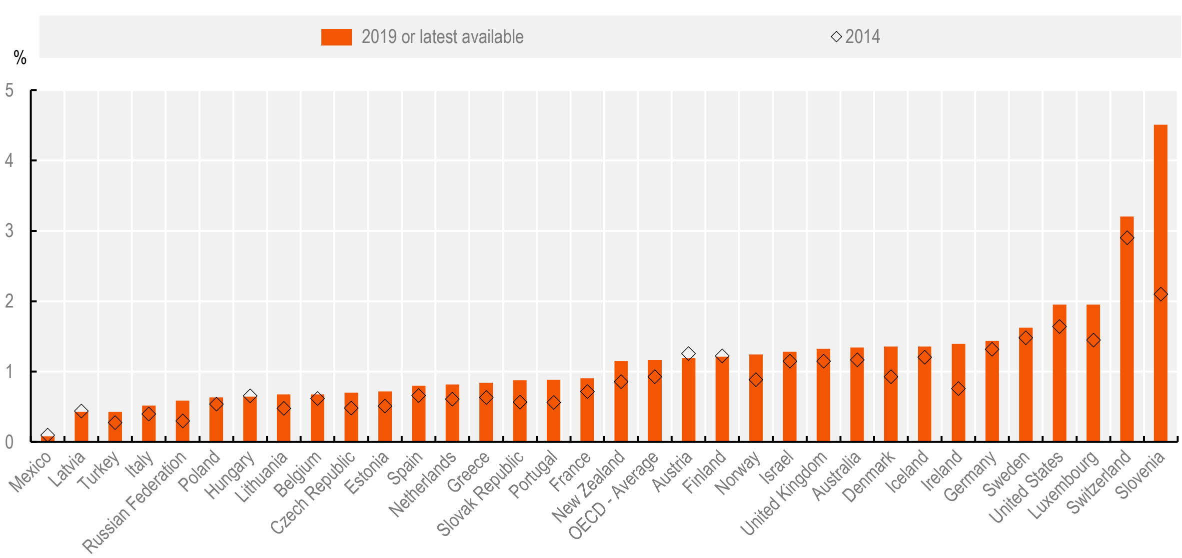
The precarity and insecurity of research careers is also a major obstacle to advancing gender equality and social diversity in the research workforce (Forrester, 2020[11]). On top of this, COVID-19 is making matters worse for many in the research precariat. Responses to the OECD Science Flash Survey 2020[2] suggest that the pandemic is having detrimental effects on job security and career opportunities in science, as well as on research funding and the time available for performing research. Younger researchers and women appear to be more vulnerable to these effects, as also shown by a recent survey by *Nature* (Nature, 2020[12]).

The shift from core institutional funding to short-term, project-based funding, together with the increasingly competitive nature of core-funding, is making research (and higher education) systems increasingly dependent on a contingent of junior staff employed on casual contracts. In Australia, 56% of researchers in higher education are postgraduate students. In Switzerland, 64% of researchers are doctoral and postdoctoral researchers. In Germany the proportion of junior scholars in the scientific staff at higher education institutions has been approximately 75% since 2010. In Finland, the number of postdoctoral researchers has increased by 144% in the last decade.[3]

The inability of traditional academic career paths to absorb the growing number of doctorate holders wishing to remain in academia is heightening the competitive pressure to extreme levels. The average share of doctorate holders aged 25-64 year-olds in the OECD, which currently stands at around 1%, has been steadily increasing (OECD, 2019[13]). Figure 3.2 presents the share of doctorate level attainment in the population aged 25-64 year olds in OECD countries. It shows a 25% average increase in doctorate holders across the OECD during the five-year period from 2014 to 2019.

Figure 3.2. Share of doctorate-level attainment in the population

25-64 years, 2014 and 2019 or latest year available



Note: The data for most countries are derived from national labour force surveys. It includes Short-cycle tertiary education (L5) for Switzerland 2014-2019. 2019 data for Russian Federation correspond to 2018 value.
Source: OECD (2020[14]), "Education at a glance: Educational attainment and labour-force status", OECD Education Statistics (database), https://doi.org/10.1787/889e8641-en (accessed on 22 September 2020).

StatLink https://doi.org/10.1787/888934223327

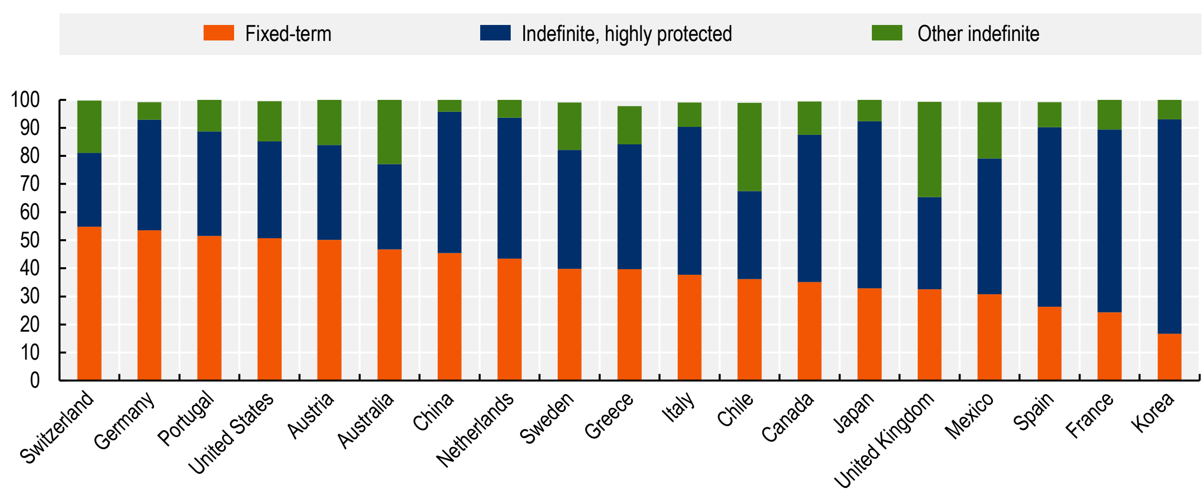
Higher education has been the traditional sector of employment for doctorate holders in most countries. However, many younger PhDs will no longer find a stable career position in academic research. Around one third of the total OECD labour force work in temporary or part-time jobs, or are self-employed (OECD, 2019[15]). The scale of precarity is even higher in the academic research sector. Results from the 2018

OECD International Survey of Scientific Authors (Bello and Galindo-Rueda, 2020[16]),[4] presented in Figure 3.3 show that, while a majority of corresponding authors in Korea, France, Spain and Japan hold an indefinite, highly protected contract (e.g. civil servant, tenure) this is not the case in most countries. In the United Kingdom and Chile, less protected (e.g. open-ended) contracts are more common. In Switzerland and Germany, the majority of corresponding authors are on fixed-term contracts. While these differences may partially reflect different conventions for authorship, it is clear that in many countries researchers who are leading scientific production do not have secure positions.

The median age of new entrants to doctoral studies across the OECD is 29 years; 60% of entrants are between 26 and 37 years old (OECD, 2019[13]). This means that the majority obtain their doctorate in their thirties. Most of those who transition to the postdoctoral stage stay there well into their late thirties and even early forties, often lingering as "postdocs", "research assistants and associates", or even "hidden researchers". They normally spend long periods pursuing research, although they may be employed in non-research roles (such as full-time teaching) while waiting for a more secure academic research position to become available. Despite a lack of preparation and training for alternative careers, many eventually "drop out" of academia in a move that is frequently stigmatised as failure. In fact, across the OECD, the majority of researchers (62.5%) eventually end up working in the business enterprise sector (OECD, 2020[17]).

Figure 3.3. Job security of corresponding authors, by country of residence

Percentage of corresponding authors, 2018, selected economies



Note: Indefinite highly protected contracts mean the respondent can only be dismissed by the employer for gross misconduct. This level of protection is typically afforded by civil servant status or tenure. Other indefinite contracts are open-ended, as opposed to fixed-term positions, which have a set duration.
Source: OECD calculations based on OECD (2018[18]) International Survey of Scientific Authors, 2018. http://oe.cd/issa.

StatLink https://doi.org/10.1787/888934223346

The precarity of research careers is particularly problematic for women. Many struggle with the pressures of a postdoctoral position and embarking on an academic career while caring for young children or elderly relatives. Gender stereotyping and systemic biases exist across society. They are also embedded in science education and research systems meaning that even when women do obtain secure positions, they are less likely than their male counterparts to advance to leadership positions (Bello and Sarrico, 2020[19]) (OECD, 2020[20]).

COVID-19 is also having a disproportionately negative effect on women researchers, particularly those at the early-career stage (Viglione, 2020[21]). Since the start of the pandemic, scientific publications have been rising more quickly for men than women. Women are more likely to lose their jobs, as they are more likely to be on fixed-term contracts. The pandemic is threatening the gender-equity gains of recent years (Gewin, 2020[22]), making it even more pressing to have a co-ordinated policy effort on gender that provides both targeted support to female researchers and addresses systemic biases, with careful monitoring of progress (Pollitzer, Smith and Vinkenburg, 2018[1]).

International mobility in the global labour market for researchers can expand opportunities – but it can also increase precarity – for early career researchers. Although mobility at the early career stage is a choice, it is also often considered a necessary step for those with longer-term ambitions in academia. Results from the OECD International Survey of Scientific Authors show that corresponding authors on fixed-term contracts are more likely to be working in a country different from the one where they earned their doctorate and are much more likely to be planning to move to another country (OECD, 2018[18]). Working conditions for foreign researchers are often worse than those for native researchers with respect to issues such as access to employment contracts, right to stay and welfare benefits. Mobility, when accompanied by short-term contracts, can entail significant personal sacrifices, especially when early career researchers are considering starting a family and/or entering the housing market, and working abroad can lead to loss of social capital in one's country of origin. It is not surprising, then, that women doctorate holders are less internationally mobile than their male counterparts.

Whether or not the short-term negative effect of COVID-19 on international mobility is destined to last, the pandemic has most likely inhibited at least a cohort of researchers from moving abroad for either doctoral education or postdoctoral work (Woolston, 2020[2]). Some countries are also likely to lose foreign research talent owing to visa expirations and new regulations for visiting workers. Immediate policy intervention is required to support the many researchers, whose already insecure positions have been made more precarious because of the pandemic. Potential actions, which are already been put in place in many countries, range from the extension of PhD studentships and research grants to ensuring visas for researchers.

However, precarity in research careers existed well before COVID-19 and will certainly not automatically disappear when the current pandemic comes to an end. Over the longer-term there are a number of areas for policy action that governments, together with funders and research organisations, will need to address if they wish to reduce this precarity, make academic research careers more attractive and promote workforce diversity.[5]

- Doctoral training: moving the emphasis from increasing the number of doctorate holders to broadening the training at doctoral level to encourage professional development, including transferable skills that can be used in a variety of economic sectors.
- Employment status: making changes to the employment status of postdoctoral researchers by including them in formal career structures (e.g. as staff scientists), and collective bargaining agreements. In this regard, Portugal has moved away from providing stipends to granting employee status for postdoctoral researchers, making open recruitment the norm. Spain is allowing researchers who have occupied fixed-term positions for some time to apply for a permanent contract in a competitive process. In Germany, the maximum duration of fixed-term contracts for the purpose of qualification is capped at six years prior to being awarded the doctoral degree and six years (medicine: nine years) after. France is introducing tenure-track positions.
- Tracking the careers of doctorate holders: collecting, analysing and publishing data on the careers of doctorate holders to provide evidence to underpin the development, implementation and effectiveness of human resource policies. For instance, Belgium has created the Observatory of

Research and Scientific Careers, Portugal has launched a Scientific Employment Observatory, and Korea is building a comprehensive database on postdoctoral researchers.

- Human resource management: improving human resource management in institutions. The European Commission has adopted the European Charter for Researchers and a Code of Conduct for the Recruitment of Researchers. The United Kingdom has developed a concordat between funders, institutions and researchers to support the career development of researchers and improve institutional human resource policies and practices. Belgium, the United Kingdom and the European Union grant human resource excellence awards to institutions demonstrating good practice.
- Funding: making funds available to enhance the independence of postdoctoral researchers and support their training and career development. The Korean Initiative for fostering Universities of Research and Innovation (KIURI) is focused on promoting the independence of postdoctoral researchers. Spain has created a programme allowing the recipient of a postdoctoral fellowship to choose the host institution. Japan is allowing young researchers employed on a research project to pursue their own research choices for up to 20% of their time. Belgium plans to increase the success rate of postdoctoral fellowships to 30%. Meanwhile, Portugal has created collaborative laboratories with the private sector, and provided fiscal incentives to employ doctorate holders.
- Gender equity: targeting funding to women in fields and seniority levels where they are under-represented; taking account of parenthood and other life circumstances in assessments for funding, recruitment and promotion; and, giving gender equality awards to institutions that demonstrate best practices. In Germany, the Women Professors programme provides targeted support for women in senior positions. In the United Kingdom the Athena SWAN charter recognises commitment to advancing the careers of women in science.
- Diversity, equity and inclusion: targeting funding at under-represented groups, defined by socio-economic status, ethnicity, language, indigeneity and disability; promoting the development and monitoring of equity, diversity and inclusion strategies at the institutional level; and collecting, analysing and publishing disaggregated data on doctorate holders by gender and other groups of interest (e.g. indigenous researchers in Canada and Australia).

Strengthening the links between academia and other sectors

There are many examples from the response to the COVID-19 pandemic where academic researchers have combined forces with other public and private sector actors to develop new knowledge and technologies (see Chapter 5). As described in the previous section, there are more doctorates working outside of academia than within and most of these work in the private sector. Nevertheless, moving out of academic research is not an easy option for many people and the two-way exchange of research personnel between sectors is minimal.

In the OECD as a whole, researchers working in higher education represented only 30% of total researchers, and those working in the government sector around 7% in 2016. Since 2005, the percentage of gross domestic expenditure on research and development (GERD) in the higher education sector has remained stable at around 17%, whilst that in the government sector has steadily decreased from 12% to around 10% in 2018 (OECD, 2020[17]). The reality is that only a minority of doctorate holders in many countries will continue in academia, even though doctoral training is still mostly focused on how to become an academic. While many postdoctoral researchers eventually find successful and satisfying alternative careers, they often report significant challenges in undertaking a transition associated with giving up long-held ambitions of an academic career and a loss of social identity (Vitae, 2016[5]).

Over the past decade, conditions have been favourable for employment in research outside of academia. While the total number of researchers has grown by 37% across the OECD, R&D expenditure per-capita has grown faster, by 68% between 2005 and 2018 (OECD, 2020[17]). In 2017, there were 8.6 researchers per 1 000 people in employment, compared with 7.0 in 2005. Doctorate holders, especially those working in the private sector, enjoy on average an earnings premium relative to other graduates. However, opportunities greatly depend on the field of study, and there are wide differences among countries in the distribution of doctoral graduates by field of study.

Mobility between academia and other sectors can help promote effective interaction between research, education and innovation as well as opening up alternative career paths. However, it is not always clear how to facilitate exchange of early career researchers between sectors. On the one hand, doctorate holders who have been trained in academia may need further training and skills to meet the needs of other sectors. On the other hand, they often face obstacles to returning to academic research after working outside academia. Training and experience that may be valued in other sectors are often not aligned with expectations for an academic career. Inter-sectoral mobility, especially at an early stage of one's career can represent a one-way ticket out of academia, with little opportunity of returning. The result can be a permanent loss of talent in the academic scientific endeavour.

Countries can take a number of actions to promote the inter-sectoral mobility of researchers:

- Collaboration in doctoral education: preparing doctorate holders for diverse careers by changing the objectives and content of doctoral training, including providing more opportunities for institutional placements during doctoral education. Several countries, including Hungary and Portugal are promoting new types of doctoral programme in collaboration with industry.
- Professional development: investing and promoting the professional development of doctoral and postdoctoral researchers, including through career advice and mentoring. In the United Kingdom, UK Research and Innovation and the Wellcome Trust fund training programmes that offer recipients a wide range of development opportunities, including collaboration with non-academic partners, to prepare them for their future careers. In Korea, the KIURI provides postdoctoral researchers with opportunities to develop their careers in industry, and promotes their independence from their research advisers.
- Publication of data on labour-market outcomes of doctorate holders: In Belgium, the Observatory of Research and Scientific Careers provides this information; in the United Kingdom, Vitae publishes results of their surveys on research careers.
- Portability of acquired benefits: The European Union has developed RESAVER, a multi-employer occupational pension solution for research organisations that enables researchers to stay with the same pension plan when moving between countries or employers.

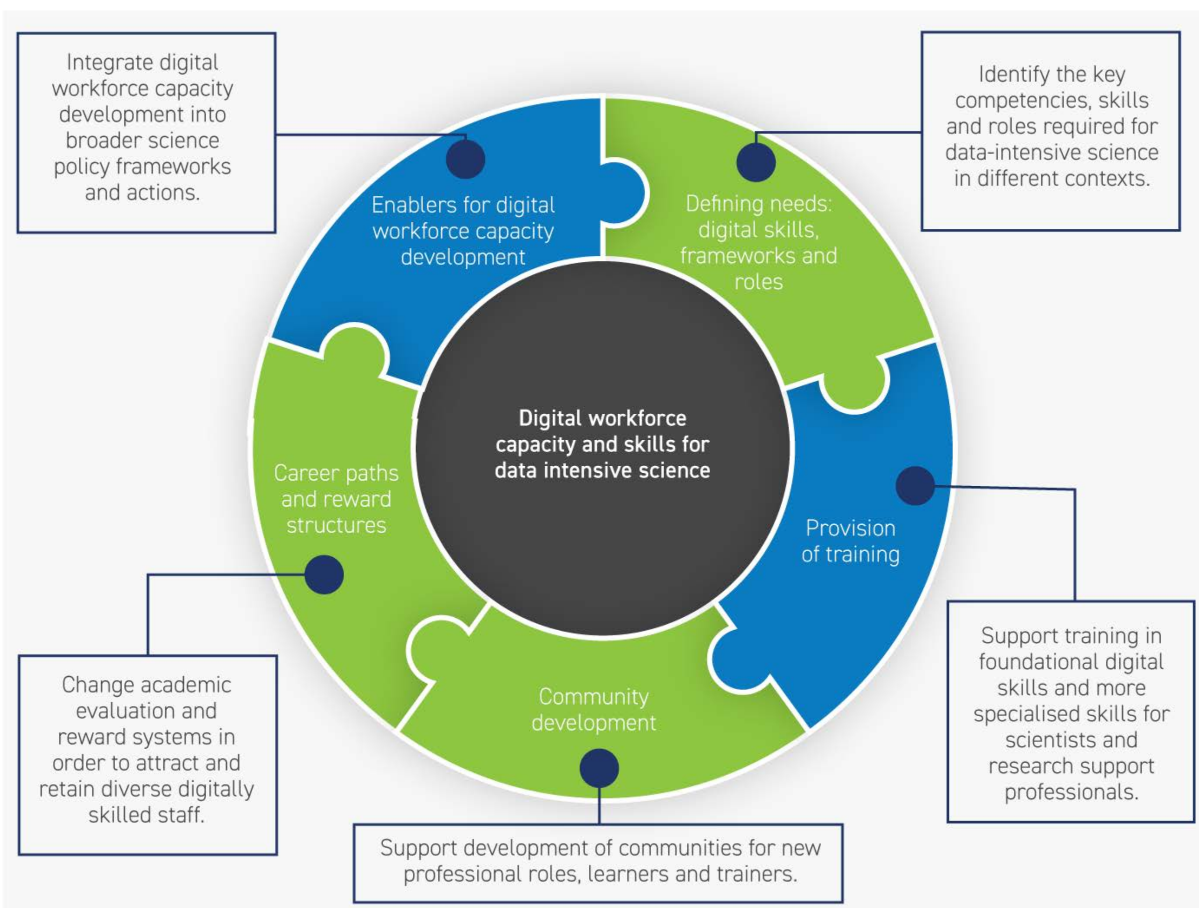
The insecurity of individuals on short-term funding in academic research has been growing. Core university and research funding is likely to decrease in some countries and some research fields after the COVID-19 crisis, and even more flexibility may be demanded of research personnel. There is also emerging evidence that small firms have been halting recruitment for highly-skilled jobs, including researcher positions, during the pandemic (Campello, Kankanhalli and Muthukrishnan, 2020[23]). These combined pressures make the exchange and sharing of research skills and promotion of inter-sectoral mobility even more necessary. It is vital to improve the resilience of the research workforce in an uncertain labour market in a way that is mutually beneficial for both academia and the private sector.

Digital transformation and data intensive science

Digitalisation is changing the practice of science and all fields of research are becoming increasingly data dependent. Digitalisation is also enabling a major shift towards open science, and increased public scrutiny is putting additional onus on ensuring the rigour and integrity of science (Dai, Shin and Smith, 2018[24]). As illustrated by the scientific response to COVID-19, these changes are happening rapidly (see Chapters 1 and 2). They present a major challenge for workforce development, particularly in scientific domains that have been historically less data-rich. Building digital workforce capacity is required at multiple levels, including: individual scientists, research teams, data service providers, research infrastructures and institutions. Traditional academic support roles, such as librarian or archivist are being re-imagined to take on some data management functions, while others are being taken on by researchers. At the same time, new professional roles are emerging, including data analyst, data steward and research software engineer (OECD, 2020[6]). Some of these are in research support roles, whilst others are actively involved in conducting research. Although different fields of research require different types and levels of digital expertise, the prevailing trend in most fields is towards working in large teams that involve a mix of researchers and research support professionals.

It has been estimated that up to 5% of the scientific research budget needs to be dedicated to the management of FAIR (findable, accessible, interoperable and re-useable) data and that 1 in 20 staff in the research workforce should be a digitally skilled research support professional (Mons, 2020[25]). In Europe alone, this means about 500 000 professionals of various kinds are necessary to support researchers through experimental design and data capture, curation, storage, analytics, publication and reuse. To achieve this workforce transition, action is required in 5 key areas, as shown in Figure 3.4.

Figure 3.4. Five key action areas and goals for capacity development in the digital research workforce



Source: OECD (2020[6]), "Building digital workforce capacity and skills for data-intensive science", OECD Science, Technology and Industry Policy Papers, No. 90, OECD Publishing, Paris, https://doi.org/10.1787/e08aa3bb-en.

National governments have an important role for to play in:

- recognising at the policy level the need for a digitally skilled workforce in research, and the importance of strategic planning that integrates the five key areas necessary to build and maintain this workforce, i.e. definition of needs, provision of training, community building, career paths and rewards, and broader enablers;
- analysing digital capacity needs in the national research workforce and the status (or preparedness level) of the research ecosystem to provide the training and other actions necessary to meet these needs; and
- facilitating and coordinating efforts to build workforce capacity at the speed and scale necessary to optimise the benefits of data-intensive science, including monitoring and assessment processes that keep pace with a changing landscape.

However, while leadership, planning and coordination are necessary at the national level, the most important actions in terms of implementation lie with universities and research institutions, which are the main venues for science education, training and research. There is an urgent need not only to train more digitally skilled scientists and research support professionals but more importantly to develop attractive and supportive academic research environments so that they do not all leave to take up better paid jobs in industry. This means developing new career paths as well as new evaluation and reward systems. The data and software outputs from research need to be considered on a par with publication outputs. More flexible career paths need to be implemented to enable people to move smoothly between different posts in academia, the public sector and the private sector at different stages of their lives, reversing the one-way outflow from academia that is draining hot research areas such as AI. At the same time, promoting diversity and lowering the obstacles to entry and progression for women and other population groups that are under-represented in the digitally skilled scientific workforce require urgent attention.

The scale and immediacy of the challenge of building digital capacity for data-intensive research, which is at the forefront of the scientific response to COVID-19, appears to be widely under-estimated. Nevertheless, a number of examples from different countries demonstrate how governments and funding agencies can successfully facilitate and support the necessary changes (OECD, 2020[6]). The German Council for Scientific Information Infrastructures has mapped out future digital educational and training needs at both vocational and scientific research levels (RfII, 2019[26]). In Australia, skilled workforce development and training is one of the five areas of activity of the Australian Research Data Commons, a national initiative supporting Australian research. The UK Arts and Humanities Research Council requires that PhD students undertake training in digital skills and provides a framework against which these skills are monitored.

Universities are also working together to address the challenges of building sustainable workforce capacity and skills for data-intensive science. In January 2020, the leaders of eight university networks from multiple nations signed the Sorbonne declaration on research data rights. The signatories committed to a number of actions including: “Encouraging our universities in setting up training and skills development programmes that create an environment to promote open research data management” (LERU, 2020[27]). At the institutional level, the Technical University of Delft in the Netherlands is funding data stewards embedded across the university and appointing researchers as data champions, as it spreads skills through peer networks as well as with training events and on-line learning facilities (OECD, 2020[6]).

Despite these and other examples of good practice, policy initiatives around digital skills and capacity tend to be ad hoc and short-term, with few examples of thorough needs assessments and longer-term strategic initiatives or structural changes to address identified gaps. This may reflect in part the diversity of public sector actors who need to work together to fully address these issues, including education and research ministries, funding agencies, and (largely autonomous) universities and academic bodies. As witnessed with regards to AI and COVID-19, the private sector also has a critical role to play, both as a supplier and a user of digitally skilled researchers and professional support staff.

Science to address societal challenges

As indicated at the beginning of this chapter and exemplified by the COVID-19 pandemic, scientific research is increasingly being called upon to address complex societal challenges. Disciplinary approaches, or indeed science alone, can only address these challenges to a limited extent. In many situations, transdisciplinary research (TDR), which combines different actors and sources of knowledge, is necessary. TDR requires additional skills and approaches and generates additional outputs to those that are normally valued in academic research.

While many young scientists are motivated to use TDR approaches and develop solutions for societal challenges, such as those embedded in the Sustainable Development Goals, it is not necessarily a good career choice for scientists wishing to establish themselves in academia. TDR is complicated, has a long lead-in time and is often conducted in large teams with no single disciplinary "home" or champion (OECD, 2020[7]). While scientific outputs and publications are important in TDR, a variety of other outputs are equally – if not more – important. These can include policy reports, public communication documents, new multi-stakeholder networks, and changes in practice, all of which are clearly required in the current pandemic response situation. Good communication and facilitation skills are essential for performing TDR, and, in larger scale projects, dedicated co-ordinators who have these skills are invaluable. However, such TDR outputs and skills are not what is normally expected to be listed on an academic CV. Even when a researcher's contributions to society are clearly excellent, it can be very difficult to get full recognition and support from peers and forge a long-term career in academia.

Recent OECD analysis (OECD, 2020[7]), including 28 in-depth case studies, indicates that governments, funding agencies and other actors in the research ecosystem have a critical role to play in providing the strategic leadership, support and enabling conditions for TDR. Specific policy actions include:

- introducing TDR learning modules in science education and postgraduate training courses;
- supporting early career researchers to engage in TDR projects (e.g. through jointly supervised PhDs) and developing more flexible career paths;
- providing individual support (e.g. fellowships) for outstanding individuals who can develop and lead TDR projects;
- extending funding and/or promoting collaboration with other donors to support capacity-building and the participation of non-academic stakeholders in TDR projects;
- allocating core resources, including personnel, to build long-term expertise in TDR methodologies and practice;
- changing peer review and evaluation processes, including by using multi-disciplinary and multi-stakeholder review processes; and
- changing evaluation and promotion criteria for individuals who engage in TDR so that they are judged not only on their scientific publications and citations, but also on their contribution to collective research outputs that are of value to stakeholders outside of science.

In response to COVID-19, a number of research funding agencies have rapidly implemented new schemes to support inter- and trans-disciplinary research, particularly with a focus on the socio-economic aspects of the pandemic (see Chapter 2). With a longer-term perspective, several countries have also been taking strategic actions to promote inter-and trans-disciplinary research (OECD, 2020[7]). For instance, the French National Research Strategy for 2014-20 is organised along a set of societal challenges and is being implemented by a series of programmes overseen by ad-hoc multi-disciplinary committees. The National research agenda in the Netherlands, which is itself the product of a major public consultation exercise (OECD, 2017[28]), is being implemented through the dedicated Research along Routes by Consortia programme, promoting partnerships between knowledge institutes and social partners.

A number of universities have also taken significant steps to break down disciplinary silos and work more closely with citizens and other stakeholders. A much-cited example is Arizona State University (ASU), whose overall mission is "advancing research and discovery of public value; and assuming fundamental responsibility for the economic, social, cultural and overall health of the communities it serves". ASU is organised into 17 colleges, with more than 170 cross-disciplinary centres and institutes. On a more limited scale, the University of Tokyo's Institute of Gerontology brings together researchers and students from different faculties and graduate schools with employees seconded from private companies and local government to promote research on the problems of an ageing society (see OECD (2020[7]) for more details of these and other examples).

While these examples are promising, they need to be diffused and scaled-up considerably if science is to produce the knowledge and technologies required to address both the complex challenges of today and those that are just around the corner. The COVID-19 pandemic provides a timely warning of the importance in this regard. Young researchers need to be encouraged to work across disciplines and sectors, rather than deterred by uncertain career prospects.

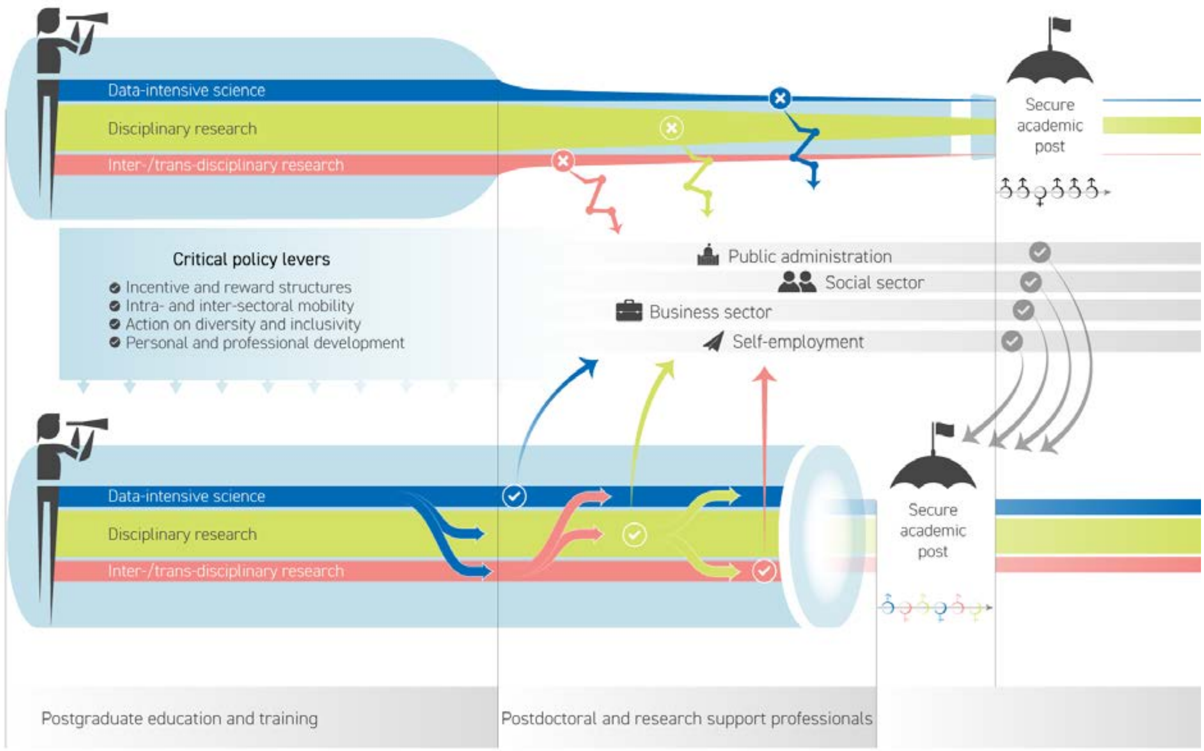
A new approach to scientific research training, evaluation and careers

Disciplinary research, merit-based competition and a focus on excellence have proven their worth and enabled technological development, innovation and economic growth in OECD countries over many decades. These traditional approaches still have an important role to play in the future. However, as the COVID-19 pandemic has starkly demonstrated, science has a critical role to play in providing solutions to complex societal challenges, including those that are embedded in the Sustainable Development Goals. At the same time, digitalisation and big data are transforming the way science is conducted, with open science and data intensive research becoming the norm across all domains. While digital technologies, such as AI and robotics, will certainly have an impact on how science meets its multiple demands in the future (see Chapter 6), the individual and collective human contribution will surely remain paramount.

The academic research system depends on the constant through flow of large numbers of PhD students and postdoctoral researchers on temporary contracts, who have limited prospects of securing permanent academic posts. The pressure to publish and the hyper-competitive environment are weighted against women and represent an obstacle to workforce diversity. Growing evidence shows that the pressure on early career researchers poses a threat to their mental health and wellbeing and can distort behaviours, to the extent of undermining the integrity of research (Wellcome, 2020[10]). COVID-19 is making the situation, for a highly skilled and highly vulnerable population of early career researchers, even worse by emphasising the systemic weaknesses that already existed.

Research is at a crossroads. A number of recent policy projects from OECD, examining precarity in research careers, digital capacity and skills, and inter- or trans-disciplinary research have concluded that major changes need to be effected to the way scientists are trained, recruited, supported, evaluated and rewarded (Figure 3.5). The COVID-19 pandemic has strongly reinforced this message. There need to be multiple flexible career options within academia and opportunities for mobility between academia and other sectors at different career stages. Positive actions need to be taken to help women and under-represented population groups enter and sustain scientific careers. Research evaluation and career progression need to move away from their dependency on bibliometric measures. Other research outputs, including data, software and a variety of policy and decision support tools, which are critical for responding to crisis situations, should be equally valued. Being a good team player and a skilled facilitator or communicator should be recognised at the same level as possessing "intellectual capacities". Science is indeed a meritocracy but there is an urgent need to redefine those merits and what constitutes excellence in all its different guises. In a system where the supply of PhD students at the point of entry far outweighs the final demand (in terms of secure academic positions), it is critical to remove the stigma of failure associated with leaving academia and support early career researchers in their different career choices. Doing so will help build more resilient research systems that are better able to deal with the aftermath of COVID-19 and other future shocks.

Figure 3.5. Towards a more diverse, healthy and effective research workforce: From bottleneck to pipeline



Note: The current bottleneck situation for academic research training and careers (top of graphic) favours disciplinary research and certain population groups, with those who leave to take up alternative careers having very limited opportunities for re-entry. In contrast, an idealised future pipeline (bottom of graphic) allows for more diverse career paths within academia and a rotating door to enable people to move in and out of other sectors during their career. The pipeline is also shorter for those who stay in academia to obtain a secure position and more attractive to women and social groups that are currently under-represented in academia. To move from the bottleneck situation to the pipeline, a number of critical policy levers need to be activated.

As illustrated by the examples provided in this chapter and in recent OECD publications on this topic, many institutions are taking actions to address the challenges for the present and future research workforce. Governments also have an important role to play in bringing together the various actors, who have a stake in the future of science to develop co-ordinated long-term strategies and actions. Many good practices and initiatives are under way in different countries, and much can be learned from international comparisons and dialogue. After all, science is a global enterprise, and a substantial share of academic researchers have worked in more than one country. The COVID-19 pandemic has brought to light both the strengths and the weaknesses of existing research systems. The post-COVID-19 period is likely to exert increasing pressure on young researchers, as research budgets get tighter, but it can also provide an opportunity to reconsider what is the real value in science, and what this means in terms of training and career paths for the future scientific workforce. COVID-19 can provide the stimulus to shift from an uncomfortable bottleneck in academic research careers to a more attractive, healthy and productive pipeline for researchers (Figure 3.5).

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Notes

[1] This information comes from country responses to the policy survey of the OECD GSF project on reducing the precarity of research careers. The project was launched in October 2019 and the final report is scheduled to be published in 2021. Its webpage can be found on the OECD STI Outlook website (http://www.oecd.org/sti/science-technology-innovation-outlook/research-precariat/).

[2] https://oecdsciencesurveys.github.io/2020flashsciencecovid/.

[3] See endnote (1) for the source.

[4] Approximately 12 000 responses from scientific authors were obtained. Although the survey response rate was only 7.55% the study's quality checks suggest that the results can be considered representative of the target population for the majority of countries and economies covered.

[5] See the OECD project on reducing the precarity of research careers. The project was launched in October 2019, and the final report is scheduled to be published early in 2021.

4 Government support for business research and innovation in a world in crisis

What factors and trends have led to today's patterns of government support for innovation in OECD economies? How has this helped shape current innovation systems? How is it relevant towards addressing the causes and effects of the current crisis? This chapter reviews how governments allocate public resources towards research and innovation, drawing in part on recent evidence from OECD projects. These interact with other major public policy discussions on the nature of government intervention and the breadth of innovation activities, as well as international debate around which subsidies are permissible today across highly interconnected economies. The chapter explores how the COVID-19 crisis may result in shifts in the volume, nature and direction of public support for innovation. It concludes with possible scenarios and their impact on the way governments will sustain future innovation activity in their societies.

Key findings

- **The R&D and innovation business response to COVID-19 has been very heterogeneous**. While for some the crisis represents an opportunity to expand such efforts, innovation capabilities in many industries are under significant stress. Yet the mobilisation of business innovation resources and capabilities is crucial for tackling the current crisis and addressing long-standing economic and societal challenges. Since close to 70% of R&D in the OECD area is nowadays carried out by firms, how governments incentivise and influence research and innovation in firms can have major implications for our future and is a badly needed element of injecting resilience into the economy and society.
- **Public innovation support policies need to be able to guide private innovation efforts to where they are most needed**, especially where market signals prove to be insufficient and coordination is most challenging. Recent OECD data and analysis shows that governments' policy mix is not entirely consistent with that ambition. R&D tax incentives are effective in achieving their generic R&D-raising objectives as long as they are consistently designed and implemented. However, they are insufficient as a means to guide innovation to broader societal needs, and represent suboptimal instruments to encourage investment in knowledge at the interface between basic research and actual product or process development.
- **Many of the assumptions underpinning the global policy consensus on the appropriate role of government in funding and promoting innovation are likely to be further challenged in the coming years**. Business innovation support today is possible within a delicate balance of international agreements that shape what national governments can do to help their businesses innovate without triggering retaliatory responses by other countries. Governments need to build a clear appreciation of the trade-offs they face in redesigning their innovation support portfolios, in parallel with their partners and competitors in other countries. National self-interest, also when it comes to business support for innovation, will be most often best served by international collaboration.
- **Governments can learn from each other to improve the design and administration of innovation support during crises**. Public support for innovation comes in many forms and is not always easy to measure, track over time or compare to facilitate mutual learning. Governments also need to continue to invest, alongside other capabilities, in evidence about their innovation support policies in order to improve them. This requires breaking down silos and developing capabilities to exploit this information. This is an ongoing priority of the OECD, both in terms of measurement and policy analysis.

Introduction

Public support has always played a key role in shaping the extent, nature and direction of innovation in modern market economies. This chapter examines the factors and trends that have led to today's patterns of government support for innovation, which itself has helped shape current innovation systems. It explores the major debates prompting a review of how governments allocate public resources towards research and innovation, interacting with other major public policy discussions on the nature of government intervention, the breadth and specificities of innovation activity, and the international governance dimension, particularly which subsidies are considered permissible across highly interconnected economies. The chapter explores how the COVID-19 crisis may result in shifts in the volume, nature and direction of public support for innovation. It concludes by outlining possible future scenarios and their impact on the way governments enact their support to innovation.

Support for business research and innovation today

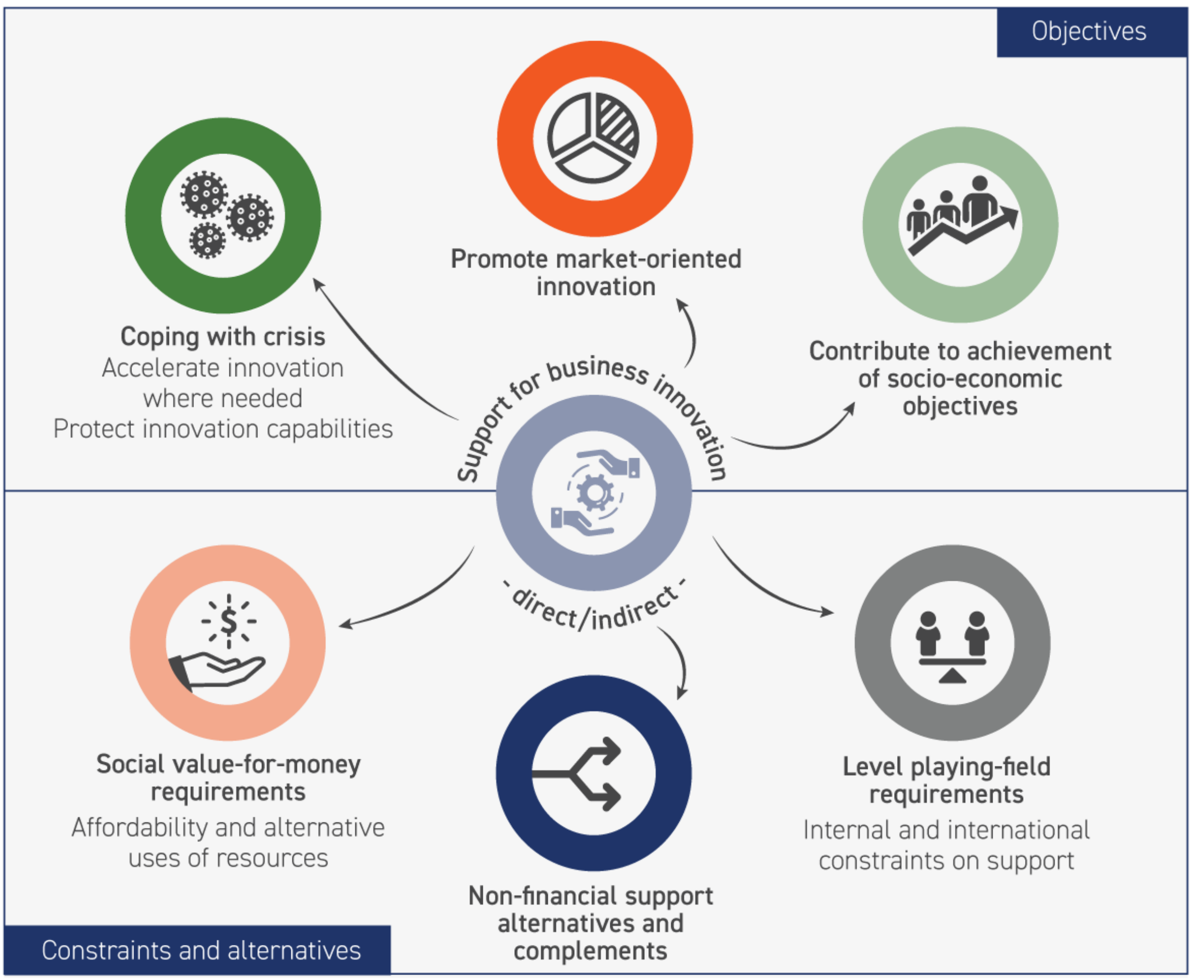
The importance of public support for innovation

In decentralised market economies, businesses are key actors in research and innovation systems, selecting, developing and implementing new ideas in pursuit of economic opportunities. This is also largely true of other economies in which the government has a high degree of business ownership and control. In addition to providing a benign socio-economic framework in which firms can fulfil their socio-economic role, government policies also actively promote investment behaviours that are deemed beneficial to society but firms may otherwise be reluctant to adopt. Investments in knowledge and its application are riddled with uncertainty and are hard to co-ordinate; further, their benefits may quickly dissipate as others stand to benefit (OECD, 2010[1]). Left to their own devices, markets may struggle to allocate resources towards such endeavours, even when they would be beneficial from a wide societal perspective.

There exist multiple ways for governments to provide financial support for innovation (OECD/Eurostat, 2018[2]). For instance, public support can focus on the inputs (e.g. firms' research and development [R&D] efforts) or outputs of the innovation activity (e.g. by reducing the taxes owed on the economic returns to R&D). The support may involve a subsidy, i.e. a net transfer of resources, more or less explicitly connected to specific innovation activities.[1] Several instruments can be used to help channel resources to firms in order to incentivise or reward innovation efforts. Governments can buy (or promise to buy) goods or services that either require or result from business innovations. They can provide finance in the form of grants or loans, or encourage others to provide such loans by providing guarantees when firms cannot repay. They can defer or forgo tax liabilities, or they can inject capital into firms in return for equity. Governments can pay third parties to provide services that firms require to innovate, or they can provide such services themselves through institutions they control, such as government labs. The transfer of technology sponsored or held by governments, or preferential access to data such as health or mobility records, are examples of in-kind support, as is the award of exclusive rights on inventions through intellectual property rights. Public investment and support for innovation is not necessarily limited to a country's territorial boundaries. For example, sovereign wealth funds and related investment vehicles buy shares in companies around the world in order to own a stake in their new technologies. Governments also provide implicit support for business innovation through the activities of state-owned enterprises, which are also part of the business sector.

Public support for innovation has played a major role in the design of industrial and economic development strategies worldwide, albeit with rather uneven approaches and results. While public support remains a hotly contested issue (Warwick and Nolan, 2014[3]) and growth-promoting industrial policies have been insufficient without complementary reforms, most successful economies have relied on them at some point in their history (Rodrik, 2010[4]). As indicated in the top part of Figure 4.1, the objectives of innovation support policy are multiple. Innovation policy makers care about identifying the most appropriate portfolio of support instruments that encourage and guide business R&D and innovation; generate solutions that transform or even create new markets; advance economic growth; and overcome long-standing societal challenges, such as health, energy and the environment, or address short-term crises. This multiplicity of objectives often calls for using a portfolio of support instruments rather than relying on a limited set of policy tools.

Figure 4.1. Confluence of objectives and constraints to government support for business innovation



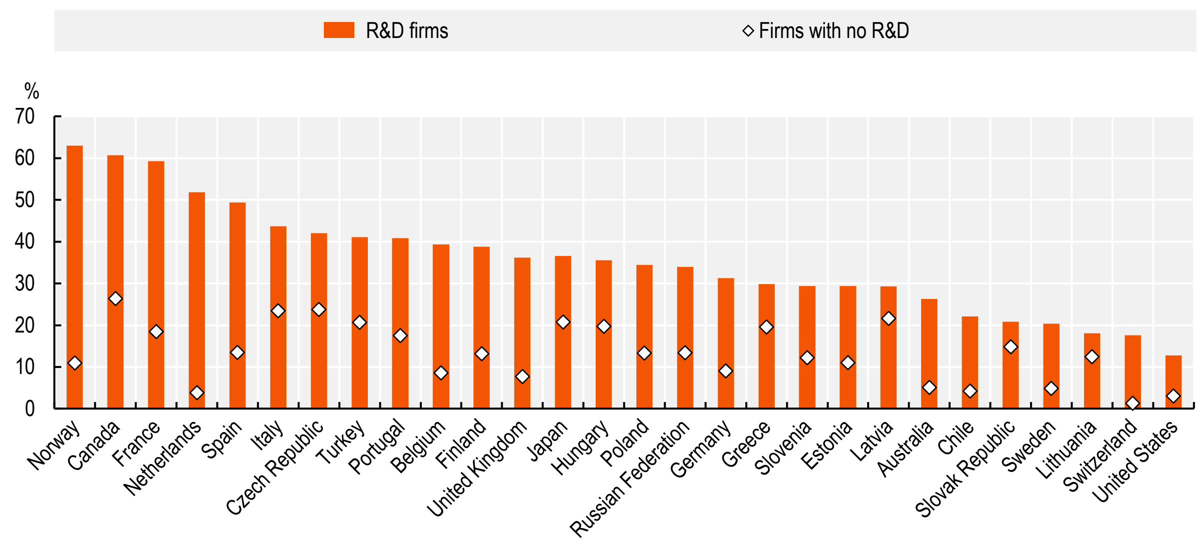
Innovation policy makers also need to take into account a number of constraints including the implications across a much wider group of policy areas, as this chapter will later discuss. In particular, finance ministries and society at large demand evidence that investments supporting business innovation yield as high a social return as investments in public infrastructure or other discretionary areas of spending. Controls need to be put in place to prevent business innovation support from becoming a form of “corporate welfare” through regulatory capture. Alternatives to support always need to be considered.

Government support for innovation before the COVID-19 crisis

Public policies promote innovation by supporting different types of firms and activities. Around the world, firms that perform R&D are far more likely to receive innovation support from the government (with a median 36% chance) than firms that only undertake non-R&D based innovation (13% median chance) (Figure 4.2). As a result, a majority of firms that receive innovation support are R&D active firms, even though they represent a minority of firms active in innovation.

Figure 4.2. R&D active firms are more likely to receive public support for innovation

Firms receiving public support as percentage of firms active in product/process innovation, 2014-16



Note: Data on public support for innovation apply to firms reporting a product or process innovation as well as firms with innovation activities related to product or process innovation. For Canada, data refer to product/process innovative firms. For Chile and Japan, data on public support apply to firms with innovation activities, whereas product/process innovation-active firms refer to firms reporting product or process innovations or with ongoing/abandoned innovation activities related to product, process, marketing or organisational innovation. For Spain, R&D status refers to 2016 only.
Source: OECD Innovation Indicators 2019 (database), http://oe.cd/inno-stats (accessed in October 2020)

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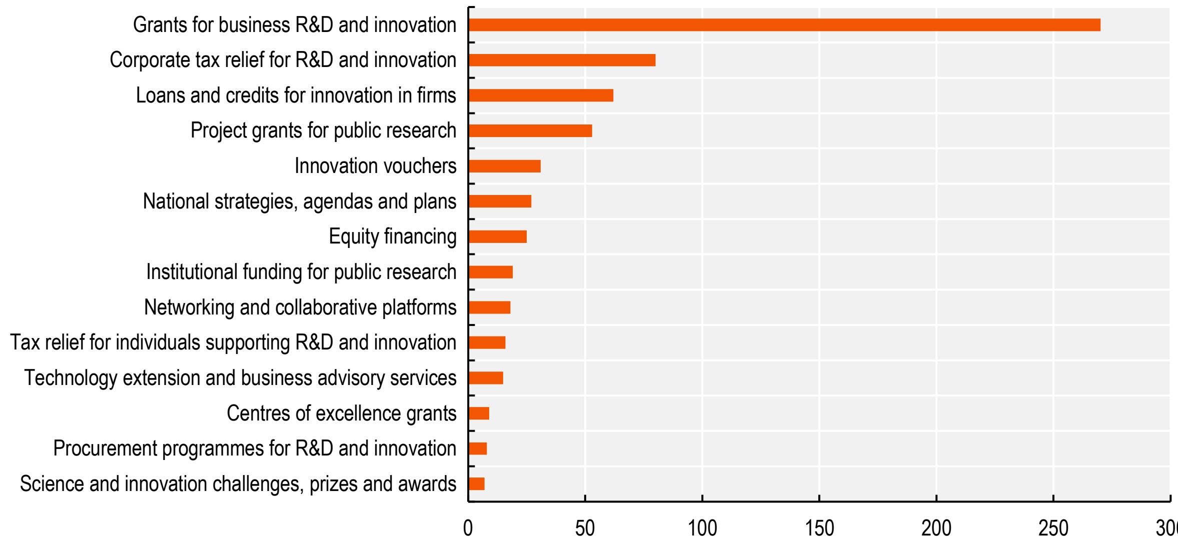
The OECD Science, Technology and Innovation Policy (STIP Compass) portal, a repository of innovation support schemes (EC-OECD, 2020[5]), shows that direct funding schemes are the most often reported instruments of financial support for R&D and innovation in terms of counts of initiatives (Figure 4.3). 40% of reported instruments in this area refer to grants for business R&D and innovation. An examination of the underlying information about these instruments shows they are highly fragmented and customised to specific target groups, compared to corporate tax incentive schemes (11% of reported support schemes). R&D tax incentive schemes tend to be unique for an entire country, echoing the tax on which those concessions apply, although these also exhibit considerable variations (Appelt, Galindo-Rueda and González Cabral, 2019[6]). Few countries report on the availability of procurement programmes for R&D and innovation, as well as the use of prizes and awards.

Figure 4.3. Policy instruments providing financial support for business R&D and innovation

Number of active policy initiatives reported by countries, top 14 instruments



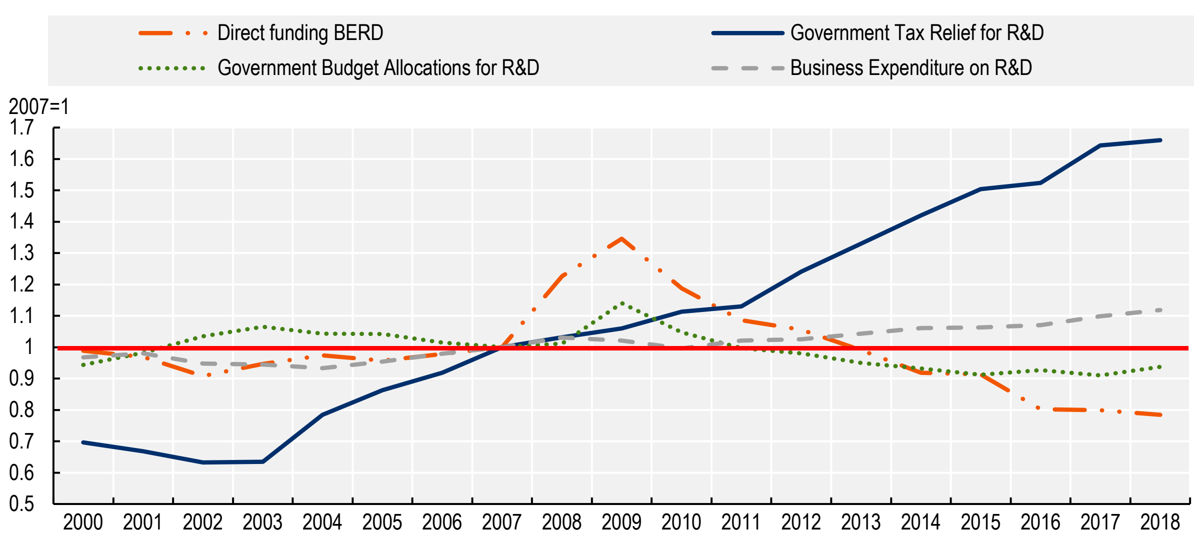
Source: (EC-OECD, 2020[5]), *OECD STIP Compass* (database), https://stip.oecd.org/stip/themes/TH31 (accessed October 2020).

StatLink https://doi.org/10.1787/888934223384

With the increasing proliferation and generosity of R&D tax incentives across OECD countries and partner economies over the last decades (Figure 4.4), the measured R&D support policy mix (Box 4.1) has shifted towards a greater reliance on tax compared to direct support instruments (Figure 4.5).

Figure 4.4. Shift in R&D support policy mix, 2000-18

Government funding of R&D in the OECD area, indexed values for key figures normalised by GDP, 2007=1



Note: 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. This chart displays figures for 37 OECD countries with the exception of GTARD figures, which exclude Israel where relevant data are not available. 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.
Source: OECD R&D Tax Incentives Database, http://oe.cd/rdtax, November 2020.

StatLink https://doi.org/10.1787/888934223403

Box 4.1. Addressing measurement gaps in government support for business innovation

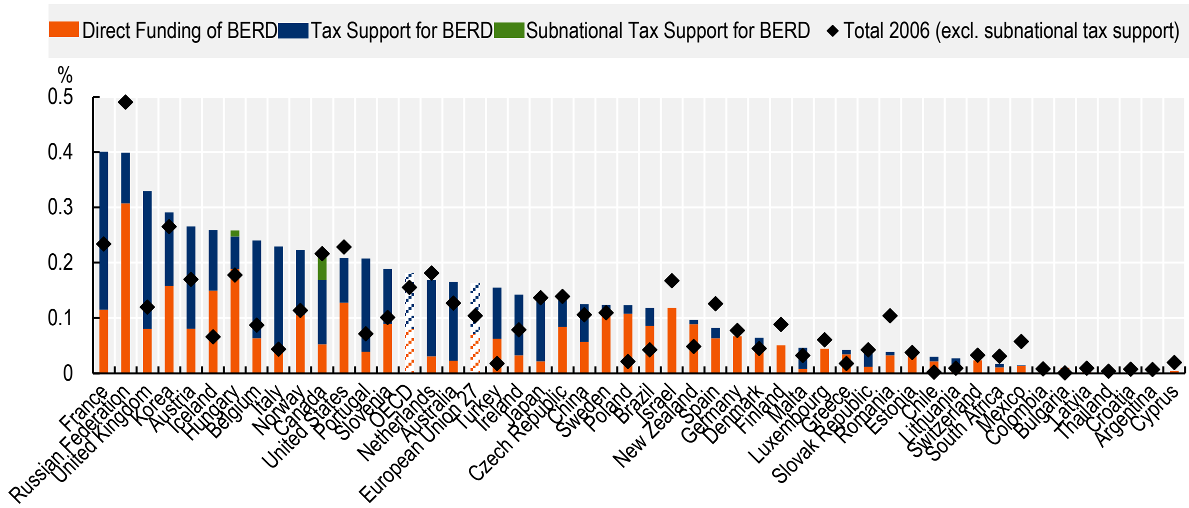
Despite sustained OECD efforts, comparative statistical information on the landscape of government support for business innovation across countries is rather incomplete. The available aggregate statistics on support for R&D focus on direct support for business R&D without distinguishing between different support types, and have only recently incorporated tax support measures. In that regard, they understate the role governments play in supporting R&D by providing explicit or implicit support to financial intermediaries or committing to purchase goods or services that implicitly requires firms to invest in R&D. The 2015 *Frascati Manual* (OECD, 2015[7]) introduced a taxonomy for tracking different forms of government support for R&D by separating grants from procurement of R&D services, pointing to the importance of capturing other indirect support mechanisms in an internationally comparable fashion. Further methodological guidance is now being prepared on means to quantify government measures of financial support, such as income-based tax incentives and innovation loans. Drawing on previous OECD efforts to document the magnitude of support for innovation, which were discontinued for lack of collaboration and evidence exchange (OECD, 1995[8]; OECD, 2001[9]), this new work takes into account:

- the need to capture the full spectrum of innovation activities, including not only R&D activities, but also diffusion activities, in line with the proposals in the 2018 Oslo Manual (OECD/Eurostat, 2018) for a more ambitious and comprehensive approach;
- the commercially sensitive and often confidential nature of the supported business activities;
- the political sensitivity of documenting support to industry, especially in light of international regulations such as international trade agreements or competition rules on state aid;
- the inherent difficulty of identifying the innovation scope of government support, given the overlap of innovation with other government strategic objectives, coupled with the general lack of a requirement to use innovation as a descriptor/classifier in administrative processes within many public authorities;
- the technical challenge of evaluating and interpreting the explicit or implicit financial flows between government and business, separating between exchanges and transfers (not all support for innovation is necessarily state aid), accounting for assets and liabilities, etc.;
- the diversity of intermediate organisations channelling government funds to business beneficiaries and their agents, which may not be businesses themselves;
- the lack of co-ordination and common standards for compiling administrative data on innovation support across and within agencies;
- the need to reconcile sponsor and beneficiary perspectives when collecting and interpreting data; and
- the policy analysis interest in inter-linking information on different support measures by recipient and with business characteristics and outcomes such as jobs, investment and productivity.

Across OECD countries, tax support represented around 56% of total government support of business R&D in 2018, compared to 36% in 2006 (Figure 4.5). The shift in the policy mix has been even more pronounced in the European Union (EU27), with tax support doubling over ten years, from 26% of total government support in 2006 to 57% % in 2018. The evolution has not been uniform across countries, as it has been dependent on several factors, including how countries have seen themselves compared to their peers. For instance, Canada decided to rebalance its federal support portfolio shortly after these international comparisons became first available and showed its high reliance on tax support.

Figure 4.5. Direct government funding and government tax support for business R&D, 2018

As a percentage of GDP



Note: 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. Estimates of total OECD direct funding of BERD cover 37 OECD countries, whereas estimates of total OECD R&D tax support (central government level) cover 36 OECD countries, excluding Israel, where R&D tax relief estimates are not available. Direct support figures refer only to intramural R&D expenditures, except for Brazil. Estimates of total OECD (EU) direct funding of BERD cover 37 OECD (27 EU) countries, whereas estimates of total OECD (EU) R&D tax support (central government level) cover 36 OECD (26) countries, excluding Israel (Croatia), where R&D tax relief estimates are not available. EU government-financed BERD in 2018 based on OECD estimate.
Source: OECD R&D Tax Incentives Database, http://oe.cd/rdtax, December 2020.

StatLink https://doi.org/10.1787/888934223422

Two notable factors have contributed to this shift. First, international trade and competition rules governing state aid have restricted support to specific firms or industries, while generic tax incentives are more likely to pass state aid tests. The progressive development of multilateral institutions to promote trade and investment flows has had a significant impact, shaping the current legal frameworks for government support to innovation (Box 4.2). Peace and economic growth required lifting barriers to trade and competition, but also sustained investment in new knowledge and its applications. Compromises were required. Policy consensus built around the idea of exempting both undirected support and support for pre-competitive innovation activities from bans on subsidies. Such bans are designed to promote competition and open markets. Where a subsidy is widely available within an economy, i.e. it is not restricted to a given enterprise or group of enterprises, international agreements tend to presume there exist no unintended distortions in the allocation of resources. Non-specific (or selective or discretionary) subsidies are therefore looked upon more leniently, but quantitative restrictions still apply on how far downstream governments can go in supporting innovation activities as the innovation activity gets closer to the market.

Second, within a majority of OECD member countries, proponents of non-specific R&D tax support have successfully argued that firms and not governments are best placed to decide which projects to invest in, thereby downsizing on bureaucracies in charge of identifying which business projects exhibit greater potential and need of support. Such laissez-faire attitudes have tempered beliefs in governments' capacities to select the best projects, deeming the business sector better apt to assess markets and technologies, predict demand, and choose which projects and companies are worthy of investment. Budgetary pressures have also led to lighter-touch funding mechanisms that appear to require less administrative overhead.

Therefore, industrial policy progressively became more "horizontally" oriented, focusing on business-friendly framework conditions and generic public support for innovation, without abandoning altogether the sectoral dimension (Hutschenreiter, Weber and Rammer, 2019[10]). These shifts have resulted in an overall re-organisation of innovation support portfolios, reducing the use of governments' discretionary powers in selecting the firms and projects to be supported.

Box 4.2. International rules shaping government support for business research and innovation

In today's globalised economies, national and supranational competition and trade authorities play a key role in setting and enforcing rules that ensure a level playing field among firms, industries and countries. The World Trade Organization (WTO) rules on subsidies have been traditionally permissive of public support towards private R&D costs. In the first years of the Agreement on Subsidies and Countervailing Measures signed in 1995, R&D subsidies were presumed not to distort trade and hence classified in the "green light" or "non-actionable" category (Maskus, 2015[11]). As this category lapsed in 2000, R&D subsidies became actionable, either by dispute settlement (which have been rare and focused on support for the aircraft industry) or unilateral countervailing duties, subject to demonstrating that the subsidies met specific criteria and had injurious effects on another WTO member. The system appears to have successfully encouraged governments to shift their public support towards non-specific instruments. This means support is not limited to an individual firm or group of enterprises, and the amounts of support provided is regulated by objective criteria for which eligibility is automatic.

The European Union's state aid rules are another case in point. These rules consider that state aid for R&D and innovation can be compatible with the internal market when it can be expected to alleviate a market failure or facilitate the development of certain economic activities, and where the ensuing distortion of competition and trade is not contrary to the common interest. The use of the selectivity criterion under this framework is akin to the WTO notion of specificity. A scheme is considered selective if the authorities administering the scheme enjoy a degree of discretionary power. By affecting the balance between certain firms and their competitors, selectivity differentiates state aid from so-called general measures that do not need to be notified. Even among measures considered to be state aid, as is often the case for R&D tax incentives, the proportionality requirement for approval is more likely to be met if the aid is awarded on the basis of transparent, objective and non-discriminatory criteria (European Commission, 2014[12]).

Restricted tendering by public authorities can also be considered an implicit form of targeted business support, even if it does not represent state aid. The WTO Revised Agreement on Government Procurement of 2012 (to which China, for example, is not yet a signatory) aims to open up government contracts to international competition, but a number of exemptions are allowed (WTO, n.d.a[13]). Individual signatories also indicate limits to the scope of application of the agreement, e.g. with respect to "set-aside" quotas for small and medium-sized enterprises (SMEs) in Canada and the United States. Most countries also exclude the provision of R&D services from the agreement's scope.

Other recent trends influencing current innovation support systems

In the past decades, the globalisation of economic activity, manifest as goods, services, capital, people, technology and knowledge have become easier to transfer across national borders, has led to a marked fragmentation of economic activity, with goods and services produced and heavily traded in international production networks known as global value chains (GVCs). Innovation support turned to be designed with a view on where countries wished to see themselves positioned in the resulting, complex global production and innovation networks (OECD, 2017[14]). Within this highly interlinked setup, business innovation activity supported by governments can have significant implications not only within the countries themselves, but also globally. To some extent, the emergence of China and other Asian economies shaping today's GVC system is a consequence of past decisions on public support. In China, public support (e.g. the Torch programme) was instrumental in the establishment of innovation clusters and the subsequent development of venture capital (VC) firms that are now investing internationally. The Made in China 2025 plan, released in 2015, became the country's blueprint for supporting its pursuit of technological autonomy while securing access to international markets in priority areas. Since then, said strategic considerations have become an increasingly regular feature of policy debate even before the onset of the COVID-19 crisis. As later discussed in the forward-looking section of this chapter, technological mistrust and trade tensions could become a mainstay of future economic relationships, both driven by and influencing decisions on public support for innovation.

Companies that push the boundary of knowledge to create workable solutions are ultimately destined to operate globally in order to reap the benefits of their innovations, unless they sell their rights to third parties. This makes multinational enterprises (MNEs) key actors in the globalisation of innovation, accounting for the bulk of R&D performance within OECD member countries. In Sweden, for example, only 10% of R&D is performed by companies without a presence in other countries; the remainder is more or less equally shared between Swedish affiliates of foreign-owned companies and Swedish majority-owned companies with subsidiaries abroad (Swedish Agency for Growth Policy Analysis, 2019[15]).

MNEs are therefore major direct recipients of government support. They can consider national incentives as one of several criteria for locating (and retaining) innovative activities in a particular territory. Innovation support systems may be designed to favour independent firms, particularly SMEs and start-ups, which face bigger barriers. While promoting new entry into R&D to new companies, concentration of R&D and R&D assets appears to have been rising recently. In the United States, firms with more than 1 000 employees have gone from accounting for 76% of all business R&D performance in 2008 to 82% in 2017.

The filings of large R&D corporations include as R&D expenses most of the costs of R&D acquired as part of takeovers of typically smaller R&D performers. The authorities responsible for merger control activities are therefore increasingly paying increased attention to their effects on overall innovation, as platform based incumbents can use their information resources to identify and acquire potential rivals early in their lifecycle before they become a competitive threat.

As MNEs operate across national jurisdictions, they have considerable flexibility in structuring their tax liabilities across the territories, moving intellectual property and associated profits. This accentuates pressures on governments to offer, within the existing rules, incentives for firms to locate their innovative activities and tax bases in the national territory. Domestic base erosion and profit shifting (BEPS) stemming from the exploitation of gaps and mismatches between different countries' tax systems affects all countries. BEPS requires additional international co-ordination to prevent, among other things, harmful practices such as incentivising business reallocation of intellectual property to more convenient jurisdictions without substantive activity requirements.

Improving the policy mix for support to business innovation

Understanding how support instruments work

The proliferation of R&D tax incentives raises important policy questions about the effectiveness of different policy tools in stimulating R&D, the heterogeneity of effects across different types of firms and the interaction of different policies. However, knowledge of "what works" in public support is somewhat limited by lack of critical data, the challenge of identifying valid counterfactuals, the multiplicity of policy objectives, and the complex chain of policies and contextual factors that determine the overall effectiveness of support policies in specific settings. The OECD microBeRD project investigates the structure, distribution and concentration of business R&D and R&D funding, modelling the incidence and impact of public support for business R&D while accounting for many such factors (Box 4.3).

The OECD recommends that governments carefully design their support for business innovation to consider the heterogeneity of potential beneficiaries (OECD, 2016[16]). This includes looking at the position of "standalone" firms without cross-border tax-planning opportunities, as well as young, innovative firms without the profit-generating capacity to benefit from allowances or credits when the instruments are tax concessions.

Box 4.3. Findings from the OECD microBeRD project on the impact of R&D tax incentives

The OECD microBeRD project investigates whether R&D tax incentives and direct funding are effective at stimulating additional R&D investment ("R&D input additionality") by business using a novel internationally distributed method of microdata-based impact analysis. Its analytical strategy combines the benefits of studies conducted at the macro level (e.g. on generalisability) and the micro level (e.g. on the ability to explore heterogeneous effects across firms). Results for 20 OECD countries show that the effects of such measures vary across different types of firms and R&D expenditures, shedding light on the mechanisms driving these effects (OECD, 2020[17]). Key policy findings from the microBeRD project include the following:

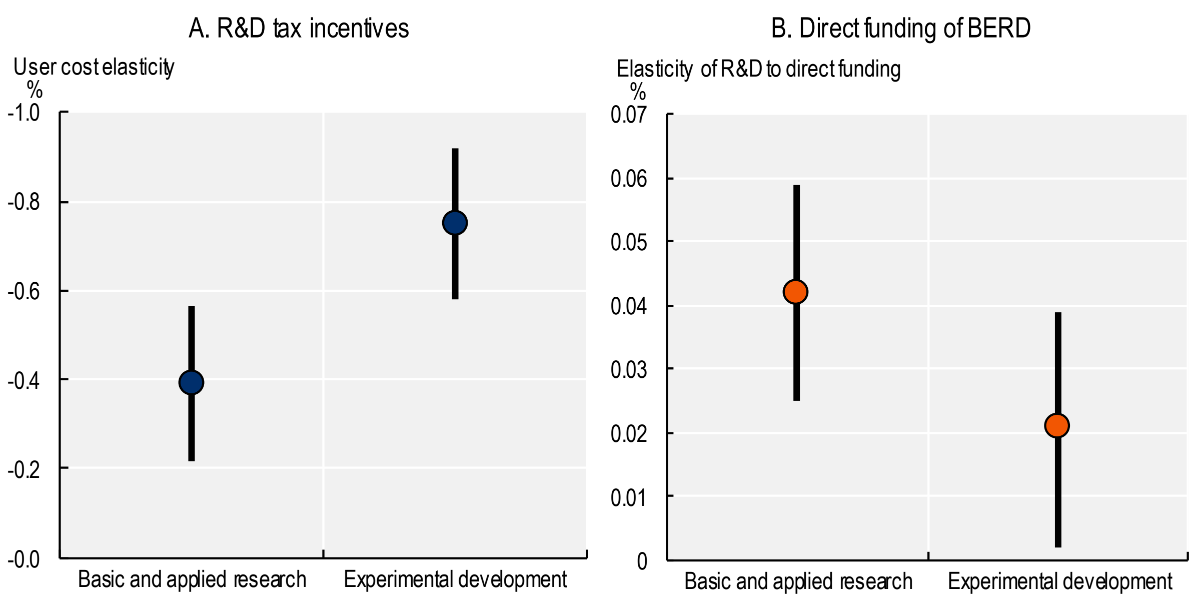
- Both R&D tax incentives and direct funding are successful in incentivising R&D investment by business. One monetary unit (euro) of either translates into around 1.4 units of business R&D.
- R&D tax incentives help increase R&D activity, principally through changes to R&D personnel and other inputs. They do not appear to affect R&D unit-labour costs, suggesting that the effects of tax incentives are not absorbed into higher wages.
- R&D tax incentives encourage additional business R&D, both because existing R&D performers increase their R&D expenditure (intensive margin) and because additional firms start to perform R&D (extensive margin).
- The input additionality of R&D tax incentives is larger for firms that perform less R&D. As smaller firms tend to perform less R&D than larger firms, SMEs show larger input additionality.
- The effect of R&D tax incentives on experimental development is about twice as large as the effect on basic and applied research, while the effect of direct funding on experimental development is half the size of the combined effect on basic and applied research. Tax incentives and direct funding, therefore, complement each other.
- Firm-level analysis within microBeRD-participating countries highlights substantial variation in the R&D input additionality of R&D tax incentives and direct funding across countries. This underscores the need for more in-depth analysis of the link between business innovation policy uptake, policy design and innovation activity and outcomes, including R&D inputs and outputs.
- Changes in R&D tax incentives targeting smaller firms or involving ceilings or thresholds tend to have stronger effects on business R&D investment, as small R&D performers appear more responsive than larger firms to the availability of R&D tax subsidies.

Source: OECD (2020[18]), "How effective are R&D tax incentives? New evidence from the OECD microBeRD project", *STI Policy Note*, OECD, Paris, http://www.oecd.org/sti/microberd-rd-tax-incentives-policy-note.pdf.

Setting aside differences in design and implementation that can blur the dividing line between tax support and grants, there appears to be a broad consensus that tax incentives are more suited in principle to encouraging R&D activities aiming to develop applications with the potential to be brought to the market within a reasonable timeframe. By contrast, direct grants are more suitable for supporting longer-term, high-risk research, as well as for targeting specific areas that either generate public goods (e.g. health and defence) or have particularly high potential for spillovers (Figure 4.6). The optimal mix of direct and indirect support will depend on both the specific circumstances and policy preferences.

Figure 4.6. Responsiveness of business R&D decisions by type of policy instrument

Elasticity of R&D to the user cost of R&D and direct



Note: This figure displays the percentage change in R&D in response to a one percentage reduction in the user cost of R&D through R&D tax incentives (user cost elasticity) and a one percentage increase in direct funding (elasticity to direct funding) respectively. Vertical lines mark the 90% confidence interval, which covers the "true" elasticity with a probability of 90%.
Source: (OECD, 2020[17]) "The effects of R&D tax incentives and their role in the innovation policy mix: Findings from the OECD microBeRD project, 2016-19", https://doi.org/10.1787/65234003-en.

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It has been advocated that public sponsorship of innovation should primarily target research by public-purpose organisations such as universities and research institutes, with residual support for business innovation assigned through non-discretionary incentives. Showing a growing division of innovation labour whereby public-purpose scientific institutions increasingly focus on research and corporations focus on developing products and processes, Arora, Belenzon, Patacconi, and Suh (2020[19]) argue that universities produce knowledge that is rarely in a form that can be readily digested and turned into new goods and services through the input of technology transfer offices. In their view, the research specialisation process might "have slowed […] the transformation of that knowledge into novel products and processes". The authors opine that a widespread return to active business engagement in research (both basic and applied) is not particularly likely, except for situations in which companies, "due to complements such as specialized equipment or proprietary data, have strong incentives to invest, especially if they can appropriate enough of the benefits by restricting spillovers to rivals". Targeted government support can only partly overcome the hollowing out of application-oriented research. Thus, policy makers have had to reconsider how to address this gap, by considering direct and indirect forms of support that match research and technology infrastructures with medium and long-term business needs, and by helping businesses boost their scientific capabilities to engage in such partnerships.

In this context, several countries have experimented with adapting to their local context programmes that are perceived to have successfully linked knowledge supply and demand in different countries. Examples include widespread policy interest in supporting proof-of-concept and commercialisation of technologies with public-sector applications through national adaptations of the Small Business Innovation Research (SBIR) programme in the United States. Howell (2017[20]) argues that the SBIR awards owe their impact (particularly in terms of attracting additional private VC funding) to their facilitation of technology prototyping and demonstration of a technology serving the US federal government and the potentially wider need. The pathway from pre-commercial procurement of R&D to actual procurement of effective solutions is quite different across countries for companies receiving SBIR-equivalent grants, depending on the possibility of governments favouring awarded SMEs during this transition to the commercial phase. Korea has implemented a recommended set-aside for contracting with SMEs for technology development purposes, in combination with a mandatory "new excellent product" purchase quota. Despite their huge potential, the implementation of demand-side innovation support policies is still hampered by a lack of policy clarity, instrument co-ordination and evidence to support the widespread use of targets (Appelt and Galindo-Rueda, 2016[21]).

Government intervention aimed at addressing failures in the market for finance for business innovation has also been the subject of increasing attention. Innovators often count intangibles as their main assets. These are difficult to deploy independently from their own ventures and personal engagement, resulting in a lack of collateral for investment and business growth in areas where the markets do not perceive a high likelihood of success. For instance, repayable government loans have played a key role in shaping technology development in the civil aerospace sector in recent decades, and VC interventions such as those implemented in Israel have attracted considerable interest worldwide. State-owned or guaranteed development banks play an important role in facilitating the flow of finance to innovative firms in many countries, including those where available statistics indicate they provide limited support. However, they expose governments to considerable liabilities, as loans may not be repaid, investments may fail, or guarantees may be called by private lenders. (Lach, Neeman and Schankerman, forthcoming[22]) describe how the design of innovation loans should correspond to project features and policy objectives, avoiding both projects with a high probability of success that will be funded by the private market regardless and those that do not justify public financing because their expected net impacts are negative. The authors also draw attention to the evidence that the role of VC firms is to provide not only finance, but also "advice" and a network of connections that enhance the probability of success of the supported start-up projects.

Implementation matters

The design of policy instruments also needs to keep up with practical considerations regarding their implementation. For example, policy design should simplify the business support landscape and reduce uncertainty, so that support requests and claims procedures give potential beneficiaries legal certainty when embarking on sponsored activities, while also protecting the public interest. This also involves operationalising RDI definitions regarding software development and other service-based activities of increasing importance for innovation. For example, the United Kingdom's tax authority released specific guidelines on the eligibility of software for R&D tax relief (HMRC, 2018[23]). The new guidelines recognise the continuous evolution of information technologies (e.g. artificial intelligence, cloud and mobile computing), as well as the ongoing development of new applications (e.g. software robots, augmented reality and internet of things). Interagency collaboration is essential to prevent double or even triple-dipping into public resources, but especially to ensure the highest possible coherence in policy delivery and fully exploit synergies in terms of expertise. Public support information systems are not always fit for purpose and are not particularly suited to conducting reliable assessments of the potential impacts of domestic reforms, as is common in other policy areas.

Regardless of the type of instrument considered, implementing business support is a complex undertaking, which requires building internal capabilities within public agencies and enhancing innovation planning among beneficiaries. This can be underpinned by a professional network of specialised intermediaries acting in the best interest of companies, while complying with the letter and spirit of the rules on public innovation support. This is particularly important for non-discretionary schemes in order to prevent an unmanageable number of potentially bogus claims that may ultimately undermine trust in the system.

Overall, governments wishing to introduce new measures in support of innovation have had to contend with multiple regulatory and budgetary restrictions that limit their margin of operation. This is evidenced by innovation support measures where the government acts as a financial investor intent on leveraging additional financial resources into long-term investments. Compliance with international subsidy control rules, and pressures to ensure that financial assets and liabilities (including those of a contingent nature) are absent from the government or the broader public sector's balance sheet (e.g. to avoid exceeding public-debt limits) shape the room for manoeuvre. In the United Kingdom, the Industry Panel Response to the UK Treasury's review of patient capital recommended that the UK government not have control over the board of the proposed new investment vehicle, or any direct or indirect influence on decisions regarding its individual investments, stating reasons of compliance rather than other arguments (HM Treasury, 2017[24]). The potential downside of forgoing control and influence stems from difficulties in ensuring value for money and maintaining directionality.

A shift towards greater directionality of business support for innovation

In contrast to the trend towards reduced directionality in innovation support, some argue that governments have erred too much in renouncing some of their discretionary powers, failing to recognise the implications of their choices in terms of guiding the markets. Such views have become more prominent in recent years. This is apparent in the Aho Group Report (Aho et al., 2006[25]), which calls for EU governments to adopt an innovation lead-user perspective, and in the growing popularity of the concept of smart specialisation (OECD, 2013[26]). This trend was further fuelled by the global financial crisis (GFC) and its aftermath. The GFC exposed a number of ways in which markets incentivise innovation towards outcomes that do not necessarily match public interests, e.g. through financial innovations that socialise risks and privatise gain, or through suspect methods to overcome regulatory controls on vehicle emissions. Greater awareness of corporate tax strategies, and concerns about growing concentration, have helped cast doubts on policies offering unconditional support to business innovation. Furthermore, a number of studies pointing to concrete examples where government interventions have played an important role in supporting the growth of new businesses and the emergence of new industries have also challenged narratives about industrial policies necessarily resulting in failures (Mazzucato, 2013[27]). In the public discourse, the attribution of merit underpinning innovation has become a hotly contested issue, highlighting the complexity of the innovation enterprise and how value is captured from the generation of ideas to their commercialisation.

The growing realisation and sense of urgency around key societal challenges has resulted in calls for outcome or mission-oriented approaches, raising questions about the adequacy of current support instruments and portfolios (Mazzucato, 2018[28]). Among the growing trends in the run-up to the current COVID-19 crisis, OECD member countries have continued to witness a progressive rehabilitation of industrial policy from the perspective of innovation, with arguments that governments should actively engage in making explicit innovation policy choices on where to focus their limited resources (e.g. (HM Government, 2009[29]; HM Government, 2017[30]), for the United Kingdom; (Ministry of Economic Affairs, 2011[31]), for the Netherlands).

Support for business innovation in times of crisis: The COVID-19 shock

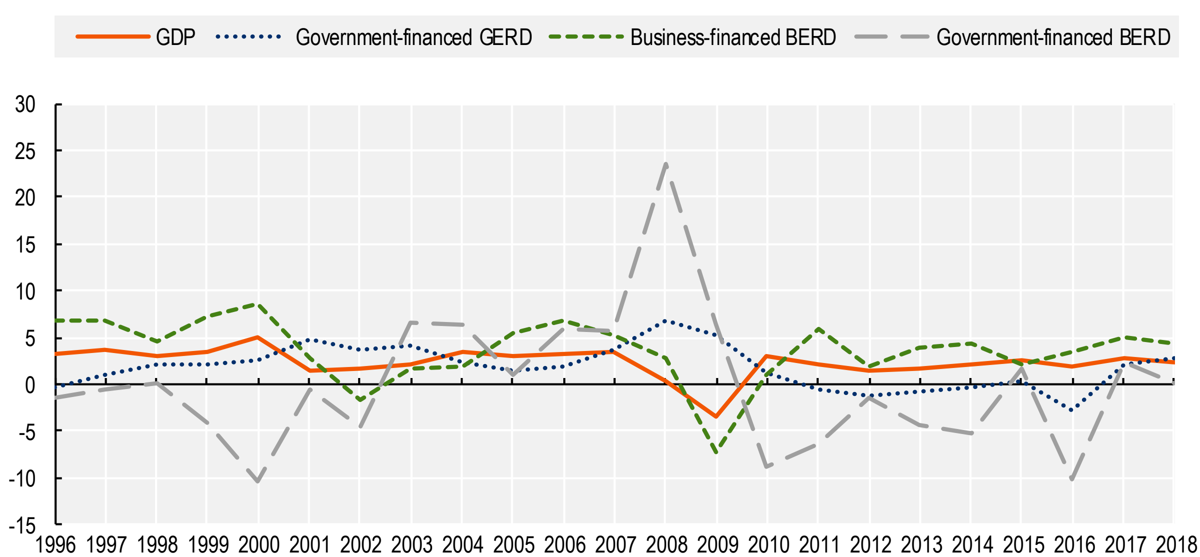
The disruption to normal financing conditions and economic activity is a major existential challenge for businesses, for which preserving innovation capabilities may shift from representing an unaffordable luxury to an imperative for survival. The COVID-19 crisis is not only a key threat to innovation systems' ability to fulfil their normal functions, but also a call for mobilising these systems to provide new solutions to the immediate health, societal and economic challenges posed by the pandemic. Against this backdrop, investments in R&D and broader innovation are essential. The COVID-19 emergency, and the measures adopted across the world to overcome its pernicious health impacts, pose major challenges for innovation systems, questioning major assumptions – about the definition of collective priorities; the bearing of risks and rewards; and the role of the market, civil society and governments – while also irreversibly endangering the survival of key productive and innovation capabilities, especially within sectors hit the hardest. The innovative potential of businesses and the broader private sector has been called upon to deliver a wide range of solutions to help cope with the health emergency and emerge from it as robustly as possible. In this context, innovation support policies can make a major difference.

Lessons from previous crises

COVID-19, like the 2008 GFC and previous economic crises, is having major negative repercussions on business RDI through multiple yet interconnected channels. The evidence shows that uncertainty is a principal driver of business decisions during crises (OECD, 2009[32]). Historically, business R&D expenditure and patent filings have moved in parallel with measures of economic activity such as GDP, slowing markedly during the economic downturns of the early 1990s and early 2000s. On an aggregate basis, investments in RDI are pro-cyclical, and thus prone to contraction in times of crisis (OECD, 2009[32]). While R&D projects already under way are expensive to interrupt, the GFC experience indicates that the business sector was the first to cut its R&D investments as conditions deteriorated (Figure 4.7).

Figure 4.7. The impact of the business cycle on business R&D and government support

OECD area, annual growth rate



Note: The estimate of government-financed business enterprise expenditure on R&D (BERD) for 2008 reflects to some extent a break in the series for federally funded support to business in the United States. This also applies to a less visible extent to the estimate of government-financed gross domestic expenditure on R&D (GERD).
Source: OECD *Main Science and Technology Indicators* (database), http://oe.cd/msti (accessed October 2020).

StatLink https://doi.org/10.1787/888934223460

Cuts to plans to subcontract R&D and other knowledge services tend to be faster to implement than adjustments to the R&D workforce, which tend to be avoided for as long as possible. Business are aware that policy makers are very sensitive to R&D workforce-adjustment decisions, bidding for support for projects that enable them to retain such a hard-to-replace workforce. During crises, as risk portfolios are revised, some R&D and technology-based operations can sometimes be sold to collaborators in the supply chain, triggering concern about potential losses of strategic capabilities, or left to spin off. In past crises, sales functions tended to be privileged over knowledge-creation activities, to boost liquidity and near-term solvency. By depressing demand, financial crises appear to be associated with overall declines in rates of product innovation as new product launches become less likely to succeed and product innovation may be more oriented towards frugal consumer behaviours. Such crises may encourage resource-saving process innovations, but only to the extent that business appreciate a tangible short-term return on the investment and are in a position to raise the necessary finance.

The policy response *during* the GFC recognised the need to mitigate the crisis's impact on productive and innovative capacities as many countries introduced stimulus and recovery packages with substantial measures to support innovation (OECD, 2009[32]; OECD, 2012[33]; Izsak et al., 2013[34]). Most countries did not substantially alter the structure of their innovation policies as an immediate response to the GFC (Pellens et al., 2018[35]). Instead, they opted to enhance existing support measures and introduce additional short-term measures to address liquidity constraints (e.g. loans, loan guarantees) and maintain business innovation activity (e.g. innovation vouchers, structural funds). Additional financial support for businesses – i.e. a sharp temporary increase in direct funding (e.g. R&D grants), coupled with a higher use of R&D tax incentives – helped attenuate the decline in business R&D investment during the GFC.

Although countries greatly differed in their reaction to the GFC and its aftermath, the crisis accentuated national innovation systems' pre-existing weaknesses. Not all economies were equally able to support business innovation. In the European Union, for example, special rules allowed countries to use the Temporary Framework for state aid. As business R&D and innovation investments recovered and resumed growth (Figure 4.7), government R&D budgets, which had proved resilient until 2010, came under increased budgetary pressure, owing to the phasing out of emergency measures and political requirements for fiscal consolidation. While this shift greatly restricted the scope for innovation policy directionality, abundant examples point to the crisis driving renewed interest in tools allowing greater innovation targeting and prioritisation. For instance, the GFC prompted a re-examination of policy attitudes towards innovation financing institutions such as national development banks, e.g. the KfW banking group in Germany, with the capacity to direct resources to businesses with innovation financing needs. KfW is one of the members of the D20 Long-Term Investors Club, which was created in 2009 and has since expanded to include, among others, the China Development Bank, the Russian state development corporation VEB.RF and the Brazilian Development Bank.[2] Based on the experiences gathered through OECD studies (OECD, 2012[33]), Box 4.4 outlines a number of lessons learned from previous economic crises as a basis for further reflection.

Box 4.4. Lessons from past crises for business innovation support

- use public support as a tool to manage and combat uncertainty as a priority
- adopt measures that help stabilise the economy and initiate recovery, ensuring it is durable and oriented towards sustainable growth, as crises expose structural weaknesses
- identify key R&D and broader innovation capabilities most exposed to the impact of the crisis and with the highest long term potential
- enhance and draw on available evidence to make the case for innovation to finance and economic ministries

- understand the scope for temporary asset-purchasing programmes conducted by monetary authorities and consider under what conditions non-financial sector assets might be eligible
- explore mechanisms to facilitate the use of knowledge-based assets as collateral for raising private finance and securing public support
- prioritise addressing rigidities and bottlenecks in implementing support
- assess the relative merits of different instruments with respect to objectives and trade-offs; consider implications for the policy support mix and balance
- have efficient appraisal systems in place, drawing on all relevant expertise within government and its delivery agencies, while engaging intermediaries that contribute to implementation
- evaluate adaptability to the local context of measures introduced elsewhere
- embed reasonable information and evaluation requirements to facilitate policy learning
- limit measures that only benefit incumbents and monitor implications of potential concentration
- engage proactively with other countries and multilateral organisations to address cross-boundary implications within the available governance frameworks, which may evolve and adapt to circumstances.

This time is different

As all crises differ, it is hard to extrapolate from past episodes, both in terms of the potential impacts of the current crisis and the lessons to be drawn regarding the appropriate policy response. In contrast to the previous financial crisis, the current phase of the COVID-19 crisis is forcing businesses to enter unchartered waters. Businesses today are constrained by a unique and probably unprecedented combination of marked supply and demand constraints, coupled with very substantive uncertainty about whether and how the crisis will be resolved. This uncertainty also makes it more complicated to identify the appropriate policy response. Chapter 1 lays out some key features of the current crisis, as well as its implications for business innovation and the general policy response. Mandated and voluntary lockdowns, combined with physical distancing measures, contribute to reduced levels of production and consumption activities – especially those requiring personal proximity and mobility. Restrictions have complex impacts across supply and demand chains.

OECD analysis of the published financial reports of large publicly listed R&D investors covering the second and third quarters of 2020 shows significant differences across and within sectors in terms of how these companies are adapting their R&D investment portfolios (see Chapter 1). Among non-traded companies, evidence is scarcer, but points (e.g. in Canada) to a threefold increase in the number of companies reporting a decline in R&D (e.g. 22% more companies reporting lower rates of manufacturing R&D vs. 6% reporting higher rates) (Statistics Canada, 2020[36]). Large businesses' quarterly reports highlight uncertainty as a major factor driving business responses and the immediate outlook. The sentiment clearly differs by sector, from potential concerns about advertising revenue, through uncertainty about the success of ongoing trials in pharmaceutical companies, to uncertainty about the future of transportation and personal services, especially if business travel and tourism continue to contract significantly even after the pandemics has been contained. Company reports highlight concerns over liquidity management, adaptation to supply chain disruption, and protecting workers and customers. In the United Kingdom, a sample of Innovate UK support beneficiaries reported that two-third of firms suggested future R&D plans remained unchanged, with the remainder slowing or cutting back on their projects (Roper and Vorley, 2020[37]).

While the underlying pandemic persists, business practices need to be constantly revised as new information becomes available and new policies are adopted. Adaptive innovation seems rather prevalent, spurred by necessity. According to Statistics Canada, over two-fifths (45.4%) of Canadian businesses reported they had added new ways to interact with or sell to customers; nearly two-fifths (38.1%) reported they had increased their internal use of virtual connections; and 2.8% of businesses indicated they had begun manufacturing new products in response to government requests to help cope with the crisis.

A distinctive feature of the COVID-19 crisis, compared to previous ones, is the realisation that innovation has a clear and explicit role to play in its containment resolution, over and above its role in the ensuing economic recovery. This is particularly obvious in the development and deployment of diagnostics, vaccines and treatments for COVID-19, but is not exclusive to the sectors that are directly preoccupied with such issues: designing new products and processes that enable greater resilience to the current and related future disruptions is important to society as a whole. A significant portion of the required innovation potential rests within the business sector. In the United States, for example, (Azoulay and Fishman, 2020[38]) point out that clinical trials have increasingly been conducted in private practices and dedicated, for-profit study sites since the 1990s. The continuity and upgrade of network services also rests on the capacity of (private or state-owned) business to adapt to the situation and provide new responses.

Business innovation support as part of the government response

As highlighted by (Gans, 2020[39]), efforts to incentivise private, market-based innovations addressing an urgent global challenge such as the pandemic face a fundamental paradox. Profit-driven innovators will ultimately wish to price their solutions at rates that will make access prohibitive to many people, which is a socially unacceptable outcome. The anticipation of "expropriation", in turn, deters private investment, an innovation incentive paradox that highlights the limitations of the market mechanism and the need to identify appropriate instruments to serve the public interest.

Most governments have steered clear of utilising market-replacing interventions within their statutory powers, such as those allowed by the Defense Production Act in the United States, which allows issuing loans to expand a vendor's capacity, controlling the distribution of a company's products and compelling companies to prioritise government orders over those of other clients. Instead, governments have mostly opted for moral persuasion and appeals to corporate responsibility, along with significant financial support, as allowed by emergency funding bills. Table 4.1 lists selected examples of recently adopted business innovation measures, split between R&D tax incentives and other initiatives. It shows that some measures focus on promoting innovation in the fight against the disease, while others seek to support the overall business innovation ecosystem at a time of distress.

Table 4.1. Selected examples of emergency government measures supporting business innovation

R&D tax incentives	
Instrument re-design	
Increase of R&D tax credit/allowance rates	• Australia (SME rates and rates for R&D-intensive large firms (R&D intensity >2%) for income years starting on or after July 1, 2021), Denmark (subject to ceiling), Iceland, Italy (Southern regions), Spain (technological innovation)
Adjustments in ceilings on qualifying R&D expenditure or R&D tax benefits	• Australia (increase in R&D expenditure ceiling for income years starting on or after July 1, 2021), Germany (increase), Iceland (increase), New Zealand (partial removal and simplification)
Administration and monitoring	
Extension of time limit for filing applications	• Australia, Canada (Quebec and British Columbia SR&ED tax credits), • Mexico, Portugal
Accelerated or earlier processing of R&D tax relief claims	• Canada (refundable claims under federal SR&ED tax credit), Poland
Advanced and/or expedited cash payments (refunds)	• Denmark, France, Ireland
Other business RDI support measures	
Improved access to funding for innovative companies	• China (R&D subsidies for SMEs), France (Investments for the Future Programme innovation grants), Germany (VC financing for start-ups), United Kingdom (investment fund for high-

	growth companies, grants and loans for SMEs focusing on R&D), Hungary (subsidies of wage costs for R&D staff), New Zealand (Callaghan Innovation's R&D Loan Scheme), Spain (partially reimbursable grants for SMEs), United Kingdom (continuity loans, grants and loans for SMEs focusing on R&D)
Postponement of application deadlines, increased flexibility for existing beneficiaries and/or assistance for new applicants	• EU28 (Horizon 2020), Austria, Germany, Norway, Spain
Funding for innovation on COVID-19 solutions	• Austria (KLIPHA-COVID19), Belgium (regional grants), Canada (Challenge programme),Czech Republic (grants), EU28 (European Innovation Council accelerator and Innovative Medicines Initiative, ERAvsCorona Action Plan), Germany (Bundesregelung Forschungs-, Entwicklungs- und Investitionsbeihilfen), Ireland (rapid response funding, direct grants and repayable advances), Italy (Innova), Korea (R&D project to foster medical device industry), Luxembourg, Malta (grants), Poland, Portugal (grants), Slovak Republic, Spain (soft loans for innovative companies with COVID-19 projects), United Kingdom (sustainable innovation fund), United States (NIH/FNIH public-private partnership for COVID-19 vaccine and treatments)

Note: This table does not attempt to provide a comprehensive representation of all measures supporting business innovation introduced by governments in response to COVID-19; such a list would be too large to present here and would require constant updating.
Source: OECD elaboration, based on the OECD STIP COVID-watch (https://stip.oecd.org/covid), OECD survey of R&D tax incentives, and other sources (OECD, 2020[40]).

Public procurement of innovations, or more generally of solutions that may require an innovation on the part of firms or other actors, is a salient form of policy response to address the innovation paradox posed by this crisis and other similar grand challenges. The transformation potential of government procurement action in response to COVID-19 is probably an order of magnitude above other forms of innovation support. In the United States, COVID-19-related federal procurement amounted to close to USD 28 billion from March to September 2020.[3] This amount is by no means entirely dedicated to new products or new applications of existing products. The information collected by the OECD ; (OECD, 2020[41]) suggests that governments are placing innovation agencies in key procurement support roles during this crisis. Authorities have tended to commit to products that are closer to the market, where the risks are mostly located downstream of the innovation chain. In many cases, however, public procurement as a form of innovation policy can contribute to societal missions through the careful design of advance market commitments and the building of public-private partnerships (Edquist and Zabala-Iturriagagoitia, 2012[42]).

In addition to the measures outlined above, countries have increasingly updated the legislative and regulatory frameworks covering support for business innovation. In April 2020, the European Commission announced the adoption of an amendment to the Temporary Framework initially adopted in March. Among other actions, the amendment extended the framework to include support for coronavirus-related R&D (European Commission, 2020[43]). The framework has since been further amended to better accommodate the position of otherwise viable start-ups which incurred losses before the COVID-19 crisis and hence would not have been considered eligible for support.[4] The United Kingdom is currently reviewing its approach to state aid, an issue that is intertwined with trade-agreement negotiations following Brexit. Bilateral trade deals, such as the agreement UK-Japan Comprehensive Economic Partnership Agreement of September 2020, contain commitments to transparency regarding the subsidies awarded and consultations over concerns about subsidies that may affect the other party, highlighting the interconnectedness between industry support and access to markets in a globalised world.

The medium to long-term outlook for business innovation support

Possible scenarios and implications

As highlighted in Chapter 1, a range of generic factors will shape the outlook for science, technology and innovation policies. These have marked implications for the future design, implementation and impact of public policies supporting business innovation.

At the time of writing, the COVID-19 pandemic is a principal driver of public policy. As long as the crisis persists, governments will be compelled to sustain and drive business participation in identifying and implementing solutions to the health crisis. Governments have been providing multiple forms of support for firms' innovative activity, recognising the need to engage the business sector in fighting the pandemic as part of the ongoing broader public health intervention.

Over the medium to longer run, evidence and perceptions of future pandemic vulnerabilities or infectious disease issues will determine whether authorities maintain and possibly expand the innovation support mechanisms developed during the current crisis to mitigate future successive pandemic shocks. A "recovery" scenario in which viral and other infectious disease outbreaks are recurrent and difficult to contain will heighten demand for a greater focus of public support on health-related R&D and innovation. This will likely diminish interest in horizontal forms of public support and will have uncertain implications on support towards other domains that may not appear to be as directly relevant to building pandemic preparedness. Under an alternative scenario in which recurrence or alternative outbreaks are perceived as less likely, there will be reduced willingness to sustain incentive mechanisms towards business driven health R&D and innovation. Resources dedicated to innovation in pandemic prevention will eventually be re-allocated to other uses, but policy makers will need to beware of the risk that core capabilities in this area might be irreversibly lost, eventually exposing societies to future risks. Indeed, the current crisis has brought into question the way innovation priorities are determined.

Paraphrasing John Maynard Keynes (Keynes, 1919[44]), future scenarios for policy will be shaped by the social and economic consequences of the COVID-19 peace and the terms on which it is ultimately achieved. A key dimension in the scenarios for socio-economic damage and the shape of a future recovery is the extent to which structural change becomes a consequence of a "new normal", where the pre-COVID baseline was a protracted period of lacklustre productivity growth compared to recent history (Andrews, Criscuolo and Gal, 2016[45]; OECD, 2019[46]). The range of possible scenarios is too broad to detail here; it relates to how people can and prefer to work, interact with each other and enjoy their leisure. Plausible scenarios have entire industries and locations transforming their models to remain viable settings of economic activity. In such cases, transformation and disruption will become regular features; governments will be called upon to support and manage such processes, beyond designing strictly people-based policies.

As happened during previous crises, tensions will likely arise between the idea of government sustaining industries and firms or re-allocating resources towards new opportunities. The cloud of uncertainty will often not allow predicting which changes will be temporary and which will be permanent. As a result, identifying the optimal response will be challenging, and the results often controversial. A key consideration for national innovation policy makers will be to identify and prioritise business innovation capabilities that should be preserved for the long run. Considerable uncertainty is likely to hold back investment for an extended period, particularly by companies with high debt (OECD, 2020c).

The room for manoeuvre for policies supporting business will be shaped by the future state of government finances and the macroeconomic policy response. The experience of the GFC highlights the plausibility of a scenario in which governments seek to reduce the currently heightened public-debt levels at a fast clip, initiating a period of rapid budgetary adjustment. Aside from the important direct impacts the timing of such a process may have on the economy, the budgetary envelope for government financial support for R&D

and innovation as a discretionary area of spend stands to fall if it is not deemed a national priority. This may trigger a search for complementary funding mechanisms, including a greater role for private, non-corporate R&D funding. Differences in budgetary responses across countries may also shift the global landscape and accentuate national differences in businesses' innovation capabilities. Firms will tend to move innovation activities to locations where the business environment, including the availability of public support, appears to be more favourable. In this context, the focus and actual implementation of short and medium-term *recovery packages* will be critical. They will straddle competing priorities, from resolving short-term business liquidity and solvency concerns, to addressing the challenges and opportunities presented by the pace and direction of digitalisation and automation, as well as the pursuit of the ecological transition. The *OECD Economic Outlook* (OECD, 2020[47]) also notes that government support for companies through wage subsidies, tax deferrals and guarantees will need to be phased out gradually in phase with the recovery, to ensure that unviable firms are not supported for an extended period.

The global crisis accentuates pressures on the international governance mechanisms that have defined the terms allowing governments to support the business sector. Such systems have demonstrated some flexibility in times of crisis as emergency frameworks have been put in place, but the yet unknown severity and duration of the current crisis casts some doubts about their future. The opportunities associated with the "next production revolution" (which is occurring through the confluence of a range of technologies, including artificial intelligence, 5G, new materials, 3D printing, nanotechnology and industrial biotechnology) have set the scene for support and regulation of business innovation to become one additional driver of the push towards greater productive technological autonomy. President Xi Jinping of the People's Republic of China, for example, points to the need to drive original innovation capabilities and achieve more "zero-to-one" breakthroughs (Xi, 2020[48]). The agreement between Germany and France in 2019 to support funding for the R&D and innovation activities of two companies in the area of next-generation lithium-ion batteries, as well as their initial industrial deployment, could be a sign of further initiatives to come. The rather fuzzy idea of technological sovereignty as a policy objective to be served by government innovation support has been exacerbated by the crisis effect on perceived dependence from supply chains controlled by a few countries. The underlying struggle for geopolitical technological hegemony, evident well before the crisis, may result in further trade tensions.

In this context, multilateral frameworks could eventually be reinforced as a result of a greater appreciation of risks and challenges that transcend national boundaries, requiring co-ordinated responses to bring new products and processes to markets. This would be especially true if transnational actors in the public and private sectors succeeded in fighting the pandemic. In such a scenario, international rules governing state aid and public procurement of innovation may ultimately result in arrangements that are more accommodating towards discretionary actions targeting priority challenges. On the other hand, the current crisis and pressures to decouple value chains may undermine trust in global governance solutions, exacerbating the existing pre-crisis discontent. This may ultimately entail a shift towards national approaches as countries – especially larger economies – seek to become more self-reliant and favour their domestic companies, instead of pursuing more distributed mechanisms to build resilience to shocks.

For instance, the COVID-19 pandemic has spurred many governments to enhance their foreign investment screening mechanisms or introduce new ones, in the midst of an already steep drop in global foreign direct investment (FDI) flows. This may bring about transformational change to policy practice on investment screening, and the way governments and societies view the benefits and risks associated with foreign investment (Novik, Pohl and Rosselot, 2020[49]). The European Commission recently connected the adoption of defensive trade measures and screening of FDI flows to new proposals for assessing the role of foreign subsidies and their potential impact on the internal market, publishing a White Paper and a consultation on the subject (European Commission, 2020[50]).

Mechanisms aiming to ensure a level playing field within and across countries may come under undue criticism at a time when they are more necessary than ever. While possibly welcoming greater flexibility, innovation policy makers also need to acknowledge the importance of the business environment and the benefits of such arrangements in terms of market access. In this context, it may be necessary to reform current systems, developing a consistent approach towards public-sector engagement towards the broader aspects of innovation rather than its R&D component alone. Networks of bilateral agreements between countries are likely to shape the delicate balance of public support for innovation, but their complexity may be too difficult to navigate, even for medium-sized countries.

In the future, the effective possibilities for public support for business innovation will also be linked to governments' ability to use the opportunities of digital transformation and adopt innovative practices. Digitalisation may completely transform the way that governments assess the merits of business claims for support and monitor the projects they fund as a portfolio. Some multilateral collaboration scenarios could enable timely information sharing between governments, such as those developed for the automatic exchange of information for tax purposes. The G20/OECD Inclusive Framework on base erosion and profit shifting has been working on reform of the international tax system to address the tax challenges arising from the digitalisation of the economy, restore stability to the international tax framework and avoid the risk of further unco-ordinated, unilateral tax measures (OECD, 2020[40]). The experience of this initiative will also shape how governments can use tax incentives as a means to attract innovation to their countries.

As implied by all of the above, political economy considerations will be critical. The outlook for the role of government in supporting and shaping innovation activity involving the business sector will depend on how society, through the prism of the current crisis and its immediate aftermath, perceives businesses as deserving beneficiaries of public assistance as they pursue innovations promoting social well-being, and views governments as capable facilitators of this process.

Conclusions

This chapter has provided innovation policy makers with an overview of the factors that have helped shape today's landscape for public support for innovation and the main questions open going forward. It has touched upon the lessons learned from recent OECD studies, particularly in relation to past crises and recent government responses to the COVID-19 crisis in the area of innovation.

The mobilisation of business innovation resources and capabilities is crucial for tackling the current crisis and addressing long-standing economic and societal challenges. As recent experience shows, how governments incentivise and influence research and innovation in firms has major implications for our future. The R&D and innovation business response to COVID-19 has been very heterogeneous. While for some the crisis represents an opportunity to expand such efforts, in many industries, innovation capabilities are under significant stress. Public support for innovation is not an exclusive concern of innovation policy makers. Its design and implementation has to take into account several implications and constraints that cut across several policy areas, thus calling for horizontal coordination and implementation approaches.

Public innovation support policies need to be able to guide private innovation efforts to where they are most needed, especially where market signals prove to be insufficient and coordination is most challenging. Recent OECD data and analysis shows that governments' policy mix is not entirely consistent with that ambition. R&D tax incentives, the undirected innovation support policy instrument that a majority of OECD governments have come to increasingly rely on in the last couple of decades, are effective in achieving their generic R&D-raising objectives as long as they are consistently designed and implemented. However, they are insufficient as a means to guide innovation to broader societal needs, and represent suboptimal instruments to encourage investment in knowledge at the interface between basic research and actual product or process development. Governments need to build balanced innovation support portfolios through mechanisms, instruments and capabilities that allow them to guide business innovation efforts, especially to areas where government is a primary user or customer of innovations.

Many of the assumptions underpinning the global policy consensus on the appropriate role of government in funding and promoting innovation are likely to be further challenged. International policy collaboration for business innovation support is critical. Business support today is possible within a delicate balance of international agreements that shape what national governments can do to help their businesses innovate without triggering retaliatory responses by other countries that restrict market access. Governments need to build a clear appreciation of the trade-offs facing them as they redesign their innovation support portfolios, in parallel with their partners and competitors in other countries. National self-interest, also when it comes to business support for innovation, will be most often best served by international collaboration.

Governments can learn from each other on how to improve the design and administration of innovation support during crises. Public support for innovation comes in many forms and is not always easy to measure, track over time or compare to facilitate mutual learning. Governments also need to continue to invest, alongside other capabilities, in evidence about their innovation support policies in order to improve them. This requires breaking down silos and developing capabilities to exploit this information. This is an ongoing priority of the OECD, both in terms of measurement and policy analysis.

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Notes

[1] According to WTO rules, a financial contribution by a government is not a subsidy unless it confers a “benefit”, to be determined by comparison with what the “market” would provide (WTO, n.d.a[13]).

[2] http://www.d20-ltic.org/.

[3] https://www.fpds.gov/fpdsng_cms/index.php/en/reports.html.

[4] The amendment extended the Temporary Framework to enable Member States to provide public support under the framework to all micro and small companies, even if they were already in financial difficulty on 31 December 2019 (see https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1221). The ability of governments to support medium-sized companies in scaling up remains a contested issue.

5 Resolving global challenges and crises through international collaboration

Collaboration lies at the heart of the science, technology and innovation (STI) response to COVID-19, where national and international collaborative platforms for technology are revolutionising vaccine design and production. The chapter argues that policy makers should capitalise on the momentum from the international community's response to COVID-19 to re-focus international STI co-operation on global public goods problems through greater transdisciplinary research, new public-private funding mechanisms, and stronger collaborative innovation models.

Key findings

- **The development of vaccine candidates has been exceptionally rapid and has drawn on nascent global R&D preparedness measures**, including support for novel platform technologies that are revolutionising vaccine design and production, and the institutionalisation of international co-ordination efforts to develop agile technology platforms that can be activated as new pathogens emerge. These relatively new arrangements are performing well, but are underfunded and dependent on a handful of countries and philanthropic institutions for financing. Governments should consider scaling them up and extending them to other global challenges where R&D preparedness is important, capitalising on the momentum from the response to COVID-19.
- **The concerted response to COVID-19 offers renewed hope that international STI co-operation can help provide solutions to other global challenges**. However, this will require reinforcing a new paradigm of international STI co-operation that places more value on challenge-driven, transdisciplinary research. In particular, governments need to work together on new financing and governance mechanisms, wherein business and private-finance actors coordinate with multilateral and national development banks to co-finance STI solutions for global challenges.
- **Government responses to the COVID-19 pandemic highlight the importance of national politics, leadership and values in influencing international STI co-operation**. Governments will need to balance national STI priorities and goals with the need for internationally co-ordinated action to address grand challenges and global public goods problems. Without such collective action, the capacities to deal with them – in the form of scientific knowledge, technology platforms and international co-ordinating institutions – will remain underdeveloped, leaving countries more exposed to global shocks. At the same time, governments need to build trust and define common and shared values to ensure a level playing field for scientific co-operation and an equitable distribution of benefits.

Introduction

The science and innovation response to COVID-19 has been a largely international effort, reflecting the steady growth of international science, technology and innovation (STI) collaboration in recent decades.[1] Much STI collaboration on COVID-19 is "bottom-up", initiated by scientists themselves. But the challenges posed by a pandemic also call for more orchestrated responses at an international level, in order to share data, identify and fill knowledge gaps, exploit complementarities and pool resources. These increasingly involve not only governments, but also businesses, philanthropies and civil society actors. Ideally, such responses should be truly global, but in their absence, bilateral and regional approaches may offer opportunities for "coalitions of the willing" to move forward, including the participation of low- and middle-income countries, many of whom bear the brunt of the worst effects of global challenges.

Public-private partnerships have proliferated in response to COVID-19, mobilising public researchers, businesses, governments and philanthropic organisations from around the world to work together on developing various countermeasures, notably vaccines, therapeutics and diagnostics. The World Health Organization (WHO) plays a convening role in many of these efforts, while various specialised global research partnerships co-ordinate and implement research and finance initiatives, most visibly in pursuit of COVID-19 vaccines. These partnerships – most of which were established in recent years in the wake of infectious disease outbreaks like Ebola – are well-regarded and are making significant contributions to the development and equitable distribution of vaccines through international co-operation. Crucially, they have been able to draw on recent global research and development (R&D) preparedness measures, including support for novel platform technologies that are set to revolutionise vaccine design and production.

The international response to COVID-19, although not free of difficulties, offers renewed hope that international STI co-operation can help provide solutions to other global challenges. Societal or grand challenges, such as climate change, food security and public health issues, are increasingly targeted by international STI co-operation, mirroring their adoption as priorities in national policies. The Sustainable Development Goals (SDGs) in particular have become a significant focus, with ongoing efforts to translate them into national and international research priorities supported by funding bodies. Targeting STI collaborative efforts on global challenges and issues related to global public goods (GPGs) will, however, require a paradigm shift in the priorities and practices of much existing STI co-operation. For instance, greater use of "blended finance" could support collaborative STI projects directed at the SDGs, pooling funding from governments, business, philanthropists and the financial community. Overall, the joint mobilisation of science, industry, government and civil society at a global level will be essential to trigger the deep transformations required to tackle challenges like the climate emergency.

Stepping up collaboration to fight COVID-19

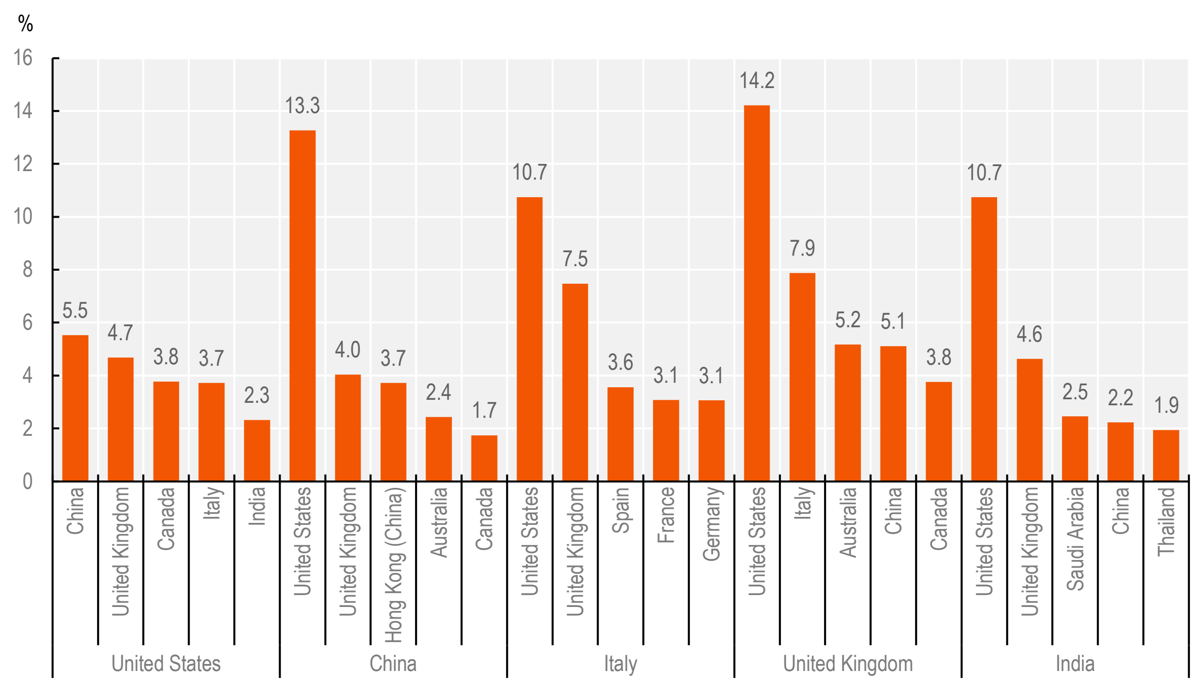
Collaboration has been a hallmark of STI responses to the pandemic crisis

International scientific co-operation on COVID-19 started through exchanges of data and genetic and viral material, originally from China to other research centres across the world, marking a relatively rapid development compared to previous pandemics. Less than 24 hours had elapsed between the sequencing of the first coronaviruses by the Chinese public health laboratories to full genome data being publicly shared on the Global Initiative on Sharing Avian Influenza Data (GISAID) EpiCoV™ database,[2] a public-private-partnership. Since then, numerous international open data-sharing platforms have sprung up to provide access to epidemiological, clinical and genomics data, as well as related studies. Protocols and standards used to collect the data are also being shared, together with analytical tools. The COVID-19 Open Research Dataset (CORD-19), created by the Allen Institute for AI in collaboration with the US government and a number of firms, foundations and publishers, contains more than 280 000 full-text machine-readable scholarly articles on COVID-19 and related coronaviruses, and serves as a basis for applying machine-learning techniques to generate new insights supporting COVID-19 research. Other initiatives include repositories of genome data (such as Nextstrain and GISAID), chemical-structure data (e.g. CAS COVID-19 antiviral candidate compounds dataset), clinical studies (e.g. ClinicalTrials.org for COVID-19-related studies) and data for modelling research (e.g. MIDAS). The European Commission launched the COVID-19 Data Portal in April 2020 to bring together relevant datasets for sharing and analysis in an effort to accelerate coronavirus research. It enables researchers to upload, access and analyse COVID-19 related reference data and specialist datasets as part of the wider European COVID-19 Data Platform.[3] Most scientific journal publishers have waived traditional access costs related to scientific articles on COVID-19 (OECD, 2020[1]).

As highlighted in Chapter 2, there continues to be an impressive output of scientific articles on COVID-19. OECD analysis of PubMed data shows that the United States and China are the two largest contributors to COVID-19 publications[4] (see Chapter 1), and are also one another's main collaborating partner (Figure 5.1). Other research confirms these patterns. For instance, an analysis by (Fry et al., 2020[2]) of all scientific articles on coronaviruses published from 1 January 2018 until 8 April 2020 found that the United States and China increased their collaboration in the wake of the COVID-19 outbreak.

Figure 5.1. Share of international scientific collaboration on COVID-19 medical research by partner economy

Top five economies, in terms of total number of documents (fractional counts), and their top 5 partner economies, from 1 January to 30 November 2020

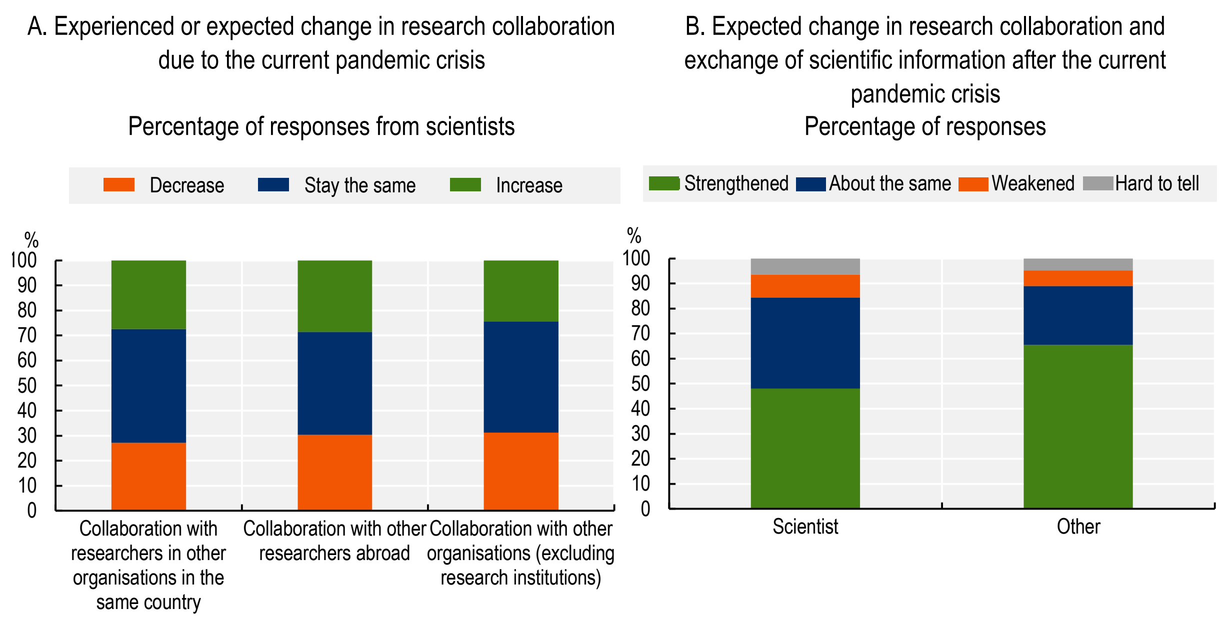


Note: The period covers 1 January to 30 November 2020 and includes 74 115 documents. The United States co-authored 16 964 documents. 84% of those were domestic co-authorships, while the remainder involved international collaboration. The top collaboration partner of the United States is China, and US-China collaboration represents 5.5% of all United States publications on COVID-19-related medical research.
Source: OECD and OCTS-OEI calculations, based on US National Institutes of Health (NIH) PubMed data, https://pubmed.ncbi.nlm.nih.gov/ (accessed 30 November 2020).

StatLink https://doi.org/10.1787/888934223479

When asked in the ongoing OECD Science Flash Survey 2020 about their experiences and expectations of research collaboration during the pandemic crisis, scientists are more or less evenly split as to whether they have experienced an increase or decrease in collaboration Figure 5.2, Panel A). However, almost half expect enhanced research collaboration and exchange of scientific information after the current pandemic crisis, while less than 10% expect weakened collaboration (Figure 5.2, Panel B).

Figure 5.2. Scientists' experiences and expectations of research collaboration during the crisis



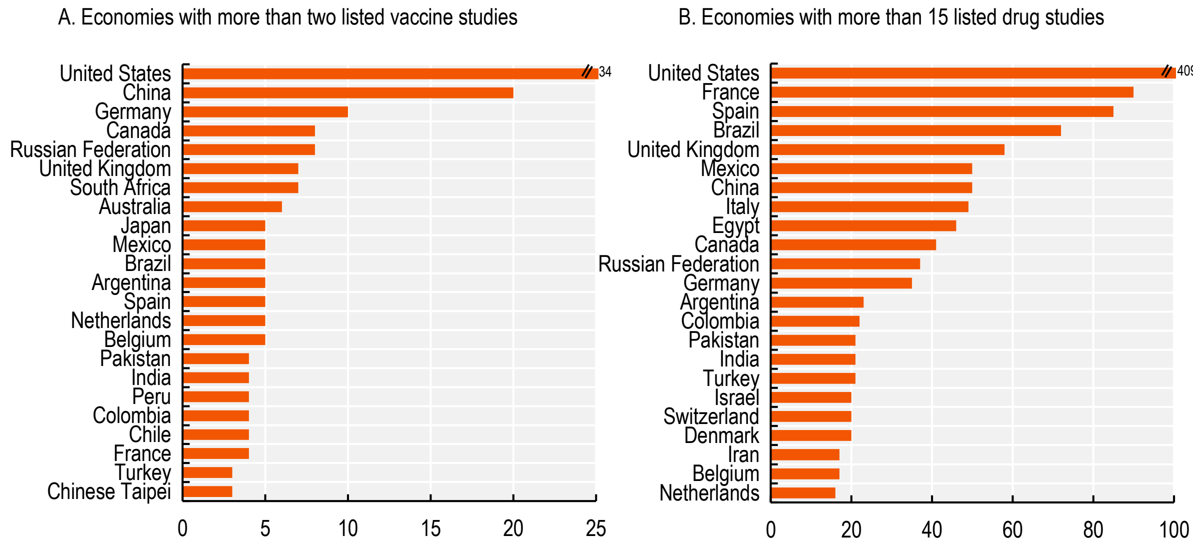
Note: For Panel A, respondents were asked, "As a result of the current crisis, have you personally experienced or do you expect to experience a change in (i) collaboration with researchers in other organisations in the same country; (ii) collaboration with other researchers abroad; and (iii) collaboration with other organisations (excluding research institutions)?" For Panel B, respondents were asked, "How do you expect the world of science to emerge out of the current crisis, in terms of collaboration and exchange of scientific information?"
Source: OECD Science Flash Survey 2020, https://oecdsciencesurveys.github.io/2020flashsciencecovid/ (accessed 12 October 2020).

StatLink https://doi.org/10.1787/888934223498

Collaborations on clinical research and clinical trials on COVID-19 have also grown significantly. Hundreds of clinical trials have been registered since early 2020, most of them to test drug candidates, but also several vaccine candidates. Figure 5.3 shows the number of COVID-19 studies registered on the NIH's portal ClinicalTrials.gov by 8 December 2020. The United States accounts for the largest number of clinical trials by far, particularly for drugs. China comes second on vaccine trials. Based on data from BioMedTracker and Pharmaprojects, two online platforms that track drug development, Bryan, Lemus and Marshall (2020[3]) found that 40% of drug therapies for COVID-19 were being developed by teams of firms (significantly higher than 21% for H1N1 influenza virus therapies, 9% for Ebola and 11% for Zika). They also found that about one-third of these collaborations are new.

Figure 5.3. Registered COVID-19 vaccine and drug studies by economy

Number of COVID-19 studies, 1 January to 8 December, 2020



Note: The charts show the number of COVID-19 studies registered at the NIH's ClinicalTrials.gov. The International Committee of Medical Journal Editors requires trial registration as a condition for publishing 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. Iran stands for Islamic Republic of Iran.

Source: United States National Institutes of Health, https://clinicaltrials.gov, (accessed 8 December 2020).

StatLink https://doi.org/10.1787/888934223517

Public-private partnerships are at the heart of COVID-19 countermeasures

Public-private partnerships (often involving several firms) are playing central roles in the fight against COVID-19. For example, the United States had allocated, through its Operation Warp Speed (OWS), more than USD 11 billion by October 2020 among more than 40 companies to fund the development of vaccines, diagnostics, therapeutics and other rapidly deployable capabilities. In parallel (and under the umbrella of OWS), the NIH is funding a public-private partnership to prioritise and accelerate development of the most promising COVID-19 treatments and vaccines (Box 5.1). Much of the funding from OWS is intended to deal with market failures associated with vaccine development and production. Many other countries have used similar rationales to fund vaccine and therapeutics research, though on a smaller scale. For example, Germany has committed around EUR 750 million to accelerate vaccine R&D through a special programme targeting three companies to set up their projects more broadly and to progress more quickly.[5] At a multilateral level, COVAX is another public-private partnership that has been playing a crucial role in vaccine development while paying special attention to the needs of low- and middle-income countries (Box 5.3).

All of these initiatives have some strategic features in common. Besides R&D, they invest in manufacturing capacity, advanced market commitments, and liability limitations, reducing uncertainties for the private sector to become involved. Moreover, to avoid delays between regulatory approval and the rolling out of vaccines, many of the activities that usually occur after completion of the R&D and marketing authorisation stages are being executed in parallel, with the result that manufacturing of some vaccines started while they were still in clinical trials. This fast track is intended to ensure a sufficient number of doses are globally available (by the end of 2021) once regulators grant their approval.

Box 5.1. US public-private partnerships for COVID-19 countermeasures

Overall, because of their scale and scope, US investments in basic and applied research and in clinical trials are providing a major boost to global efforts to develop COVID-19 vaccines and therapeutics

Operation Warp Speed (OWS)

The goal of OWS is to produce and deliver 300 million doses of safe and effective vaccines, with initial doses available by January 2021, as part of a broader strategy to accelerate the development, manufacturing and distribution of COVID-19 vaccines, therapeutics and diagnostics (collectively known as countermeasures). By early October 2020, OWS had invested more than USD 11 billion into seven vaccine candidates, with funding coming from the United States Congress, including through the Coronavirus Aid, Relief, and Economic Security Act (the CARES Act). To accelerate development while maintaining safety and efficacy standards, OWS has been selecting the most promising countermeasure candidates and providing co-ordinated government support. Protocols for demonstrating safety and efficacy are being aligned, allowing trials to proceed more quickly. The protocols for the trials are overseen by the federal government. Rather than eliminating steps from traditional development timelines, these are proceeding simultaneously, such that manufacturing of a promising vaccine at an industrial scale can start well before the complete demonstration of its efficacy and safety, which would normally be required. The federal government is making investments in the necessary manufacturing capacity at its own risk, giving firms confidence that they can invest aggressively in development, and allowing faster distribution of an eventual vaccine. The manufacturing capacity developed will be used for whatever vaccine is eventually successful, regardless of which firms have developed the capacity. OWS is a partnership among components of the Department of Health and Human Services that engage with private firms and other federal agencies.

National Institutes of Health – Accelerating COVID-19 Therapeutic Interventions and Vaccines (ACTIV)

Announced in April 2020, ACTIV is a public-private partnership headed by the NIH to develop a co-ordinated research strategy for prioritising and accelerating development of the most promising treatments and vaccines. It acts, for example, by streamlining clinical trials, co-ordinating regulatory processes and/or leveraging assets among all partners to rapidly respond to COVID-19. Co-ordinated by the Foundation for the National Institutes of Health, ACTIV brings the NIH together with its sibling agencies in the Department of Health and Human Services, other government agencies, OWS, the European Medicines Agency, representatives from academia, philanthropic organisations (including the Bill & Melinda Gates Foundation and the Fred Hutchinson Cancer Research Center), and 20 biopharmaceutical companies.[6]

Sources: OWS website: https://www.hhs.gov/coronavirus/explaining-operation-warp-speed/index.html (accessed 16 October 2020); NIH ACTIV website: https://www.nih.gov/research-training/medical-research-initiatives/activ (accessed 16 October 2020).

STI co-operation supporting timely and globally equitable solutions to COVID-19

Identifying and developing appropriate and viable COVID-19 tests, treatments and vaccines require large investments with a high level of risk. This means countries need to pool their investments globally. In this regard, the WHO is playing a lead convening role in formulating STI responses to COVID-19 (see Box 5.2). It has published an R&D Roadmap for COVID-19, and is a partner in the influential Access to COVID-19 Tools (ACT) Accelerator, a global collaboration to accelerate development, production, and equitable access to COVID-19 tests, treatments, and vaccines (see Box 5.3).

Building on the philosophy that no single country can beat COVID-19 on its own, the ACT-Accelerator works to shape the market for solutions and incentivise manufacturers to invest in developing and manufacturing their supply. The ACT-Accelerator also offers governments access to a portfolio of solutions that spread the risk of failure of individual treatment or vaccine candidates, as well as other solutions (across multiple geographies and multiple technical platforms) should one of them prove not to be viable (WHO, 2020[4]). The ACT-Accelerator is organised into four pillars of work, led by different organisations. The most prominent is the vaccine pillar, known as COVAX (see Box 5.3), which is led by the Coalition for Epidemic Preparedness Innovation (CEPI) and the Global Alliance for Vaccines and Immunizations (GAVI). As outlined in Box 5.2, CEPI funds R&D and up-scaling processes into a diverse portfolio of COVID-19 vaccine candidates, while GAVI focuses on the procurement and allocation of vaccines.

Box 5.2. Selected key organisations supporting international STI collaboration on COVID-19

World Health Organization (WHO)

The WHO is leading the international response to the COVID-19 pandemic. It has published an R&D Roadmap for COVID-19 and established the ACT-Accelerator with the assistance of Global Research Collaboration for Infectious Disease Preparedness (GloPID-R), an international network of research-funding organisations. The ACT-Accelerator brings together governments, the private sector, philanthropic entities and other international organisations to accelerate development, production and equitable access to COVID-19 tests, treatments and vaccines. The WHO also set up the Solidarity Trial to facilitate the robust worldwide comparison of unproven treatments for COVID-19. Box 5.3 provides more details on these and other initiatives.

Coalition for Epidemic Preparedness Innovation (CEPI)

Established in 2017, CEPI is a global partnership between public, private, philanthropic and civil society organisations that aims to accelerate the development of vaccines (based on the WHO R&D Blueprint of emerging infectious pathogens) and enable equitable access to these vaccines for affected populations during outbreaks. CEPI takes an end-to-end approach, operating as both a funder and a facilitator. It focuses on vaccine development, licensure and manufacturing while supporting the efforts of vaccine discovery and delivery. Among its tasks, it funds new and innovative platform technologies with the potential to accelerate the development and manufacture of vaccines against previously unknown pathogens, the so-called “Disease X” from the WHO Blueprint. Based on platform technology work and funded research on Middle East Respiratory Syndrome (MERS), CEPI was able to quickly start building up a COVID-19 vaccine R&D portfolio in January 2020. CEPI has been expanding its COVID-19 work and is currently funding R&D for nine different vaccine candidates with the aim of providing up to 2 billion vaccine doses by the end of 2021.

Global Alliance for Vaccines and Immunizations (GAVI)

Created in 2000, GAVI is an international organisation that brings together the public, private and philanthropic sectors with the shared goal of creating equal access to new and underused vaccines for children living in the world’s poorest countries. It does this by creating robust markets for vaccines and other immunisation products, thereby allowing manufacturers to plan production based on known demand, and low- and middle-income countries to buy suitable products at prices they can afford. With the support of CEPI and the WHO, GAVI is responsible for administering the COVAX facility, described in Box 5.3.

Global Research Collaboration for Infectious Disease Preparedness (GloPID-R)

GloPID-R is an international network of research-funding organisations. It was launched in 2013 by the heads of international research organisations to facilitate, accelerate and deepen collaboration among research funders on emerging diseases by investing to strengthen global research preparedness between crises, and mobilising resources to respond rapidly and effectively to significant infectious disease outbreaks. In the COVID-19 context, GloPID-R has convened working groups on priority research, together with the UK Collaborative on Development Research. It has also created an online database of funded research projects mapped to the WHO R&D Roadmap. The European Commission finances the GloPID-R Secretariat, which is split between the Mérieux Foundation and the University of Oxford.

Sources: WHO website, https://www.who.int/; CEPI website, https://cepi.net/; GAVI website, https://www.gavi.org/; GloPID-R website, https://www.glopid-r.org/ (accessed 16 October, 2020).

Box 5.3. Main international collaborative initiatives

WHO R&D Blueprint

Following the Ebola outbreak in West Africa, the WHO drew up in 2016 a global strategy and preparedness plan. Known as the R&D Blueprint, the plan aims to support the rapid activation of R&D activities during epidemics[7] and fast-track the availability of effective tests, vaccines and medicines. The WHO uses the R&D Blueprint to convene a broad global coalition of experts from medical, scientific and regulatory backgrounds to work on a given priority disease, leading to the creation of an R&D roadmap for that disease. The R&D roadmap is then used to guide the response to outbreaks through both urgent actions and developing ways to improve the global response for future epidemics. As part of the WHO's response to COVID-19, the R&D Blueprint was activated to accelerate diagnostics, vaccines and therapeutics for the new virus. In collaboration with GloPID-R, in February 2020 the WHO organised a global forum on research and innovation for COVID-19 where experts identified key knowledge gaps and research priorities. The WHO published its resulting R&D Roadmap for COVID-19 in March 2020, outlining immediate, mid-term and longer-term priorities to build a robust global research response to the crisis.

WHO Access to COVID-19 Tools (ACT) Accelerator

The ACT-Accelerator is a global collaboration to accelerate development, production and equitable access to COVID-19 diagnostics, therapeutics and vaccines. Launched in April 2020 and building on the commitment made by G20 leaders in March 2020 to the Coronavirus Global Response, the ACT-Accelerator is a framework for collaboration, rather than a decision-making body or new organisation. It is organised into four pillars of work – diagnostics, treatment, vaccines and health system strengthening – led by a range of collaborating organisations, including the Bill & Melinda Gates Foundation; CEPI; GAVI; the Global Fund to fight AIDS, Tuberculosis and Malaria; Unitaid; the Foundation for Innovative New Diagnostics; the Wellcome Trust; the World Bank; and the WHO. The ACT-Accelerator has ambitious targets: it aims to provide 245 million courses of treatment and 500 million diagnostic tests to low- and middle-income countries in 2021, and 2 billion vaccine doses to the world by the end of 2021.

COVAX

COVAX is one of the four pillars of the ACT-Accelerator, dedicated to advancing the work on vaccine development, manufacturing, procurement and delivery at scale, as well as policy and allocation. COVAX enables risky investments in production capacity across several vaccine candidates to ensure that doses can be made immediately available at scale upon regulatory approval. COVAX combines the power and expertise of CEPI's R&D role on the "push side" with GAVI's procurement and allocation function on the "pull side", e.g. through the COVAX AMC. Through portfolio diversification, pooling of financial and scientific resources, and economies of scale, participating governments and blocs[8] can hedge the risk of backing unsuccessful candidates, just as governments with limited or no ability to finance their own bilateral procurement can be assured of access to life-saving vaccines that would otherwise have been beyond their reach.

WHO Solidarity Trial

Solidarity is an international clinical trial launched by the WHO and partner organisations to help find an effective treatment for COVID-19. It is one of the largest international randomised trials for COVID-19 treatments, enrolling almost 12 000 patients in 500 hospital sites in over 30 countries. Enrolling patients in a single randomised trial helps facilitate the robust worldwide comparison of unproven treatments, overcoming the risk of multiple small trials not generating the strong evidence needed to determine the relative effectiveness of potential treatments.

Sources: WHO R&D Blueprint website, https://www.who.int/publications/m/item/a-coordinated-global-research-roadmap (accessed 25 October 2020); ACT-Accelerator website, https://www.who.int/initiatives/act-accelerator; COVAX website, https://www.who.int/initiatives/act-accelerator/covax; WHO Solidarity Trial website, https://www.who.int/emergencies/diseases/novel-coronavirus-2019/global-research-on-novel-coronavirus-2019-ncov/solidarity-clinical-trial-for-covid-19-treatments. All accessed 16 October 2020.

Health systems will need to vaccinate 50% to 75% of the global population to end the pandemic. This requires building manufacturing and distribution capacity, ensuring a new vaccine is affordable, deciding who should get access first and planning massive vaccination campaigns at a global scale. Vaccines have been described as GPGs, but this will not be the case initially with COVID-19 vaccines, since their limited supply will mean they are neither non-excludable or non-rival (Bollyky and Bown, 2020[5]). Several countries, as well as the European Union, have concluded advanced purchase agreements with COVID-19 vaccine manufacturers. More than 10 billion doses of COVID-19 vaccines had been pre-ordered by late-2020, accounting for most of the manufacturing capacity for the leading vaccine candidates in 2021. High-income countries bought up broad portfolios of products early in the pandemic, placing bets on a number of candidates. Canada, the United States, the United Kingdom, Australia and the European Union have each pre-ordered more than four doses of COVID-19 vaccines per person. Countries with excess doses could ultimately donate these to COVAX (Mullard, 2020[6]; Callaway, 2020[7]).

To avoid a situation where a small number of wealthy economies secure the global supply of vaccines only for themselves, COVAX has also signed advanced purchase agreements to secure manufacturing capacity and vaccine doses even before any vaccines were licensed. COVAX aims for affordable, fair and equitable access to safe and effective COVID-19 vaccines for all. More than 180 countries and economies are now involved,[9] including 92 low-income economies that would otherwise be unable to afford these vaccines and will be supported through an advanced market commitment (AMC).[10] To gain access to 1 billion doses for AMC-eligible economies, GAVI's COVAX AMC has set an initial fundraising goal of USD 2 billion by the end of 2020 to reserve and accelerate the production of doses. Already by October 2020, GAVI had reached USD 1.8 billion in contributions and pledges from sovereign donors, the private sector and philanthropic sources.[11] At least USD 5 billion more will be needed in 2021 to procure doses as they come through the portfolio.

COVAX also provides direct protection for countries that already have their own bilateral deals with vaccine manufacturers by increasing their chances of securing safe and efficacious vaccine doses, given that not all candidates will ultimately be successful. COVAX also offers indirect protection by covering low-income countries that would otherwise be unable to afford these vaccines, thereby reducing the chances of a COVID-19 resurgence in their territories that could quickly spread across the globe (WHO, 2020[8]). Accordingly, most OECD countries are now members of COVAX.

The essential roles of global R&D preparedness

Development of vaccine candidates has been exceptionally rapid. Hundreds of vaccines are currently in development across the world; three had announced Phase 3 clinical trials results by the end of November 2020; and one had already gained regulatory approval in several jurisdictions by early-December and was being administered to vulnerable groups. This scale, combined with the scope of utilising a range of different technology platforms, increases the chances of success. While most would agree that the world was ill-prepared for COVID-19, despite repeated warnings that a new pandemic was "a question of 'when', not 'if'" (Global Preparedness Monitoring Board, 2019[9]), certain steps – such as long-term commitments to basic research, as well as various technological and institutional innovations at the global level – had been undertaken in recent years to improve global R&D preparedness, and these appear to have paid off to some extent.

The WHO R&D Blueprint was an important cornerstone (Box 5.3), prioritising, accelerating and co-ordinating product-related R&D for epidemic risk diseases with no existing treatments. The diseases covered included the so-called "Disease X", caused by a hypothetical pathogen not yet known to infect humans. R&D funding for the pathogens listed on the WHO R&D Blueprint list was provided by CEPI, including a call for proposals for the development of platform technologies able to expedite some stages of clinical development and permit advance development of multiple vaccine candidates at the same time. Such technologies can also be extended to manufacturing, allowing progress in setting up production facilities before the targets of the upcoming vaccines are even decided (see Chapter 7). Platform technology approaches include DNA and messenger RNA vaccines, adjuvants, monoclonal antibodies and broad-spectrum antivirals (Hall, Jamieson and Wardle, 2019[10]; van Riel and de Wit, 2020[11]).

Its work on platform technologies enabled CEPI to respond very quickly to the outbreak at the end of January 2020. Within two weeks of the publication of the SARS-CoV-2 sequence, it was able to leverage and support several of its research partners to begin developing vaccines against the virus (WHO, 2020[8]). The existence of vaccine development partners for MERS, combined with readily available funding and established expertise, enabled the rapid roll-out of vaccine development for COVID-19, using an accelerated paradigm to conduct development and scale up activities in parallel. Major research groups and research-funding agencies had already switched their vaccine development strategies to invest in novel vaccine platforms for particular virus families, which also helped considerably (Keusch and Lurie, 2020[12]). With the ongoing approval of a first generation of vaccines, CEPI is establishing the 'Wave 2 Portfolio' of COVID-19 vaccine candidates, which aims to optimise the vaccines that are available in the longer term.[12]

CEPI is an example of a "collaborative platform", an emerging form of multisector partnership in which participants co-develop new technologies and processes with significant potential for advancing health and more resilient societies (OECD, forthcoming[13]). Collaborative platforms are convergence spaces that bring together a high diversity of stakeholders, disciplines, technologies and cultures. In the area of healthcare, they can optimise access to and use of information generated in research, clinical settings and markets for the benefit of patient care. They offer opportunities for experimentation in health innovation and de-risking research on emerging technologies, complex health challenges (e.g. dementia, antibiotic resistance and pandemics), and products with limited markets and potentially low returns on investment. The pooling of resources, competencies and complementary skills enables communication across sectors, manages risks, offers access to infrastructure and drives technology translation. Besides CEPI, several other healthcare collaborative platforms are wholly committed to ensuring equitable access to research data and products related to COVID-19. These include the Joint European Disruption Initiative (JEDI) Billion Molecules against COVID-19 Grand Challenge, and the Research Investment for Global Health Technology Fund (The RIGHT Fund).

The momentum created by the pandemic offers opportunities to establish effective and sustainable global mechanisms to support the range and scope of R&D necessary to confront a wider range of potential health emergencies (Global Preparedness Monitoring Board, 2020[14]). For example, ACT-Accelerator and COVAX represent major innovations. They indicate that with effective global leadership, it is possible to support market commitments, procurements and the fair global allocation of vaccines (Keusch and Lurie, 2020[12]). They have also promoted the technological advancement of the tools they have invested in (WHO, 2020[4]). Collaborative responses to COVID-19 have also seen the emergence of an array of new intellectual property rights (IPR) agreements to support access to medicines, possibly laying the groundwork for new modalities of R&D on GPGs moving forward.

The crisis has also exposed several shortcomings that need to be addressed for STI collaboration to play its full role in building resilience, and addressing future crises and grand challenges.

- Despite its strong performance, CEPI was formed to deal with regional epidemics and lacks sufficient funding for a global pandemic response. Its funding derives from a mix of R&D funding and traditional development assistance that relies on a small number of generous countries and private foundations. There are calls to expand CEPI's funding base, drawing on national and regional health security budgets that have yet to be established. This would allow CEPI to become a lead actor in the context of global health security (Global Preparedness Monitoring Board, 2020[14]). Options like these will need to be discussed more broadly in the wider context of the lessons learnt from the current pandemic.
- GloPID-R was created with funder and research co-ordination in mind. However, because there was no ready pool of funding to draw on and country limitations with regard to speed were not fully anticipated at the outset, it has not been able to move as quickly as needed to respond to the pandemic (Keusch and Lurie, 2020[12]).
- While much attention has focused on COVID-19 vaccines, improving R&D preparedness for therapeutics may require a similar mechanism to CEPI and vaccines. Furthermore, despite the obvious need, little innovation has taken place over the last five years in novel platforms and technologies for diagnostic tests (Hall, Jamieson and Wardle, 2019[10]; Keusch and Lurie, 2020[12]).
- Rapid activation is a "cost of preparedness". This approach was taken by CEPI as part of its preparedness efforts with regards to vaccine development. Extending such an approach to diagnostics and therapeutics would require governments worldwide to rethink the concept of health security budgets and invest in the necessary infrastructure. One approach is that global funders agree on a reasonable, "no regrets" annual budget underpinning preparedness, and ensure those resources are always available and can be rapidly released (Keusch and Lurie, 2020[12]).
- Early research on COVID-19 was plagued by too much uncoordinated experimentation and a lack of adherence to shared standards on pre-clinical research, impeding the generation of robust evidence to underpin medical knowledge (OECD, 2020[15]). With so much development happening in parallel, organising clinical trials has been challenging. The WHO Solidarity Trial (Box 5.3) represents a novel and potentially capacity-building effort on clinical trials, which could be replicated (Keusch and Lurie, 2020[12]). The OECD Recommendation on the Governance of Clinical Trials (OECD, 2012[16]) is also relevant here, as the persistent lack of harmonisation between national regulations slows down the implementation of international clinical trials (OECD, 2020[17]).

These are some early observations concerning the successes and shortcomings of the international STI response to COVID-19. In time, as countries move from response to recovery, a fuller analysis and evaluation will be needed to draw lessons that should prove invaluable in informing STI collaboration for other "grand challenges", as discussed below.

Beyond COVID-19, international STI collaboration is needed to meet global challenges

Global public goods and global challenges

There is a sense of urgency to direct international STI co-operation activities towards "global challenges", broadly defined as persistent, complex and large-scale problems facing humanity. Such challenges require co-operative resources, because no single country can solve them alone (OECD, 2012[18]). A common feature that has characterised the collective response to COVID-19, through organisations and platforms like GAVI and CEPI, is the notion that certain global challenges are not simply challenges that require international co-operation, but that the very nature of the global challenge represents the under-provision of a GPG. A GPG is a good where "it is rational, from the perspective of a group of nations collectively, to produce for universal consumption, and for which it is irrational to exclude an individual nation from consuming, irrespective of whether that nation contributes to its financing" (Woodward and Smith, 2003[19]). Another definition is that GPGs are public goods that "cannot or will not be adequately addressed by individual countries acting alone and that are defined through a broad international consensus or a legitimate process of decision-making" (ITFGPG, 2006[20]; Miedzinski et al., 2020[21]). GPGs share certain properties with public goods, i.e. their non-excludability and non-rivalry. Non-excludability means that once provided, the public good is available to all to consume; non-rivalry means that consumption of the public good by one party does not reduce the amount available to the others.[13] A practical example of a GPG is greenhouse emissions control or a vaccine against a highly communicable disease that protects human populations in more than one country. Of course, vaccines are not *intrinsically* non-excludable because they are produced by private firms who can limit their universal accessibility through the price mechanism, but policy interventions in the form of government purchases and distribution through public health systems, for example, can make them less or non-excludable. Because of their limited economic resources, developing countries are especially exposed to global challenges and the under-provision of GPGs, and support from the international community is therefore essential.

The global challenges are heterogeneous. Some derive from public goods problems on a global scale, while others derive from global challenges on a national or bilateral/regional scale (e.g. pollution generated and concentrated in cross-border regions). While not all global challenges are public good problems, very little multilateral collaboration is around public-good production. On the contrary, policy-makers undertake collaboration where they can identify direct (and preferably quantifiable) benefits, in the form of increments to GDP, employment, or exports (Smith, 2017[22]). The challenge for countries is how to balance their national STI priorities and goals (e.g. competitiveness and research excellence) with the need for co-ordinated collective action at the international level to address global challenges, including GPG problems.

The international STI policy community needs to encourage a more collaborative mode of STI, in which shared goals and missions underpin individual and collective STI actions. However, mobilising international STI collaboration to address GPGs and global challenges faces several hurdles, the most notable being that collective action for the provision of the good suffers from an economic problem common to the provision of public goods; i.e. their under-provision by markets. Whereas a national public good can be provided by governments through taxation, there is no global government that can mobilise global tax revenues to provide such goods directly or through public procurement. Additional challenges include:

- different national research foci and limited alignment between national and global STI priorities;

- unwillingness of individual countries to pay the costs of action ("tragedy of the commons");
- lack of knowledge of different national capabilities, especially in developing countries;
- lack of trust and legal regimes, including appropriate IPR protection, especially in less-developed economies;
- low government and business capacity in some countries, including low number of researchers and lack of necessary research infrastructure to enable international co-operation;
- major problems to meet the necessary scale of investment and technological uncertainty requiring multiple search paths;
- governance arrangements to co-ordinate and manage multiple actors, necessary not only to advance the necessary STI, but also to deploy systems that deliver technological solutions; and
- implementation challenges including the lack of appropriate interface organisations such as technology extension centres or community organisations that can apply solutions to the local context.

Compounding the effects of these hurdles, international co-operation in research remains dominated by collaborations aiming first and foremost to advance the knowledge frontier or share costs on international research infrastructure, and to a much lesser extent to develop solutions to societal problems. Moreover, the direction of international research co-operation remains primarily driven by the "bottom-up" priorities of individual researchers and research performing organisations, even if a number of collaborations on climate change, global health, renewable energy or sustainable agriculture are initiated through "top-down" processes.

In this regard, the current paradigm for international co-operation in science can be seen to focus on: (i) raising the quality of national public research systems; (ii) sharing costs though scientific collaboration on basic research; (iii) promoting the international mobility of researchers for the (mutual) benefit of multiple partners; and (iv) internationalising public research. This paradigm has been successful in advancing knowledge among countries with the capacity to engage in research collaboration, i.e. mainly OECD countries; Brazil, Russia, India and China; and some emerging economies. With some notable exceptions in East Asia, it has been less successful in helping developing countries mobilise STI for their own development. Instead, these countries have relied on STI-related official development assistance (ODA) and multilateral development bank finance; imports of foreign technology and foreign direct investment; and, for middle-income countries, their own investments in education and science. Cost sharing under this paradigm is generally characterised by national control over funding: each country funds its share of international collaboration rather creating a "common pot" of funding (with the exception of the European Union's Framework and Horizon programmes). The response to COVID-19 by research funders has been similarly focused mainly at the national level, although it has been characterised also by co-ordination among national research funding agencies, for example, through GloPID-R (see Box 5.2).

Towards a new paradigm for international collaboration on STI

A focus on GPGs and global challenges requires a new paradigm for international STI co-operation that goes beyond cost-sharing and expanding fundamental knowledge through co-operation in basic research or mega-science projects. The immediacy and urgency of the current pandemic has brought home the need for a new paradigm of international co-operation in STI. This new paradigm will require new financing and governance mechanisms that bring together business and private-finance actors with multilateral and national development banks. These include tax and regulatory policies that will allow the international research system to incentivise and reward businesses and financial institutions to invest in solutions to GPGs. The new paradigm will also require specific institutional capabilities for multi-stakeholder partnerships to broker, orchestrate and fund global challenge-driven STI programmes. These new arrangements will need to manage growing tensions between the need for more global co-operation and the increasingly inward-looking nature of national policies, which are more protective of STI as a source of national security and independence. These, and other challenges, are further discussed below.

International STI co-operation is fragmented

Research-funding agencies have a great deal of expertise in funding international collaborative projects that promote research excellence in specific disciplines and areas, but they are less well equipped to fund and organise collaboration to address grand challenges – especially those involving developing countries. Some very real practical challenges impede international collaboration, such as visas and work permits for researchers, or purely national grant schemes that do not allow financing international projects. Many research-oriented collaborations are uncoordinated on a global scale, many of the potential synergies from sharing costs or information are lost, and there exists a risk of duplicating research and innovation efforts. Data on international co-operative R&D projects around global challenges and the SDGs are also lacking, and yet such data would greatly enhance the ability of decision makers to monitor and evaluate these activities, and prioritise successful experiences. To reduce this fragmentation of international efforts, co-ordination of national public research agendas oriented toward global challenges is essential.

Institutional elements of the new paradigm aimed at building GPGs and addressing global challenges through international STI collaboration are already in place, but need to be consolidated and reinforced. Some of these institutional set-ups can build upon existing organisations, such as Canada's International Development Research Centre (IDRC), whose Technology and Innovation Program leverages science and advanced technologies, including digital innovations to build human capital to support inclusive growth in developing countries. New partnerships will also need to be created, such as the United Kingdom's Newton Fund, which was created in 2014 to fund collaborations on global challenges between academics and innovators in the United Kingdom and developing countries.

There already exist several examples of international collaboration focused on mobilising STI for global challenges. They range from mandate-based international organisations (e.g. the Consultative Group for International Agricultural Research, the International Energy Agency and Mission Innovation, and the Global Knowledge Centre for Antimicrobial Resistance R&D) to partnerships initiated by governments and philanthropies such as CEPI (see Box 5.2). One characteristic of these new partnerships is the involvement of a broader range of stakeholders, including companies, civil society groups and notably private philanthropic organisations.

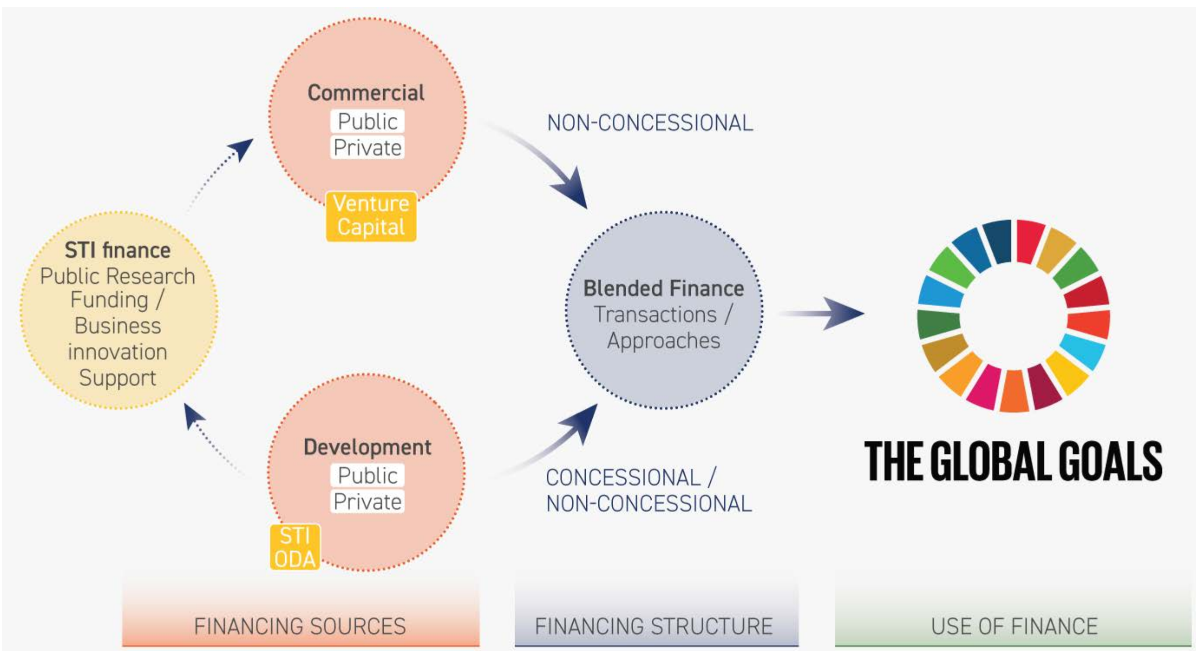
International financing of GPGs: the case of blended finance in STI

Addressing and delivering on global challenges, including GPGs, will require financial resources that exceed most countries' budgets for domestic public resources. Many estimates have been made of the investments needed to achieve the SDGs by 2030. One estimate points to an overall need for a USD 7 trillion annual investment up to 2030, representing 7-10% of global gross domestic product and 25-40% of annual global investment. By comparison, only USD 1.4 trillion are invested annually to meet the SDGs, leaving a vast investment gap. For developing countries alone, the investment gap has been estimated at around USD 2.5 trillion per year (Remøe and Cervantes, forthcoming[23]). Closing this gap will require mobilising financial resources from public coffers as well as the private sector, including investment banks, philanthropic sources and multilateral institutions.

Hence, many governments seek to combine public financial resources with private financing. "Blended finance", in the space of SDGs and Agenda 2030, has been defined as the strategic use of development finance for the mobilisation of additional finance towards the SDGs for and in developing countries. Blended finance has also been described as hybrid finance, or as a combination of concessional and commercial funding provided by public or philanthropic development partners, along with private partners. It can be structured around various formats combining grants, debt, equity or guarantees (insurance) from public/philanthropic and private sources. The concept is also linked to the more general concept of social-impact investments.

A main idea of blended finance in STI is mobilising capital that would not otherwise be committed to development-related projects, including developing technology to create solutions that are relevant to the SDGs. Through blending financing, commercial capital may be moved to benefit society while also providing reasonable returns to investors. Thus, frameworks that remove disincentives and bottlenecks preventing private investors from targeting countries, sectors or technology areas for additional funding are needed (Figure 5.4).

Figure 5.4. Expanding the OECD framework for "blended finance" to STI finance



Source: Adapted from OECD Tri Hita Karana Forum on Blended Finance, http://www.thkforum.org (accessed 15 October 2020).

One example of such a framework is Deutsche Bank's Universal Green Energy Access Programme (UGEAP), which typically becomes involved when public actors provide a "first-loss" facility that buffers private investment. The UGEAP is, for example, active in African countries, where it contributes to universal electricity access. Another example is the European Investment Bank's recent Malaria Fund initiative to develop a cure.

Many schemes in development finance use these concepts to finance green technologies, agriculture technologies and health technologies when a private-only finance model does not work owing to market failures. However, fewer schemes seem to have been established (so far) to finance riskier technological innovation that requires a portfolio of projects. Combining private and public sources of finance is not new in STI, and risk-reduction schemes for private partners typically comprise grants or subsidies. Ultimately, blended finance implies an equal sharing of risk through joint positions regarding return on investments, and risk profiles and positions may be designed differentially according to project specificities (Remøe, 2020[24]).

Geopolitical developments and their impact on international STI co-operation

Although COVID-19 has led to greater calls for international co-operation, it has also led countries to reassess their reliance on global value chains – especially for essential goods – and consider national actions to strengthen their citizens' access to critical technologies, goods and services. This goal can appear in contrast with the GPG paradigm for international co-operation, where cross-border public R&D investments are a way to invest in a country's own national security and economic and technological development.

Indeed, efforts to mobilise national funding for projects related to global challenges can create tensions between the design of programmes to benefit national taxpayers and the realities of international economic and technological interdependence. Policy makers face strong (and understandable) pressures to ensure that foreign universities or firms are not taking a "free ride" on public R&D investment, with concerns expressed about subsidies, trade-related investment measures and IPR, to name only a few (see Chapter 4).

However, the response to these pressures often consists of increased restrictions on international scientific and technological co-operation, international researcher mobility and technology exports. Such measures may be counterproductive, especially if other countries can supply technology, as well as higher education and research opportunities to foreign students. Moreover, foreign firms can easily shift production to lower-cost countries to avoid trade tariffs, and can always acquire firms in foreign markets to diversify their production.

To balance the benefits and risks of international co-operation, governments will need to revamp the international rules for technology exchange and international STI co-operation, allowing allow them to rebuild trust, and find common and shared values. One such rule involves the notions of mutual benefit and reciprocity that have long guided international relations. Mutual benefit and reciprocity play out differently in research collaboration than they do in collaboration on innovation that is closer to the market. Concerns and even frictions between countries over "reciprocal access" to one another's innovation systems have been growing, including over access to soft and hard research infrastructure (e.g. skilled personnel, open-science and open-data systems), as well as to technology markets.

Scientific integrity and academic freedom in international scientific co-operation is another issue, which has normally been the domain of scientific academies and universities. Governments increasingly seek to promote a common understanding of these values as a way not only to ensure a level playing field for co-operation, but also to limit the risks to scientific co-operation, such as fraud or theft of intellectual property or research data.

Of course, public policies are just one element of the "national innovation systems" of OECD countries. The performance of these systems within the most advanced economies depends on the actions and decisions of business enterprises. For example, new policies that allow greater scrutiny of mergers and acquisitions to protect national interests have led to stronger controls on inward investment in "strategic sectors". Concerns over access by one country's firms to another country's technology base may be well-founded, but their resolution is likely to be slow because firms operate globally.[14]

The role of international organisations

International organisations have a role to play in helping link national investment strategies to global challenges. In the COVID-19 context, the WHO continues to lead the international response to the immediate health crisis (see Box 5.2), for example, through the ACT-Accelerator (see Box 5.3). As part of the OECD's strategic response to the COVID-19 pandemic,[15] the Committee for Scientific and Technological Policy (CSTP) has created a policy platform, the STIP COVID-19 Watch, to monitor and collect information on countries' responses to the COVID-19 crisis around a core set of issues, including scientific advice arrangements, promotion of R&D collaboration, and the STI content of economic stimulus packages (OECD, 2020[25]).

The EU has similarly been active on the STI policy front through its ERAvsCorona Action Plan (European Commission, 2020[26]) launched in April 2020 that sets out key measures to co-ordinate, share and jointly increase support for research and innovation to address COVID-19, in line with the objectives and tools of the European Research Area. The United Nations has also mobilised its agencies to contribute to the UN Research Roadmap for the COVID-19 Recovery.[16] The Roadmap articulates five research priorities for each of the five pillars identified in the UN Framework for the Immediate Socio Economic Response to COVID-19. The UN Roadmap aims to guide global research efforts, minimise research gaps and duplication, and foster partnerships in order to accelerate progress toward the SDGs. The UN initiative on STI Roadmaps for the SDGs is an another example of a policy exercise aiming to help member states engage multiple stakeholders, including development aid agencies, economic ministries and STI ministries, to align investments and policies to direct and scale up support for the SDGs (Box 5.3).

Box 5.4. STI Roadmaps for the SDGs as a tool to support international STI co-operation on global challenges

As part of the Technology Facilitation Mechanism (TFM), the United Nations' Inter-agency Task Team (IATT) has been working towards developing STI Roadmaps for SDGs as a tool to strengthen international co-operation on global challenges. STI for SDGs Roadmaps can help align national STI policy agendas with the SDGs, and develop new instruments and partnerships for international STI co-operation on global challenges in both developing and developed countries. The evidence suggests that the most effective collaborations are aligned with the domestic policy agendas of key partners.

The STI for SDGs Roadmaps are based on the following pillars:

- Pillar 1 – Building up national STI capabilities to address the SDGs: focus on strengthening national STI capabilities, mostly in developing countries, to address challenges underpinning the SDGs; any well-functioning national innovation system needs to be connected internationally.
- Pillar 2 – Boosting international knowledge and technology flows for the SDGs: focus on expanding international flows of relevant knowledge and technology across countries, and supporting cross-country STI collaborations addressing the SDGs.
- Pillar 3 – Brokering international STI collaborations for the SDGs: focus on brokering international collective STI actions aiming to tackle global challenges, notably GPGs.

The work of the United Nations Interagency Task Team on Science, Technology and Innovation for the SDGs Roadmaps illustrates the potential benefits of policy roadmapping. In particular:

- Donor countries can improve policy coherence by streamlining challenge-oriented STI policies with ODA.
- Developing countries can co-ordinate and synergise STI-related efforts among ministries, international partners and key stakeholders.
- Countries, international organisations and key partners at the global level can engage in concerted analytical and facilitation efforts to share knowledge and experience, disseminate and apply good practices, and design new or improved mechanisms.

- Scientists need to be mobilised around the globe through international collaborations (e.g. the Intergovernmental Panel on Climate Change of the United Nations [IPCC]) focused on orchestrating and conducting collective actions to co-develop and deploy innovations at the adequate scale to achieve transformative impact.

Source: United Nations (2020[27]), *Guidebook for the Preparation of STI for SDGs Roadmaps*, https://sustainabledevelopment.un.org/content/documents/26937Guidebook_STI_for_SDG_Roadmaps_final_Edition.pdf.

Outlook for international STI collaboration

Despite the various restrictions brought about by the COVID-19 crisis, the immediate response of the international scientific community gives rise to optimism that international co-operation remains strong and will continue to advance. The response also generates hope that STI co-operation for grand challenges and GPGs can finally become a core objective of the scientific community, alongside advancing knowledge and the scientific frontiers that have characterised much STI collaboration in the 20th century. Such a shift will not be straightforward, and will require scientific institutions to adapt by placing more value on challenge-driven, transdisciplinary research than is currently the case (see Chapter 3).

The collective action to combat COVID-19 provides some useful lessons and new approaches for enhanced global STI co-operation. Governments need to take bolder initiatives to increase support to STI co-operation for both grand challenges and GPGs. R&D preparedness to manage numerous potential global crises besides human-disease pandemics should be a leading policy priority. The speed with which research groups and biopharmaceutical firms are developing COVID-19 vaccines builds on years of basic research investment, as well as the recent institutionalisation of international co-ordination efforts (in the form of CEPI and its partners) to develop agile technology platforms that can be activated as new pathogens emerge. Although these relatively new arrangements are performing well, they are underfunded and dependent on a handful of countries and philanthropic institutions for financing. Pending discussions among governments and other stakeholders, they could be scaled up and extended to other areas where R&D preparedness for crises is important, capitalising on the momentum from the response to COVID-19.

Many global grand challenges do not present themselves in the same way as a pandemic. Global challenges like climate change and biodiversity loss are "slow-burning" crises that can only be tackled through international STI collaboration. This chapter has argued for a new paradigm of international STI co-operation. It has shown that elements of such a paradigm are already in place, but need to be consolidated and reinforced. In particular, governments need to work together on new financing and governance mechanisms, wherein business and private-finance actors work with multilateral and national development banks to co-finance STI solutions for global challenges and GPG problems. The rapid and unprecedented mobilisation of public and private R&D funding for COVAX has demonstrated that new innovative funding models can be deployed to address global challenges through international STI co-operation.

Effective and transparent multilateral institutions and programmes have a role to play in this new paradigm. Programmes such as the International Clinical Trials Registry Platform are helping countries share information and data on COVID-19 vaccine trials. Existing international organisations and research infrastructures (see Chapter 2) are being mobilised to analyse data on the coronavirus and provide solutions to local research teams in diverse areas, from diagnostics to medical equipment. In time, new institutions (or new mandates for existing institutions) will be needed. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services is an example of a fresh intergovernmental initiative to protect biodiversity.

Government responses to the COVID-19 pandemic highlight the importance of national politics, leadership and values in influencing international STI co-operation (Cohen, 2020[28]). Governments will need to balance national STI priorities and goals with the need for internationally co-ordinated action to address the grand challenges and GPG problems. Without such collective action, the capacities to deal with them – in the form of scientific knowledge, technology platforms and international co-ordinating institutions – will remain underdeveloped, leaving countries more exposed to global shocks.

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Notes

[1] Much of this growth has been enabled by the increased mobility of researchers and the growth of science in middle-income countries.

[2] https://www.gisaid.org/.

[3] https://www.covid19dataportal.org/.

[4] If taken together, the European Union is the second largest contributor to the scientific literature on COVID-19. It also has almost the same number of co-authored papers as the United States – 16 483 in the first 11 months of 2020, 77% of which were domestic co-authorships, compared to 16 964 in the United States, 84% of which were domestic.

[5] https://www.bmbf.de/de/karliczek-unsere-foerderung-ebnet-der-impfstoff-forschung-gegen-covid-19-den-weg-12729.html.

[6] The ACTIV website lists the following companies as participants: AbbVie, Amgen, AstraZeneca, Bristol Myers Squibb, Eisai, Eli Lilly and Company, Evotec, Gilead, GlaxoSmithKline, Johnson & Johnson, Merck & Co., Moderna, Novartis, Novavax, Pfizer, Rhythm Therapeutics, Roche-Genentech, Sanofi, Takeda and Vir Biotechnology.

[7] The R&D Blueprint was subsequently updated in 2017. See https://www.who.int/teams/blueprint/about.

[8] The European Union is a major funder of COVAX.

[9] After China joined COVAX in October 2020, the only large countries remaining outside of the facility at the end of 2020 are the United States and Russian Federation.

[10] In an advance market commitment (AMC), buyers commit in advance to purchasing a specified volume of a health technology still in development at a guaranteed price and if it meets specific criteria. Thus, AMCs not only incentivise R&D, but also the production and delivery of the final product, because funds are only disbursed upon its purchase. Once the guaranteed volume is purchased, the manufacturer is contractually obliged to supply further volumes at a lower price. A two-stage pricing system is therefore in place: one relatively high price, guaranteed up to a fixed volume purchased, which provides a risk-adjusted return to the R&D investment made by the producer; and a second, lower price, set at a level closer to the cost of production (the "base price"). Criteria specified in the commitment include technical requirements such as the disease to be prevented or treated, the target population, minimum efficacy, dosage, route of administration, storage, and quality and safety requirements. AMCs can also specify conditions for procurement, licensing of IPR and affordability or access (OECD, 2020[15]).

[11] The funding will be used to support the procurement of safe and effective COVID-19 vaccines for 92 AMC-eligible countries, which include all economies with a gross national income per capita under USD 4 000.

[12] According to the CEPI website, "Wave 2 vaccines are candidates in early stages of development that offer scientific, technical or manufacturing differentiation compared to candidates currently in advanced development. They will be selected based on characteristics that could make them particularly suitable for use in specific target populations – such as older or immune-compromised individuals, or pregnant women – and also in low-resource settings where logistical challenges can make the use of certain vaccine approaches more challenging. The selection criteria include potential to protect from COVID-19 after a single vaccine dose, temperature stability, manufacturing scalability, improved or differentiated immune response, and the use of different antigens. Vaccine candidates in the Wave 2 Portfolio will be subject to global access commitments which will require vaccine output funded by CEPI's investment to be made available for procurement and allocation through COVAX." (CEPI, 2020[30]).

[13] Elinor Ostrom made a vital contribution to thinking on public goods by focusing on subtractability of the resource units, which allowed her to distinguish between public goods and common-pool resources (CPRs). CPRs are "a natural or man-made resource system that is sufficiently large as to make it costly (but not impossible) to exclude potential beneficiaries from obtaining benefits from its use" (Ostrom, 2015[29]). Whereas crowding effects and overuse problems are irrelevant for public goods (e.g. weather forecasts), they are chronic for CPRs, where overconsumption can lead to temporary or permanent negative impacts on man-made structures or biological resources.

[14] Similarly, global firms can tap into R&D tax credits in one country but choose to operate production in other countries for competitive reasons, depriving the country offering the tax subsidy of broader economic returns.

[15] https://www.oecd.org/coronavirus/en/.

[16] https://www.un.org/en/pdfs/UNCOVID19ResearchRoadmap.pdf.

6 Why accelerate the development and deployment of robots?

Robots are an iconic technology of the digital era, whose sophistication and diversity are growing rapidly. Autonomous vehicles, drones and automated vacuum cleaners are all widely known. Laboratory robots; collaborative industrial robots; ocean-going, space-faring, search-and-rescue robots; and robot surgeons, among many others, are less widely known. Progress in robotics is essential to make life easier, cleaner, healthier and richer. Robots have also aided the response to COVID-19, but their potential to help manage a range of crises is just beginning to be tapped. Robotics could play a major role in healthcare, increasing the resilience of health systems. Their role in combating future waves of the virus, or entirely new contagions, should be recognised and supported. Governments should scale up investment in research and development for robotics, support the wider diffusion of robots, and develop standards and innovation-friendly regulation. This chapter examines frontier developments in robotics, emerging applications across society and the diverse impacts of robots. Governments can use a number of tools to accelerate the deployment of socially valuable robot systems. They should act now.

Key findings

- **Robots can help to combat infectious disease and increase the resilience of health systems. In some applications, like elder care, better robots are likely to become essential. But good policy is needed to realise these aims**. Governments should: create a portfolio of targeted innovation prizes, which have features well-suited to advancing robotics; deploy tools such as regulatory sandboxes to help companies adapt to a particularly complex regulatory landscape; accelerate deployment of existing robot solutions in health systems, for instance by providing platforms that highlight leading-edge solutions; help develop and share useful data for training AI-enabled robots, especially in niche applications where data samples are small; and support the development of healthcare innovation hubs that bring together healthcare providers, research and academia, industry and regulators.
- **Despite often negative public perceptions, robots could make life richer, healthier, safer and easier, and governments can do much to accelerate these beneficial outcomes**. Governments should: invest in the R&D needed to solve widely identified research problems; help to broker and support public-private research partnerships, and support technology transfer; support robot uptake in firms, especially SMEs; deploy tools such as test-beds to help companies de-risk investments; facilitate SME participation in standards processes; and support digital connectivity, particularly 5G broadband.
- **Over time, advances in robotics could increase many aspects of societal resilience – from responding to the effects of natural disasters, to coping with population ageing**. To this end, governments should: encourage innovation in education and training initiatives; increase awareness in government of the current and potential uses of robotics – which will also help prepare for more effective uses of robots in future crises; advance research in systems for protecting and operating critical infrastructures and for crisis response; adopt a positive stance on the role of robots in advancing the public good; and, strengthen the security of cyber-physical systems.

Introduction

This chapter examines frontier developments in robotics and the applications of robots across the economy and society. It considers robots' diverse impacts, and the science and technology policies that can focus these impacts for maximum social benefit. It pays particular attention to the roles of robots in healthcare. These include laboratory robots, robot surgeons, robots that help reduce injuries to nurses (which exceed those of any other class of manual worker) and robots that assist people with autism spectrum disorder. Robots have so far played a minor role in the COVID-19 pandemic, and their uses in health systems are far below their potential. This reflects general unfamiliarity with potential robot applications, the high cost of leading-edge robot systems, institutional inertia and the incipient nature of some uses. Low wages, especially among care workers, also discourage investments in assistive robots. However, with suitable policies in place, robots could provide significant support in addressing future crises – including new contagions – while increasing the overall resilience of health systems and society.

The promise of robotics

Robots are an iconic technology of the digital era,[1] sitting at the centre of many topics in science and technology policy. Advances in many fields of science, digital technology and artificial intelligence (AI) are increasing the sophistication and diversity of robots. Their development and future impacts will be shaped by policies on basic and applied research and development (R&D), as well as taxation, public-private partnerships, technology diffusion, regulation and legal frameworks, technical standards, and digital connectivity and security. Indeed, some major recent advances in robotics trace directly to public policy, such as the challenge prizes run by the Defense Advanced Research Projects Agency (DARPA) in the United States.

The economic and social impact of robots is expected to increase greatly in coming years.[2] With the exception of surgical robots, exoskeletons and advanced prosthetics, and systems to aid rehabilitation, most robots used in healthcare today serve relatively simple functions, such as delivering medicines and transporting waste. Wider diffusion and more sophisticated applications will be spurred by advancing technologies. Among many current developments, cell-sized robot prototypes can traverse the body's circulatory system, gathering information and downloading it after a task is performed; using AI and cameras to precisely apply nasal swabs, a newly developed robot can improve sample quality and lower infection exposure for nurses; and robot surgeons are set to provide human surgeons with feedback during operations. If more lethal or contagious pathogens than COVID-19 arise in the future, new robot systems could confer greater resilience on society as a whole. They might, for example, operate essential services such as waste treatment, power generation and public transport, which in the current crisis have only functioned thanks to risk-exposed workers.

Robots also occupy a unique place in the public imagination. Humans react differently to objects in physical space than to objects on screens. Experiments show that people unconsciously treat robots as if they were human (Fussell et al., 2008[1]).[3] As robots come to possess more social attributes than current systems, how they are used, and how people interact with them, is set to change in possibly surprising ways. Autonomous vehicles, drones, vacuum cleaners and lawn mowers are all widely known. Less familiar systems include laboratory robots; collaborative industrial robots; ocean-going, space-faring, and search-and-rescue robots; and robot surgeons.

Robots also represent the most significant interface between AI and the physical world. Developments in both fields have been deeply intertwined. Advances in machine vision and AI were initially spurred by the goal of better robot navigation; in turn, robots served as platforms for demonstrating more capable AIs. Some consider that robots provide the best setting for tackling some crucial challenges of AI research. They argue that using AI in systems with a human-like form is more likely to allow research to find how to create AIs with human-like attributes, such as “common sense”. At the very least, the so-called “Moravec paradox” – that robots often easily do things that humans find difficult, and vice versa – points to fertile terrain for discovery. Beyond research, it is also through the actions of robots that many questions in AI governance will arise and require solutions.

Robots as a strategic technology

Some governments attribute strategic importance to robotics. Although national priorities vary, a common concern is the impact of robots on competitiveness. Because they are faster, stronger, more precise and consistent than workers, robots have vastly raised productivity in critical parts of the economy, such as the automotive industry. They will do so again in an expanding range of sectors and processes, as robotics advances.

Advanced robotics is also important to counteract sluggish labour productivity growth in many countries for the past decades. Progress in robotics creates global market opportunities, which some countries plan to supply. Accordingly, governments frequently voice concerns when leading robotics companies pass into foreign ownership, as openly expressed in a number of national robot strategies (e.g. in Japan and the United States). As Box 6.1 shows, the People’s Republic of China is perhaps pre-eminent in terms of its strategic ambition in robotics.

Box 6.1. China’s development of a world-class robotics sector

No country is more active than China in developing an advanced robotics industry. Among other measures, China has acquired established robotics companies abroad, with support from central and provincial governments. The acquisitions have often been esteemed German and Italian robot manufacturers and integrators (i.e. companies that assist others to deploy robots). Examples include Germany’s robot integrator KraussMaffei, acquired in 2016 by a consortium led by the state-owned China National Chemical Corporation, and the jewel in the crown of European robot manufacturers, Germany’s Kuka AG, acquired in 2016 by China’s home appliance maker Midea.

China’s National Development Plan for Robotics (2016-20) announced its goal of developing a domestic industrial robot sector technically equal to the leading international competitors, which would supply at least 45% of the domestic market, and expand production of robots for seniors and medical care.

A national robotics roadmap was prepared after the launch of the strategic manufacturing plan “Made in China 2025”, issued in 2015. It identifies key technologies and components for industrial and service robots; opportunities to strengthen co-ordination between research and application; and initiatives for standardisation, quality assessment and certification. In November 2016, China announced its first robot-certification scheme, and issued the first certificates. China has also become a leader in patent filings for robotics.

Compared to countries such as Japan and Korea, robot density in China is low. However, Chinese regions that lead in manufacturing mechanical and electrical products, such as the southeast provinces, have initiated large-scale “Robots Replace Humans” programmes. Many provincial governments also subsidise firms that buy robots.

Emerging robot capabilities

Robots are not a single technology. Rather, they embody combinations of technologies, some of which are developing faster than others. Some of the building blocks of progress in robotics include advances in sensors, such as laser systems with improved range and angle resolution; control systems, such as cloud-based robots and predictive control; actuators, such as dexterous grippers; and materials science, e.g. to help robots harvest energy from their surroundings.

Progress in manufacturing technology, such as laser sintering (a form of 3D printing) and micro-scale moulding, lowers costs and helps build more capabilities into robots. The proliferation of robot types and capacities also come from advances in basic and applied science. Neuroscience, biomechanics, materials science, computer science and mathematics are just some of the relevant fields. New fields, such as computational psychiatry, will also contribute to progress in robotics. Robots have even become tools of basic science in their own right, for instance, by helping to understand better how humans walk.

This section reviews some emerging developments in robotics. Many are recent research achievements or prototypes, which could be some years from commercial use. Others are just beginning to find commercial applications. These developments suggest the nature of future possibilities.

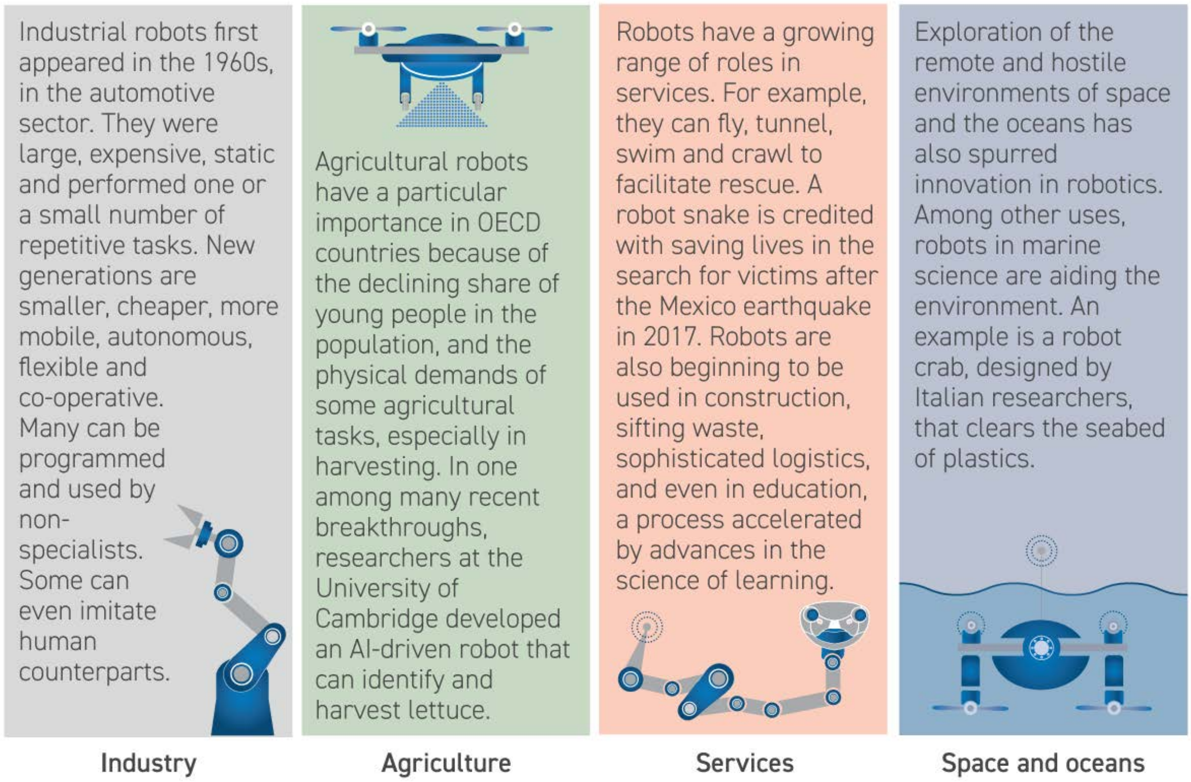
Soft robotics: until recently, robots were physically rigid. Advances in fields such as materials science, actuators (forms of motor that converts energy into work), sensing and modelling have produced an emerging class of deformable and compliant robots that can squeeze, stretch, climb, shape-change and self-heal (Terryn et al., 2017[2]). Research in soft robotics aims to further develop abilities to grow, evolve, self-heal and biodegrade (Laschi, Mazzolai and Cianchetti, 2016[3]). Many developments in soft robotics are inspired by examples from the natural world.

Miniaturisation: together with advanced fabrication, Moore's Law has helped engineers build ever-smaller robots.[4] In one of the most striking examples of miniaturisation to date, researchers at MIT recently built self-powered robots the size of a human cell. These robots are able to follow pre-programmed instructions, as well as sense, record and store information about their environment, gathering data that can be downloaded once a task is completed. While these robots are at the laboratory stage, potential uses exist in medical diagnostics and industry (Chandler, 2018[4]).

Increased intelligence: in the late 1990s, most robots possessed only insect-grade intelligence. Today, progress in AI, particularly machine learning, is revolutionising robotics. Combining AI with other innovations is conferring a myriad of new capabilities on robots, including greater autonomy. Major developments include better vision, learning transfer between robots and across robot swarms, learning in virtual environments, learning by doing, learning by curiosity, emotional awareness, better object manipulation and more collaborative robots ("cobots").

Thanks to these growing capabilities, robots have current and potential applications in many areas of the economy (Figure 6.1).

Figure 6.1. Current and emerging robot applications span the economy



Sources: Haridy (2020[5]), "Machine Learning helps robot harvest lettuce for the first time", https://newatlas.com/robot-harvest-lettuce-vegetable-machine-learning-agriculture/60465/; Hutson (2017[6]), "Searching for survivors of the Mexico earthquake – with snake robots", https://www.sciencemag.org/news/2017/10/searching-survivors-mexico-earthquake-snake-robots; Ridden (2019[7]). "Plastic hunting robot crab takes its first dive", https://newatlas.com/silver-2-plastic-hunting-robot-crab/60097/

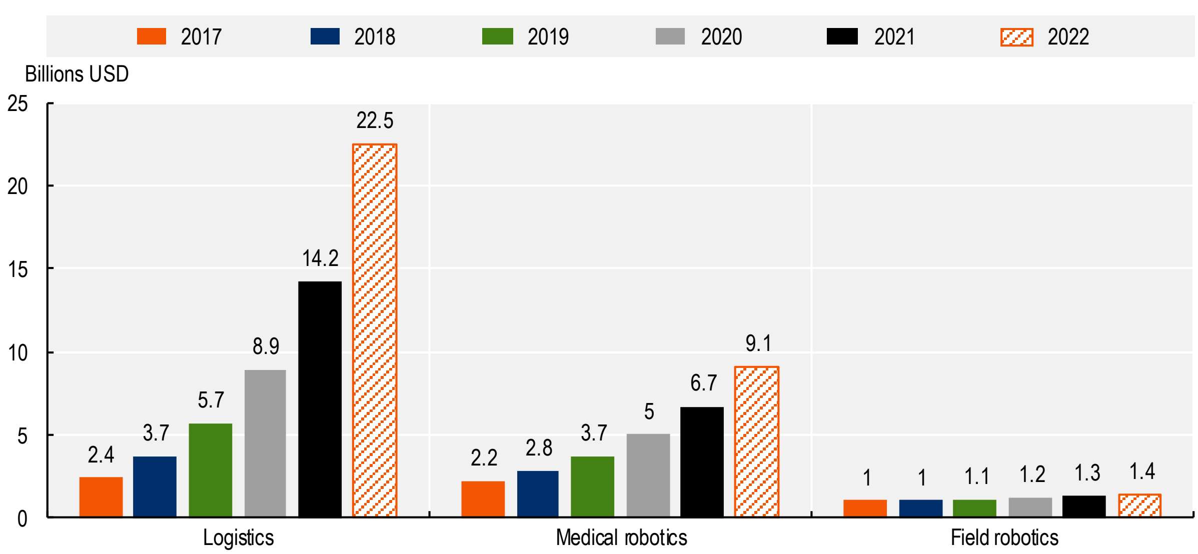
Robots and jobs

Machine-driven substitution of workers is the subject of a large and growing literature, which this chapter does not aim to assess. However, industrial robots – especially the more recent models – differ in important ways from other types of automation, such as computer numerical control systems. For instance, they can be reprogrammed and flexibly applied to diverse tasks. Atkinson (2019[8]) reviews the robot-specific research. He shows that many firm-level studies find only limited job destruction or loss of total hours worked attributable to robots. In some cases, significant increases in manufacturing employment are seen a few years after adoption, often because of increased product demand. When industrial robots are shown to have reduced the hours worked, this has applied primarily to low-skilled workers; the declines are less pronounced for workers with mid-level skills. Although little studied to date, robots in the health sector are unlikely to have major impacts on job numbers as they mainly augment the capabilities of health workers (e.g. by lowering injury risk), rather than substituting for them. The opportunity to work with robots might in fact make some health-sector jobs more attractive, especially among the younger population.

Current and emerging uses of robots in healthcare

This chapter pays particular attention to robots in healthcare, given the possible role of robots in ameliorating the current COVID-19 crisis or future outbreaks of infectious diseases. In 2018, global sales of medical robots reached USD 2.8 billion. Some 5 100 units were sold in 2018, a number that is forecast to rise to 19 700 units by 2022 (IFR, 2019[9]) (Figure 6.2). Robots have many roles in healthcare; some are well established, but others are just beginning to appear in health systems. Applications range from aiding laboratory research, surgery and physical rehabilitation, to delivering medicines, transporting waste, combating loneliness, and improving medical diagnostics and treatments. Moreover, by improving working conditions in many occupations outside of healthcare, robots can alleviate expensive medical problems, benefitting firms and society more broadly.

Figure 6.2. Global purchases and main applications of service robots for professional use, 2017-22



Note: Field robots are non-factory robots designed for unstructured and often dynamic environments on land, sea and air, e.g. in mining, agriculture and underwater exploration.
Source: IFR (2019[9]), World Robotics 2019, https://ifr.org (accessed September 2019).

StatLink https://doi.org/10.1787/888934223536

COVID-19 has focused attention on how robots might reduce infection risks and stress among frontline health workers. As the crisis escalated, leading roboticists wrote an editorial in *Science Robotics*, a journal of the American Association for the Advancement of Science, stressing the potential of robots to combat the COVID-19 pandemic and infectious diseases more generally. To enhance preparedness, the authors called on governments to target and fund multidisciplinary basic and applied science, bringing together scientists, engineers and infectious disease professionals to work in partnership with government agencies and industry (Yang et al., 2020[10]).

With a few notable exceptions, (e.g. surgical robots), most uses of robots in healthcare today are relatively simple (e.g. drones for delivering medicines). As technologies advance, broader diffusion and more sophisticated applications are set to emerge, potentially increasing the resilience of health systems to new diseases. Over a longer period, comprehensive use of robot systems in elderly care is likely to become essential as the global population ages.

The remainder of this section considers the main categories of robot use in healthcare, with an emphasis on COVID-19. It also highlights some of the existing challenges to progress.

Robots in the laboratory

Laboratory automation is increasingly essential in many fields of science. Robots have helped automate routine laboratory processes for some years. Today, AI-driven laboratory robots can go beyond this mechanical task, executing closed-loop cycles of testing, hypothesis generation and renewed testing. Hundreds of hypotheses can be generated and tested in parallel. Such systems can also automatically record experimental procedures and associated metadata, which are important for reproducing research. In 2009, "Adam", a laboratory robot developed by researchers at the universities of Aberystwyth and Cambridge in the United Kingdom, became the first such system to make an independent scientific discovery (concerning the genomics of baker's yeast). Such robots can greatly speed experimentation, e.g. by screening and testing thousands of pharmaceutical compounds per day. As well as contributing to research, laboratory robots have also helped accelerate testing for COVID-19. For example, the VIB-VUB Centre for Structural Biology in Brussels uses its KingFisher robot to perform an additional 1 000 tests per day (euRobotics, 2020[11]). On the downside, laboratory robots remain costly and difficult to use.

However, adding AI to robots is not enough to improve the entire process of laboratory testing, especially in a crisis. Greater flexibility in handling, combining vision, gripping tools, and grip sensing, is also needed. During the first wave of the COVID-19 pandemic, laboratories faced shortages of test kits, and medical practitioners sent patient samples in many types of containers, with no standardised shapes and sizes. Human dexterity was needed to handle, open and extract the samples for testing. Most automated processes could not have dealt with this variance. Some robot systems could have done this, but were not used owing to the high costs of installation, programming and peripheral sensing. This manipulation challenge is a generic problem in robotics and requires further progress.

Robots in patient screening and initial care

In the second quarter of 2020, during the first COVID-19 peak, patients arriving at Antwerp's University Hospital in Belgium were met by a robot that checked whether they were wearing masks, ensured these were properly positioned, screened for signs of fever and admitted those who could safely attend an appointment. The system, which speaks 35 languages, reduces crowding among waiting patients and lowers infection risk for staff (Parrock, 2020[12]).

Nasal and throat swabs are currently the standard for initial diagnostic testing for COVID-19. This requires qualified personnel, whose time is scarce when demand is high. In response, researchers have developed a fully automated robot that performs the delicate task of taking coronavirus swabs. Using AI and cameras to apply the swab precisely, it can improve sample quality and lower infection exposure for nurses (Filks and Skydsgaard, 2020[13]).

Researchers aim to achieve greater functionality for remote interaction with patients, such as through high-resolution cameras to measure pulse rate from the skin. Since drawing blood carries a high risk of exposure for medical staff, engineers are examining ultrasound imaging of veins for robotic venepuncture (Yang et al., 2018[14]). Assisting emergency medical technicians (EMTs) is even more challenging. EMTs perform complex cognitive and physical tasks, such as rapid assessment of a patient's condition or inserting breathing tubes. If AI-enabled robots could assist EMTs, more attention might shift to the most urgent procedures.

Robot surgeons

The first documented use of a robot assisting surgeons occurred in 1985, when a robot arm helped to biopsy neurological tissue. Surgical robots are now categorised under three broad types: active systems that perform pre-programmed tasks under human supervision; semi-active systems, where a surgeon complements an active system; and systems under a surgeon's sole control which precisely reproduce the surgeon's hand movements (Lane, 2018[15]). Most experts consider fully autonomous robot surgeons a distant prospect.

Several thousand prostate operations using minimally invasive robots are performed every year in the United States. The robotic procedures reportedly lead to shorter admission periods, fewer infections and faster recovery (CCC/CRA, 2009[16]). Robotic kidney transplantation is increasing at transplant centres around the world. The first surgery with the patient and the surgeon in different countries took place in 2001. Some systems allow the surgeon a physical sensation of what the robot touches. Non-invasive abdominal surgery, kidney surgery, orthopaedic surgery and neurosurgery are now all part of the medical robotics market.

To complement the work of surgeons, robots can be designed with more limbs, digits and freedom of movement than a human. They do not tire or get distracted, and they can operate with extreme and consistent accuracy. A new system, the Microsure Musa, developed for super-microsurgery, can even compensate for human traits such as hand tremor. Thus, robots may help to lower the frequency of preventable surgical errors.

The main challenge in surgical robotics is achieving greater autonomy. The predictability in which industrial robots work is not available to surgical robots. Vastly greater variation and uncertainty exist in patients' bodies and surgical needs, and in the actual implementation of surgical procedures. Beyond traditional but limited clinical decision-support tools – such as decision trees – engineers are attempting to integrate the most synergistic features of human and machine intelligence, with humans and machines collaborating to enhance *in situ* surgical decision-making (Loftus et al., 2020[17]). Among many other topics, research is examining how robot surgeons might learn from the human surgeon, follow the surgeon's gaze, share control of some steps in an operation, and even record and provide feedback to the surgeon.

Another research challenge concerns the clinical efficacy and secondary outcomes of robotic surgery. Claims of efficacy in some procedures are contested. In some circumstances, the need to reconfigure the robot's tools during surgery could lengthen the time spent by the patient under anaesthesia. Cost-benefit analyses on the use of surgical robots might also miss some variables relevant to a crisis like COVID-19, such as the value of treating patients with greater than usual speed when hospital beds are scarce.

Robotic exoskeletons

An exoskeleton is a hard or soft structure that fits around one or more body parts, affording physical support. Wearable exoskeletons, for instance, can reduce a surgeon's fatigue during long operations. Passive exoskeletons, which only give static support, are now complemented by active systems that amplify some aspect(s) of the wearer's abilities.

One use of exoskeletons is physical rehabilitation. Systems can interpret the kinetic properties of a person's movements, helping patients such as stroke victims perform therapeutic movements precisely. Some exoskeletons give performance and motivational feedback, adjusting the difficulty of therapeutic tasks. A notable recent breakthrough comes from the French Alternative Energies and Atomic Commission, which developed a brain-controlled exoskeleton that allows a subject with four paralysed limbs to walk, achieving control over arms and legs. This achievement stems partly from progress in "neurobotics", the study of the brain in conjunction with technology.

Robots in the supply chain

In a growing number of Chinese towns and cities, drones are being used to share information (over loudspeakers), spray disinfectant, deliver medical supplies and even take people's temperatures (using thermal imaging). Drones routinely fly to the centre for disease control in Xinchang County, traversing China's first anti-epidemic "urban air transport channel" (Cozzens, 2020[18]). Such systems could also help deliver medical supplies to remote regions. For instance, companies in the United Kingdom have partnered to deliver COVID-19 tests to a remote island off the Scottish coast. Drones could also be helpful in developing countries, where road coverage may be limited and/or roads are poorly maintained.

Autonomous hospital-delivery robots

Robots are freeing the time of hospital staff by autonomously transporting hazardous materials, laboratory specimens, medications and meals for persons in quarantine. Many hospital robots can respond to requests placed through touchscreen interfaces, performing tasks and returning independently to charging points. Robots are also being designed to perform tasks in hospital kitchens and pantries.

Robot disinfectors

Hospital-acquired (nosocomial) infections are a leading cause of death in OECD countries, also imposing major costs on health systems. Short-wave highly energetic ultra-violet (UV) light can destroy genetic material in bacteria and viruses. Robots using high-intensity UV light can disinfect frequently touched areas, creating more sanitary conditions, lowering the workload for hospital staff and reducing risk exposure compared to manual disinfection. In response to COVID-19, Bucharest Robots deployed a UV-based robot that disinfected a hospital space spanning 7 500 m^2 in just a few hours (euRobotics, 2020[11]). Robotic disinfection systems have existed for many years but are not yet widely deployed, partly because of their limited ability to navigate in uncertain environments, as well as detect and reach shadow areas. Progress in such areas is needed.

Micro-robots for drug delivery

There exist two main classes of medical micro-robots – man-made and bio-hybrid. In the man-made category, robots are just emerging that sense and record information about micro-scale environments in the body, and move under their own power. Bio-hybrid systems, for their part, integrate biological and man-made components (such as nano-tubes, nano-particles and micro-machines). The biological components have functionalities that complement the man-made parts. Bacteria, for example, can self-propel in ways that most man-made systems cannot, leading researchers to examine if bacteria swarms can be used to push man-made drug delivery devices. Bacterial micro-robots have been the main object of research in the field of bio-hybrid systems, and have begun to be used more widely in drug delivery.

Research priorities for micro-robotic drug delivery include developing biodegradable and non-toxic systems capable of high autonomy and intelligent targeting, catheter-based robot delivery near disease targets, monitoring and controlling of swarms of micro-robots, and therapies best suited for robotic delivery (Yang et al., 2018[14]).

Robots supporting mental health

Research has recently begun on robots and mental health. Loneliness is a growing problem in OECD countries, and the isolation felt by many during the COVID-19 lockdowns has itself created mental stress. Robot systems can diminish loneliness in some people. Research has shown that a robot speaking encouraging phrases can positively affect a subject’s mood and game-playing performance. Interaction with the PARO therapeutic robot – which looks like a seal – has improved the mood of dementia patients and reduced feelings of isolation (Robinson, Broadbent and MacDonald, 2015[19]).

Autism spectrum disorder (ASD), which affects around 1 in 160 children worldwide, is another target for research. For example, to study if they could improve social skills in children with ASD, (Scassellati et al., 2018[20]) took robots out of the laboratory setting, where experiments are usually brief, and into homes and longer-term interactions. The robots helped to teach social skills such as taking turns, seeing the perspective of others and making eye contact. The research showed that personalized therapeutic robotics could eventually aid parents and therapists and provide children with ASD with more comprehensive care.

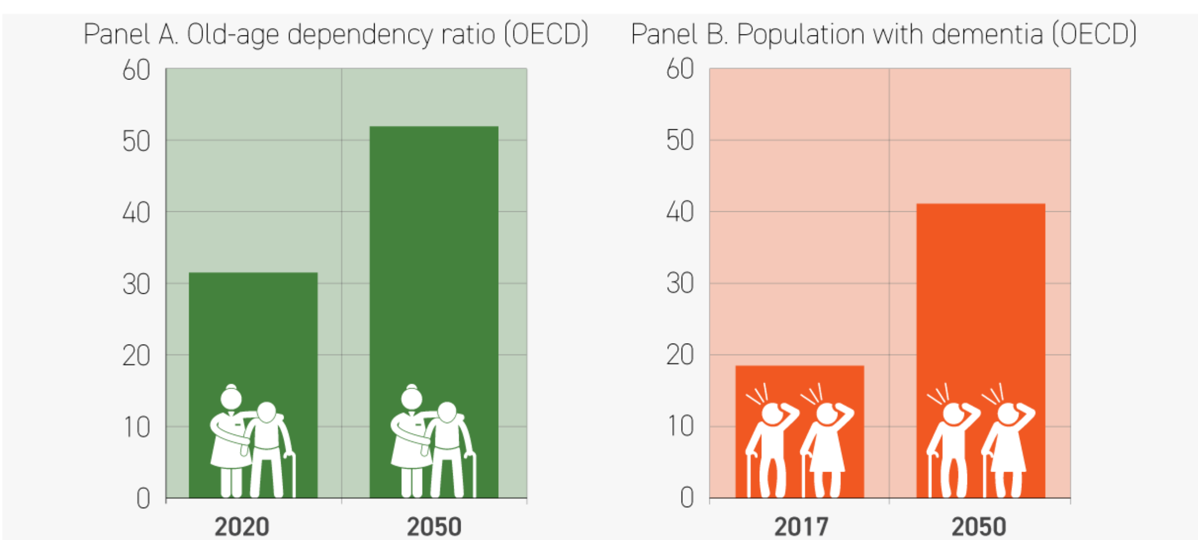
Research is needed to develop more effective social robots. Such robots would build and maintain multidimensional models of human counterparts, understanding more of what they know, believe, feel and intend, while also accounting for context (Yang et al., 2018[14]). Contributing to this goal, Canada's National Research Council aims to help develop robots that process emotional responses.

Robots in elderly care and nursing homes

Population ageing in OECD countries and the ensuing prospect of widespread age-related physical, cognitive and socio-emotional decline (Figure 6.3) have spurred interest in how robots might help. With the world's oldest population, Japan is the global leader in robotics for elder care. One priority is how robots might complement the caregiver workforce, which is projected to grow significantly. The United States alone could need 2.5 million additional long-term care workers by 2030 (Bryant, 2017[21]). Various companies make social robots for elder care. These perform basic non-medical tasks, such as reminding the elderly to take medications, while also providing cognitive stimulation and a form of companionship. A related development is systems that connect users to navigable mobile robots, allowing them to experience sights and sounds in the robot's environment. These systems, which provide telepresence, are proliferating thanks to their simplicity and wide range of uses, including helping convalescent or immobile patients interact with family members at home, young patients attend school and persons of any age visit museums. One drawback to such robots is their cost. Hence, some companies have developed simpler designs that interface with the user's own tablet computer.

Elder care raises particular challenges for robot systems. For instance, older people – especially the most impaired – interact with caregivers differently from younger adults. Robotic care for individuals requires better understanding and modelling of verbal and non-verbal communication between the elderly, human carers and robot systems. More research is also required on the outcomes of older persons' interactions with social robots. Another need is lowering costs while ensuring safety.

Figure 6.3. Increasing old-age dependency and growing share of the population with dementia



Note: In Panel A, the old-age dependency ratio is defined as the number of individuals older than 65 years for every 100 persons of working age (20 to 64 years).

Sources: OECD (2019[22]), *Pensions at a Glance 2019: OECD and G20 Indicators*, OECD Publishing, Paris, https://doi.org/10.1787/b6d3dcfc-en (Panel A); OECD (2018[23]), "Care Needed: Improving the Lives of People with Dementia", *OECD Health Policy Studies*, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264085107-en (Panel B).

Robots and public policy

This section examines selected public policies that are relevant to the development of robotics, and the use of robots in firms and public services (the full range of policies includes topics such as connectivity and cybersecurity, not covered here) (Nolan, forthcoming[24]). The section also considers options for governments to influence the direction of future developments in order to meet short- and long-term societal challenges. Several governments have national robotics strategies in place (Box 6.2).

Box 6.2. Examples of national robotics strategies

Led by China, Japan, Germany, Korea and the United States, all robotics-related strategies aim to increase applications in industry, with differences however in funding priorities.

Japan was the world's leading industrial robot manufacturer in 2018, delivering 52% of the global supply. Under the New Robot Strategy, the country increased its R&D budget for robotics to USD 351 million in 2019, with the aim of making Japan the world leader in robotics innovation.

Korea's Intelligent Robot Development and Supply Promotion Act focuses on the role of robots in advanced manufacturing. The country's 2019 Basic Plan for Intelligent Robots proposed targeting public and private support at promising areas of robot development and use.

The European Union's Horizon 2020 programme supports many fields of robotics R&D, including manufacturing, healthcare, transportation, agriculture and consumer technologies. The European Commission committed EUR 780 million (euros) over seven years, beginning in 2014. The European Union's 2018-2020 Work Programme includes funding for robotics in industry and core technologies such as AI and cognition, cognitive mechatronics, socially co-operative human-robot interaction, and model-based design and configuration tools.

The United Kingdom's 2020 Robotics and Autonomous Systems programme is a national strategy to capture value across the industrial and innovation system through co-ordinated development of assets, challenges, clusters and skills.[5]

Although the United States does not possess an overall industrial or automation policy, there have been efforts to develop national strategies for robotics, AI, drones and autonomous vehicles. The National Robotics Initiative (NRI) supports robotics R&D. NRI-2.0 focuses on cobots and encourages collaboration between academia, industry, non-profits and other organisations, in the same vein as the Advanced Robots for Manufacturing Institute and regional robotics clusters. At USD 35 million, the NRI budget for 2019 was relatively small.

Source: Demaitre (2020[25]), "Robotics R&D still driven by government initiatives worldwide, says IFR report", https://www.therobotreport.com/robotics-rnd-still-driven-government-support-worldwide-says-ifr/.

Interdisciplinarity in robotics research

Addressing research challenges in robotics requires interdisciplinary collaborations, for example among physicists, mathematicians, materials scientists, engineers and biologists, in both public and private-sector organisations. Policy needs to ensure robotics is not hindered by obstacles to cross-disciplinary research, such as hiring, promotion and tenure policies, and by funding systems favouring traditional disciplines (see Chapter 3). Ethical, legal and social implications of robotics, which are often hard to foresee, also need to be a part of research.

Robotics research needs public-private partnerships

The complexity of some research challenges may exceed the research capacities of even the largest individual institutions, necessitating a spectrum of public-private research partnerships (see Chapter 5). In terms of resources and focus, such partnerships can help create synergies between basic and applied research. Partnerships should also involve engineers, who usually play a major role in finding the best ways to implement robotic solutions. The Advanced Robotics for Manufacturing Institute (ARM) in the United States is one example of a research partnership model. ARM aims to create and deploy robotic technology by integrating industry practices and institutional knowledge across many disciplines, from materials science to human and machine behaviour modelling. Another example is euRobotics, the private-sector pillar of the Partnership for Robotics in Europe (SPARC). With EUR 700 million in funding from the European Commission over 2014-20 and triple that amount from European industry, SPARC is the largest civilian-funded robotics innovation programme in the world.

Support for technology transfer

Policy might also direct the trajectory of robotics development by providing targeted support for technology commercialisation. Many institutional settings affect knowledge transfer and commercialisation, from licensing and patenting arrangements, to the *modus operandi* of intermediary organisations (e.g. technology transfer offices). Policy should aim to optimise this ecosystem regardless of the type of technology. Where social priorities are urgent, however, technology transfer in specific fields might be facilitated. For example, a mobile disinfection robot was awarded the euRobotics Technology Transfer Award 2020.

Moonshots for robotics in society

Grants, R&D-based procurement and innovation prizes all have a role to play in tackling research “grand challenges” for robotics, and aligning robotics with societal needs. Public- and private-sector challenge prizes have played a prominent role in the recent development of robotics. In the United States, DARPA, the Office of Naval Research and the National Aeronautics Space Administration (NASA) have all run challenge prizes in robotics. From a policy perspective, challenge prizes are attractive because of the relatively small public investments involved: the NASA Space Robotics Challenge awarded the winning team a total of USD 300 000. Summed across all competitors, the R&D effort elicited by such a prize might dwarf the prize money. Moreover, competitions can help identify talented individuals and teams, drawing attention to ideas that deserve a second chance.

Challenge competitions in robotics could be envisaged for a range of major social goals, such as helping older adults to live longer and with more autonomy in their own homes. A portfolio of challenge competitions could also be considered for healthcare, and more specifically COVID-19 and infectious diseases. Some competitions could focus on critical safety and efficacy-enhancing tasks that cannot yet be performed by robots. Comprehensive consultation with health workers and other stakeholders might help identify and prioritise competition goals.

Diffusion of robots in healthcare

General unfamiliarity with the potential uses of robots, combined with the high cost of leading-edge robot systems, institutional inertia and the incipient nature of some applications, has constrained the application of robots in health systems. Low wages, especially among care workers, also discourage investments in assistive robots.

Among other steps, governments could examine how to accelerate the deployment of existing robot solutions, e.g. by providing platforms that highlight leading-edge solutions. The evidence indicates that public reporting of technology use by hospitals can accelerate the pace of adoption (Skinner and Staiger, 2015[26]). A high level of familiarity with robot technologies could have another positive consequence in a crisis situation, in that it could increase readiness to rapidly repurpose or innovate with currently available robot solutions. This might be quicker and more effective than relying on older robots stockpiled in preparation for a crisis. During the Fukushima disaster, for example, stockpiled robots were reportedly less suitable than routinely used commercial models. The specific capabilities (e.g. radiation resistance and advanced mobility) of older robots designed for interventions in nuclear facilities were outweighed by their slow speed and limited energy storage.

Education and training

Workforce skills are the most critical variable in an institution's ability to adopt new technology. Populations with broad and strong generic skills – i.e. literacy, numeracy and problem solving – are better positioned to acquire fast-changing technical knowledge. More specifically, some countries are rapidly developing curricula relevant to education and training in robotics at all levels. China, for instance, is developing robotics education tailored to primary schools.

Skill-related needs are also in flux. As robots are deployed more widely, demand will likely rise for roles such as "robot co-ordinators" who oversee robots and respond to malfunctions. Not all robot-related jobs are software jobs – many concern hardware. Training could help open such jobs to workers who possess mechanical skills taught in vocational courses. Many of the necessary skills do not require a four-year degree. Shorter courses could help, especially if delivered at scale. In the United States, for example, the intensive 12-week Rockwell programme trains and certifies underemployed veterans as instrumentation, control and automation technicians.

Regulation

Regulating robotics is an increasingly complex endeavour, owing to rapid technical change, growing robot capabilities and novel forms of human-robot interaction. For example, as intelligent robots become more widely used in care facilities or domestic settings, they might gather sensitive personal data, e.g. on religious or political views. Technically, such data could also be shared across robots, or with third parties (the OECD is currently working with independent experts to develop practical guidelines for implementing the OECD AI Principles; among other topics, it is examining how regulatory authorities can best address the challenges raised by AI).[6] Regulation has multifaceted goals, i.e. to provide producers with certainty, protect consumers and facilitate innovation. The aim is to create a regulatory framework that best balances all three goals. The space available in this chapter is not sufficient to review the differences across jurisdictions, the intricacies of legal scholarship and the comparative merits of competing legal proposals. Thus, this section only touches on some main challenges, drawing heavily on (Holder et al., 2016[27]).

An obvious concern is that the field of robotics changes faster than regulatory frameworks (see Chapter 8). While existing laws are often adequate to resolve potential legal disputes arising from the use of robots, some changes may be necessary. For instance, while it is now technically feasible for a surgeon to operate on a patient in another country, legal frameworks do not yet stipulate which country's laws would apply in the case of a mishap.

Another new issue regulation may need to address is the human-like appearance of some robots. If people unconsciously attribute an especially high degree of agency to humanoid robots, they might be less prone to question the instructions or behaviour of such systems. This could have implications for the protection of consumers, who might overly trust human-like robots and become more susceptible to misleading information. For the same reason, the safety of some critical systems could also be impaired when human operators deal with humanoid robots. Safeguards may therefore be needed in the future so that robots are not overly anthropomorphic.

A central question for wider robot use – and the insurance industry – concerns legal liability. The major legal conundrum relates to machine learning in the field. Today, if an unintelligent robot is programmed incorrectly and harms someone, liability lies with the user, not the robot manufacturer. In the case of robots with AI-enabled control functions, two possibilities exist:

1. The robot goes to school before being deployed, i.e. learning takes place at the manufacturer.
2. The robot learns during operation, including new tasks not imagined by the manufacturer.

The first option presents a technical challenge for manufacturers of AI-enabled robots as they ponder how to guarantee that the learning process will not produce unforeseen consequences, without testing the robot exhaustively in every situation. The second option may be simpler (provided the first option cannot be solved). Clearly, the manufacturer cannot be held responsible for the robot's actions if it does not control the environment in which it is used, the situations it learns from, and so on. A possible solution might be to certify a robot's baseline learned capabilities; once the user unlocks a learning process, however, the warranty is void.

Autonomy levels for road vehicles exists on a scale from 1 to 5. For medical robots, there exists no established definition of autonomy levels. Such a definition is more complicated to achieve: the range of tasks, working environments, technologies and risks to be considered is much greater than for road vehicles. Defined levels of autonomy effectively allocate technologies to different regulatory approval procedures, which vary in stringency, cost and time. A categorisation of autonomy for medical robots is necessary for the entire sector (Yang et al., 2018[14]).

It is also important to examine whether regulation hinders new robotic solutions. In a crisis situation such as COVID-19, regulation for some robot applications might justifiably de-emphasise risk avoidance and lower liability for innovators. A case in point could be regulations governing robotic delivery systems, which present fewer safety implications if a population is in lockdown.

Lastly, complex regulation can hinder robot adoption, particularly in small and medium-size firms, which typically lack teams specialising in regulatory compliance. Public programmes exist to help such firms deploy robots when regulation is hard to interpret.[7] However, a better solution would be to begin with a more amenable regulatory framework.

Conclusion

Progress in robotics could increase standards of living, quality of life and societal resilience, as well as strengthen healthcare systems. The potential of robotics is vast, but has only begun to be achieved. Governments possess a number of tools to accelerate the deployment of socially valuable robots. Support for both public R&D and public-private partnerships is essential, and the community of robot scientists and engineers broadly agrees on priorities (Nolan, forthcoming[24]). Policy makers can shape the course of future of developments to better meet challenges in areas such as healthcare, productivity growth, disruptive effects on labour markets, and new or increased skill needs. As with many digital technologies (even mature technologies such as cloud computing), the diffusion of robots across the economy and health systems is vastly below potential. This shortfall has a variety of causes, all of which can be influenced through public policy. As robots acquire new capabilities, they raise new policy issues, from privacy to legal liability. Robots can do more for society than is the case today, but active policy is a prerequisite.

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Notes

[1] The Oxford English Dictionary defines a robot in two ways. The first definition is "a machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer." Under this definition, smart phones are robots: they perceive something (through microphones, cameras and text input), and they act on their perceptions (putting appointments in calendars, sending money, etc.). The second definition – although the distinction between the two is not strictly technical – is "a machine resembling a human being and able to replicate certain human movements and functions automatically." This chapter focuses on machines that more closely accord with the second sense.

[2] As Colin Angle, co-founder of iRobot, the world's most successful consumer robotics company, recently put it, "we are just about none of the way to achieving the potential of robotics".

[3] When they first appeared, YouTube clips of Boston Dynamic's "Atlas" robot performing backflips and appearing eerily human went viral. In 2015, MIT demonstrated the quadruped robot "Cheetah" leaping untethered over obstacles at a speed of 23 kilometres per hour. Here again, the images were unprecedented and arrestingly lifelike.

[4] The term "Moore's Law" refers to a trend of exponential shrinking of transistors on integrated circuits, described by Gordon Moore in 1965.

[5] www.ukras.org.

[6] https://oecd.ai/.

[7] See, for example, the EU-funded COVR project (www.safearoundrobots.com).

7 Accelerating innovation to meet global challenges: The role of engineering biology

Life science innovation will be critical for addressing the major challenges of our time, from pandemics, through climate change, to transitioning to sustainable production systems. Synthetic biology, also known as “engineering biology”, aims to harness biologic processes to act as a platform technology across a wide range of key economic sectors. What is required to create the enabling conditions for the field, and how might the field contribute solutions to the complex problems we face? This chapter locates the challenges of the pandemic and sustainability, writ large within the landscape of key advantages and advances in engineering biology. Beginning with the “biofoundry”, these approaches to engineering practice promise to open up new opportunities for manufacturing. These span a wide range of sectors and products, whether new materials, greener chemicals or – most pertinent for this particular moment – diagnostics and vaccines.

Key findings

- **The COVID-19 crisis underlines the need to promote a mission of health resilience**, both on shorter and longer time horizons, requiring robust investment in health science and technology. Promising new technologies like engineering biology deserve consideration as a possible means towards the achievement of health resilience as a longer-term mission. The field's development could be driven through mission-oriented policies in order to assure alignment of technology development and the goal of health resilience.
- **Governments could establish and support pre-competitive infrastructure and collaborative platforms**, such as networked biofoundries and research consortia, by ensuring long-term and stable funding. Such research and translational infrastructures could de-risk private investment and accelerate commercialisation.
- **Collaborative platforms, built around biofoundries and other emerging technologies, can help deepen the engagement of broader society with emerging technologies**. In that context, the societal engagement of collaborative platforms with actors outside its innovation activities is becoming increasingly important. Maintaining levels of public involvement and engagement over the platform lifetime can build the mutual trust and social contract that needs to support the enterprise.
- **Governments should encourage the development of multidisciplinary environments and transdisciplinary skills to promote convergence**. Engineering biology extends beyond traditional discipline boundaries, drawing from engineering, biology, data science and physical sciences. Multidisciplinary environments are key to its success, and rely on people who can communicate across disciplines.

Introduction

The race is on to limit the effects of climate change by all available means. With around 70 000 derived products (Cayuela Valencia, 2013[1]), chemistry is the largest commercial enterprise on the planet, but is responsible for very large greenhouse gas (GHG) emissions. Moreover, the chemical and petrochemical industry is the largest contributor to industrial (fossil) energy demand worldwide (Griffin, Hammond and Norman, 2018[2]). The appeal of engineering biology lies in the fact that biological reactions require renewable carbon resources (e.g. sugarcane) as feedstocks and reactions occur at low temperatures and ambient pressures, requiring few energy inputs, in direct contrast to the incumbent fossil economy.

Engineering (or "synthetic") biology as a discipline of basic biology research started early in the 21st century (Cameron, Bashor and Collins, 2014[3]), and its applications to various branches of manufacturing were clear from the outset. The terms "engineering biology" and "synthetic biology" are now considered synonymous, even though practitioners see some nuances. If there is a difference, it is that engineering biology is an attempt to turn biotechnology into a discipline more reminiscent of engineering than biology, i.e. more sharply focused on industrial production.

The arrival of the COVID-19 pandemic has highlighted problems associated with society's readiness to deal with emerging viruses and pandemics, underscoring the importance of new biotechnology approaches. Indeed, COVID-19 may represent an opportunity for engineering biology to exert a tangible economic and social impact on health.

This chapter first examines the recent emergence of the new technology platform in engineering biology called the "biofoundry" – a promising new vehicle to speed up the development of useful constructs. The chapter then turns to the possible application of engineering biology and the biofoundry to vaccines and diagnostics, which are critically important in the context of the COVID-19 pandemic. While engineering biology has struggled to make an impact on liquid fuels and commodity chemicals (where the largest gains in GHG emissions reductions are to be made), there is hope that it could play a significant role in other fields. Third, the discussion reviews emerging trends in the development of bio-based products, from spider silk to encoding information using DNA. Finally, it sets out a suite of policy considerations that would prove useful for developing road maps and other policy interventions related to engineering biology.

The promise of biofoundries

The field of engineering biology has advanced rapidly in recent years (Opgenorth et al., 2019[4]), to the point where a Design-Build-Test-Learn cycle (DBTL) has emerged. This has been made possible by robotics and machine learning that can integrate and enhance human intervention (Figure 7.1). This cycle is encapsulated in the biofoundry, where many candidate molecules can be run iteratively through the DBTL cycle to quickly obtain an optimised candidate.

The technical challenges are many, but one of the greatest challenges for engineering biology is scale-up. The reasons lie with the technical details of biology: the feedstocks have to be dilute; the bioprocess is slow; and the products are also dilute, requiring considerable effort to concentrate and purify (Wu and Maravelias, 2019[5]). In chemistry, by contrast, the opposite is true: feedstocks are concentrated; reactions are fast; and products are concentrated, requiring less effort and cost to purify. For these reasons, biology will continue to struggle to compete with chemistry, particularly as the chemical industry is also rising to the challenge of sustainability (Horváth, 2018[6]).

Biofoundries are highly automated facilities that allow the co-ordinated use of laboratory robots. They are based on information infrastructures that enable programming robots and other equipment within the biofoundry to follow detailed, complex workflows (Chao et al., 2017[7]). Bio-designers are able to produce genetic constructs which, when placed in a cell (or chassis, such as *Escherichia coli*, or *E. coli*), act as an instruction set for the cell to produce other molecules that it would not naturally produce.

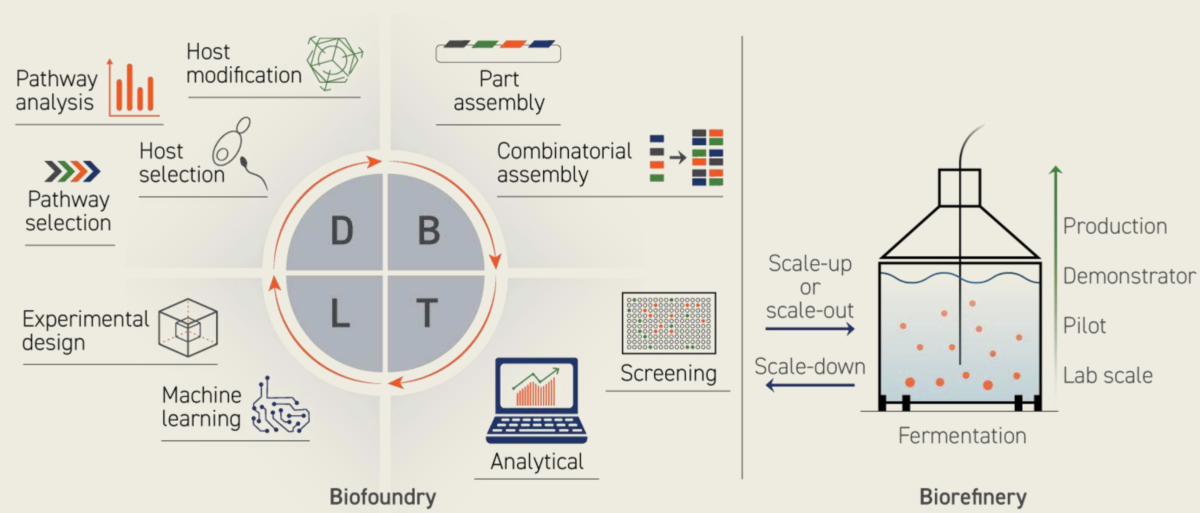
The hope is that biofoundries will greatly reduce the time from idea to product, and improve the reliability and reproducibility that have been lacking until now in biotechnology. One of the drivers of engineering biology is the aim to increase reproducibility so as to enable the quantitative precision required for modern manufacturing. Standards, automation and machine learning are key to the success of this approach, which is applicable to both research and industrial production (Box 7.1).

Box 7.1. How biofoundries work

Biofoundries rely on the ability to modularise gene constructs and then study the behaviour of the construct using a technique called "characterisation". Typically, a construct is characterised over several days, systematically following a workflow protocol. The workflow approach is designed to greatly increase reliability and reproducibility, with machine learning being key to speeding up the cycle. When a gene construct has been fully characterised, the process should be geographically transferable, thus building the link to distributed manufacturing. Many industrial bioprocesses have never had the biocatalyst optimised in any way to deal with the conditions of fermentation or maximise productivity. Thus, the biofoundry may represent a "missing link" in industrial bioprocessing.

The combination of bio-design tools and biofoundries is producing the digital biology that could revolutionise the manufacture of many desirable bio-based products. A feature of the biofoundry approach consistent with modern manufacturing is that the design site (the biofoundry) can be totally separated from the manufacturing site (typically the biorefinery).

Figure 7.1. The biofoundry's DBTL cycle

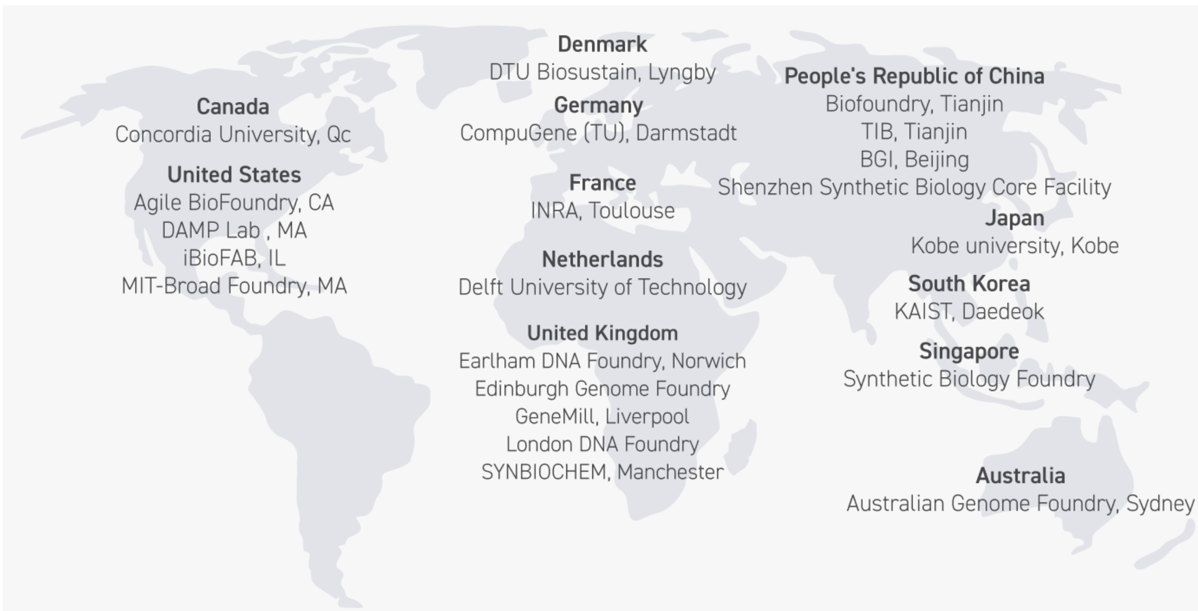


Note: The iterative DBTL cycle forms the core of the biofoundry. Biofoundries design DNA parts through computational methods and assemble those parts, prototyping and testing the performance of designs in living cells. These are followed by the application of machine learning tools to inform the design process. Iterations of the DBTL cycle result in genetic designs that aim to fulfil the design specifications.

The biofoundry as a public-private partnership

Biofoundries exist, albeit in small numbers (Figure 7.2). As with other areas of bio-based production, the private sector may not be willing to take the risk of building expensive infrastructure in the absence of supportive policy or a market in which the products can compete on price. To advance the diffusion of this technology, many biofoundries have been built using public support.

Figure 7.2. A limited but growing number of public biofoundries



Ideally, private-sector enterprises can interact with public facilities to advance their R&D capabilities, creating true public-private partnerships. When industry sectors come together to identify high-risk, capital-intensive fundamental research questions aligned with government priorities, high-impact partnerships can result, and major barriers preventing bioeconomy advances can be overcome. There exist relatively few working models for such partnerships, but the Agile BioFoundry (ABF) in the United States is an interesting example (Box 7.2). The ABF acts as a nucleus for developing industrial and innovation ecosystems for the bioeconomy. Some of the best-known synthetic biology companies in the United States have worked on projects with the ABF (Philp and Winickoff, 2019[8]). A biofoundry like the ABF is able to perform this function because it aligns perfectly with a central tenet of distributed manufacturing, namely, that much of the physical supply chain is replaced by digital information. Such infrastructure is expected to enable smaller (and even micro-scale) manufacturing much closer to the end user (Srai et al., 2016[9]).

Box 7.2. The Agile BioFoundry

The ABF is a facility of the U.S. Department of Energy (DOE). This public infrastructure investment totalling USD 20 million per year is designed to increase US industrial competitiveness while creating opportunities for private-sector growth and jobs. Any legal entity within the United States or abroad is eligible to use the platform, subject to DOE review/approval and the terms specified in the two primary contractual mechanisms governing the performed work: Collaborative Research and Development Agreements (CRADAs) and the Strategic Partnership Program (SPP).[1] The ABF operates under full cost-recovery accounting practices, meaning that collaborators pay for labour and laboratory consumables.

Interaction is strongly influenced by intellectual property (IP) arrangements, which are governed by the contracting mechanism (CRADA vs. SPP). For SPP projects, which are typically smaller in scope than CRADAs, a US-owned partner (such as a company) using non-federal funding to pay for the project can elect title to all project inventions. For CRADA projects, IP ownership follows inventorship. If DOE funding supports any of the work (i.e. "for DOE lab inventions"), the collaborator can choose between a six-month no-cost option on a royalty-bearing exclusive licence in a field of use, or an 18-month no-cost option on a royalty-bearing non-exclusive licence in all fields of use. The CRADA is non-negotiable. If no DOE funds are used for the project, the CRADA is negotiable, and the collaborator is offered the standard six-month option on an exclusive licence in a field of use.

It is possible, as part of CRADA projects, for companies to embed their employees within the ABF as they pursue the collaborative work. Non-governmental organisations and foundations may help co-ordinate activities (e.g. through the Global Biofoundry Alliance (Hillson et al., 2019[10])) and set the standards practised at the ABF (e.g. the Synthetic Biology Open Language).[2]

Potential applications

Vaccines

Despite several important outbreaks of viral disease during the first decades of the 21st century, the vaccine industry is being challenged. An important study (National Academies of Sciences, Engineering, and Medicine, 2020[11]) indicated that the amount spent by the United States on vaccines "appears to be insignificant compared with that spent on other medical and social interventions that may have lesser social benefits." Fixed costs for traditional vaccine production plants are very high. Even if there exists theoretically no shortage of a particular vaccine, there is every chance that there exists a shortage in the places where it is most needed – i.e. close to the location of disease outbreak. Transportation of vaccines often depends on a very robust cold chain, but many instances of cold-chain temperature failures have been recorded.

Engineering biology could present a useful set of tools in this context. Several COVID-19 vaccines either in current use or in late-stage clinical trials are messenger RNA (mRNA) vaccines, which are amenable to an engineering biology approach. The mRNA is specifically designed to produce the exact antigens required to counteract the target virus. Many prototypes can be designed and built in biofoundries. This approach presents a number of advantages. First, production/manufacture can be achieved directly in the laboratory, cell-free and egg-free. Second, instead of transporting a vaccine over a cold chain that often fails, it is digital information that is transferred to a small production plant close to where the vaccine is actually needed. Third and most importantly, speed is of the essence. (Ulmer, Mansoura and Geall, 2015[12]) described a proof of concept for the production of a self-amplifying mRNA influenza vaccine, from gene synthesis to formulation and release, in 13 days, which they anticipated could be reduced to 5 days.

Various existing non-commercial biofoundries offer an integrated infrastructure, including automated high-throughput equipment to enable prototyping biological testing standards and developing liquid-handling workflows for diagnostic testing of SARS-CoV-2 (Crone et al., 2020[13]). The biofoundry can also be applied to the design of certain vaccine types (Ulmer, Mansoura and Geall, 2015[12]).

Beyond the potential of engineering biology in vaccine design, it is also important to consider its use in design and optimisation of vaccine (and other viral vector) bio-manufacturing processes and cell lines to enhance production. Similarly, engineering biology has myriad applications in design and optimisation of cellular therapeutics, and their parallel manufacturing processes; this becomes important when considering point of care delivery of cell products.

In some sectors – particularly chemistry – replacing the economies-of-scale model is difficult, since great efficiencies have been achieved by centralised, large-scale manufacturing. In pharmaceutical production, however, there exist compelling reasons for the industry to scale down (National Academies of Sciences, Engineering, and Medicine, 2020[11]). An essential enabler is that many pharmaceuticals – especially biopharmaceuticals – do not respond to economies of scale. This is certainly true of vaccines: compared to commodity chemicals, they are high-value, low production-volume products. Simply increasing production volume would not translate into lower costs or prices.

The engineering biology approach also lends itself to the vision of so-called distributed manufacturing[3] in small facilities at many locations that might offer a more attractive production model. The combination of remote design facilities like biofoundries and small-scale production plants located as close as possible to the point of care makes sense in a world that needs to act much more urgently when threatened by new disease outbreaks and pandemics. The pharmaceuticals industry is, in fact, looking at ways to downsize: biopharmaceuticals do not respond to economies of scale in the same way that commodity chemicals do.

Distributed manufacturing could help "democratise" the responses to pandemics (National Academies of Sciences, Engineering, and Medicine, 2020[14]) and oppose the spectre of "vaccine nationalism" (Weintraub, Bitton and Rosenberg, 2020[15]). Vaccine manufacturers in developing countries already supply more than half of the vaccines used in developing-country immunisation programmes, so the capabilities exist. Implementing distributed manufacturing is a matter of political will and further diffusion of the relevant technologies.

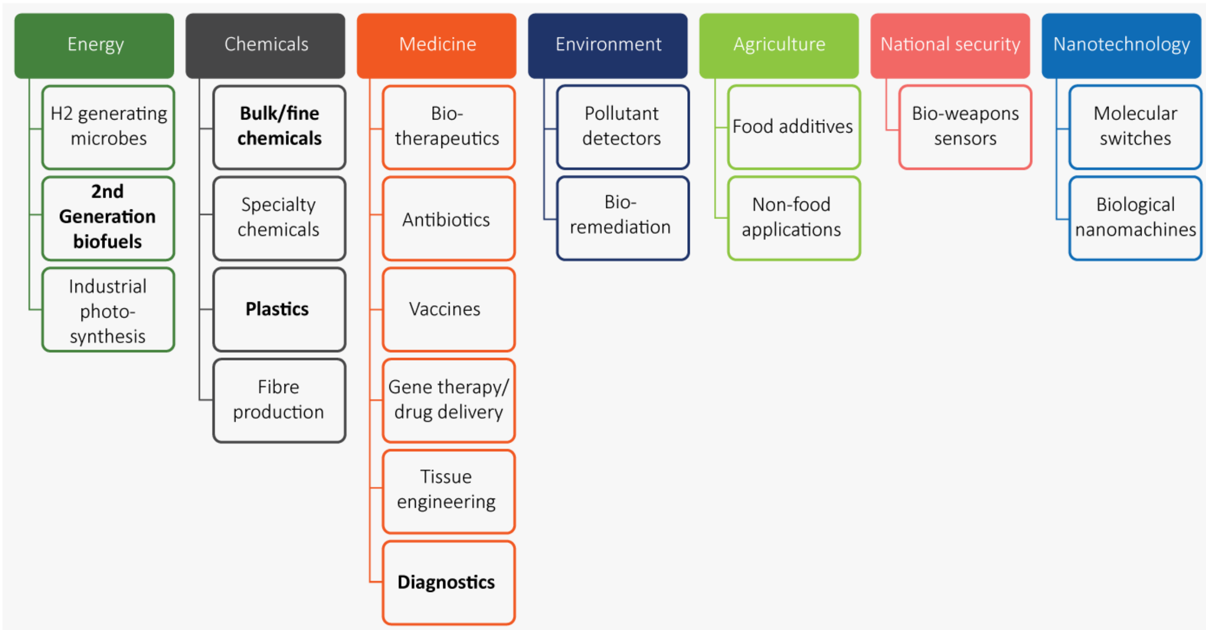
Diagnostics and medical devices

Beyond vaccines, the biofoundry/distributed manufacturing approach is also applicable to diagnostics and medical devices. The potential of the approach was demonstrated by (Crone et al., 2020[13]), who showed that an automated SARS-CoV-2 clinical diagnostics technical platform designed and developed in a biofoundry could be quickly deployed and scaled.

Other trends in bio-based products

Engineering biology partly owes its appeal to its ability to act as a platform technology across a wide range of the most important economic sectors (Figure 7.3). The need to reduce carbon emissions and fossil-fuel consumption also represents an opportunity for engineering biology to emerge as a service and manufacturing sector: by 2100, more than 95% of chemicals and polymers may need to be derived from renewable resources (Devaney, 2016[16]). Applications for engineering biology even exist in space: the National Aeronautics and Space Administration in the United States, for example, supports engineering biology to reduce the risks associated with space exploration (U.S. Government Accountability Office, 2018[17]). Back on Earth, engineering biology could be used to engineer microbes to produce targeted nutrients for human consumption, while bacteria could be manipulated to produce lightweight construction tools and materials. With this range of applications in mind, engineering biology needs to make the leap from a science-centred discipline to a field of engineering that incorporates modern paradigms of manufacturing.

Figure 7.3. Engineering biology: A potential platform in many important economic sectors



Note: applications in bold are those for which the earliest impacts have yet to be seen.

The shift from biofuels to higher-value bio-based products

Consistent with an alignment on sustainability goals, the earliest commercial scale efforts in engineering biology focused on producing liquid biofuels. Some high-profile initial public offerings targeting this area were launched in 2010-12, especially in the United States. Despite many research successes, these companies were unprepared for the magnitude of the task of bringing a liquid biofuel to sufficient scale to significantly influence the market for fossil fuels (Westfall and Gardner, 2011[18]). Further, there was much criticism about the sustainability of the feedstock used, and their impacts on carbon emissions.

"Second-generation" engineering biology companies have since emerged, targeting higher-value, lower production-volume products (Check Hayden, 2014[19]). The commercialisation of synthetic biology vanillin is one notable recent success. Used in many products, synthetic vanillin is typically produced from petrochemicals or chemically derived from lignin (wood pulp). The Swiss company Evolva created a genetically modified yeast that converts sugars to vanillin. It is the first major synthetic biology food additive to hit supermarkets, and others are in development. Flavours and fragrances can command prices ranging from USD 10 to USD 10 000 per kilogramme, compared with around USD 1 per kilogramme for biofuels.

New materials: Spider silks

The application of engineering biology to the development of new materials is a promising avenue for innovation. Spider silks, the sturdiest known biological materials, are an interesting example. They are stronger than steel and tougher than Kevlar® but also flexible, with a large range of applications. Spider silks are lightweight and virtually invisible to the human immune system, leading to "revolutionary potential" for medicine and industry (Babb et al., 2017[20]). Engineering biologists are interested in spider silks because they can be customised for different materials and applications. Among the newer potential applications of spider silk are microphones in hearing aids and cell phones. The German company AMSilk has entered into an agreement with Airbus to develop structural materials for aircraft using synthetic spider silk, and Adidas has developed a biodegradable shoe using this material. Silk also has high-value applications in cosmetics, and Givaudan has acquired the cosmetics business of AMSilk.

Adipic acid as a petrochemical equivalent

Whereas spider silk represents an entirely new industrial material, many of the products derived from synthetic biology are petrochemical drop-ins, i.e. bio-based, sustainable equivalents of an existing petrochemical. Switching to bio-based alternatives has proven difficult for a variety of reasons, including that many of these petrochemicals are produced very efficiently (although unsustainably, with large GHG emissions). A classic example is adipic acid, one of the most important small molecules in the modern chemicals industry and an intermediate in the production of nylon. Industrial production of adipic acid relies on fossil feedstocks and produces large amounts of nitrous oxide, a GHG that is 300 times more potent than carbon dioxide (CO_2). (Suitor, Varzandeh and Wallace, 2020[21]) described the first synthesis of adipic acid from guaiacol, a lignin-derived feedstock, in the biotechnology industry workhorse bacterium *E. coli*. Lignin is available in large quantities and is recalcitrant to many applications. It is effectively a waste product, and its conversion to adipic acid using synthetic biology keeps it in circulation, contributing both to the bioeconomy and the circular economy.

Green chemistry

Green chemistry and automated chemistry are obvious technologies for convergence with engineering biology. Automated chemistry is also developing rapidly, using the same principles as engineering biology, i.e. robotics, artificial intelligence and machine learning (Coley et al., 2019[22]).

A potential example of chemistry/biology convergence is graphene, which conducts electricity better than copper and will eventually find its way into consumer electronics. Electricity conductance and flexibility mean that graphene has a very wide range of potential applications, from energy-storage devices to lighting and displays, solar panels, tyres, bicycle frames and fashion items (Mertens, 2018[23]). For example, deformable graphene batteries with flexible, foldable, and/or stretchable capabilities are ideal for wearable and portable electronics (Ye et al., 2018[24]), and graphene may be the material of choice for 3D printable batteries. However, the cost of graphene has until now been much higher than mass-market applications can support.

Researchers at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia have created a new method of graphene synthesis, which involves heating cheap and available soybean oil in air until it breaks down into carbon-building units that are essential for the synthesis of graphene (Seo et al., 2017[25]). The CSIRO researchers demonstrated the versatility of the method by using other renewable carbon-containing materials, such as butter. It is conceivable that automated biology could produce the optimum bio-based feedstocks for this conversion, while automated chemistry would create graphene molecules for different applications.

Long-term data storage

By 2040, if all data were stored for instant access, the global data archive would consume 10 to 100 times the expected supply of microchip-grade silicon (Zhirnov et al., 2016[26]). Without radical change, a data crunch may be unavoidable. The storage potential of DNA is shown to vastly exceed the storage potential of all other media. In fact, it is estimated that all the world's data could be stored in one kilogramme of DNA (Extance, 2016[27]). At first sight, it seems far-fetched to store digital data in DNA, but this technology is already leaving research laboratories: companies such as Twist Bioscience are seriously engaging with DNA storage for research and commercial purposes.[4] Although currently expensive, storage costs are likely to drop as the customer base increases.

Emerging issues and policy implications

Several governments, notably the People's Republic of China, the United Kingdom and the United States, have invested heavily in engineering biology. To sustain such commitments, the engineering biology community needs to provide more examples of success in transforming ideas into commercial products and services (OECD, 2014[28]). Creating the enabling conditions for the development of engineering biology would require a range of policy interventions addressing specific issues along bio-based value chains, as well as more generic framework conditions. Among the most critical policy interventions in this area are those discussed in Figure 7.4, notably: developing a pre-competitive infrastructure and innovation ecosystem for engineering biology, addressing systemic business risk in bio-based value chains, ensuring the sustainability of feedstocks and supply chains, enhancing policy co-ordination, promoting public acceptance of these technologies and preventing potential digital-security risks.

Figure 7.4. A bioeconomy policy framework

FEEDSTOCK	TECHNOLOGY	INDUSTRIALISATION	MARKET
OBJECTIVES			
Stimulating availability of bio-resources	**Strengthen skills and technology base**	**Trigger investments in new manufacturing**	**Increased sustainability and value creation**
VALUE CHAIN SPECIFIC POLICIES			
Resource regulations and permits	Targeted R&D grant programmes	Public technology scale-up and pilot facilities	Product standards and norms
Transportation and logistics infrastructure	Specific education and training programmes	Financial support for first-of-kind (flagship) projects	Price subsidies and product tax policies
Feedstock specific trade regulations	Technology cluster and network support	Targeted government investments programmes	Product mandates and bans policies
GENERIC POLICIES			
Biomass sustainability assessment studies	Broad scope R&D grant programmes	Start-up and SME support	Sustainability labels and their communication
Governance and regulation efficiency	Tax incentives for applied R&D	Industry-oriented education programmes	Public awareness and acceptance campaigns
Waste management policies	Stimulate international partnerships	Techno-economic feasibility studies	Tax on CO_2 emissions
International trade agreements	Exchange programmes and apprenticeship	Private investment stimulating policies	Public procurement of bio-based products

Source: Ole Jørgen Marvik and Jim Philp (2020[29]), The systemic challenge of the bioeconomy: A policy framework for transitioning towards a sustainable carbon cycle economy, https://doi.org/10.15252/embr.202051478.

Pre-competitive public infrastructure

Perhaps the most pressing issue for governments today is to develop the basic pre-competitive infrastructure and innovation ecosystems for engineering biology. An interesting test case is the United Kingdom, which has invested since 2014 some GBP 350 million in synthetic and engineering biology infrastructure, comprising basic research centres, biofoundries and an industrial translation centre. Since then, around 180 engineering biology companies have been launched, and public investment has leveraged approximately a six-fold private investment.[5]

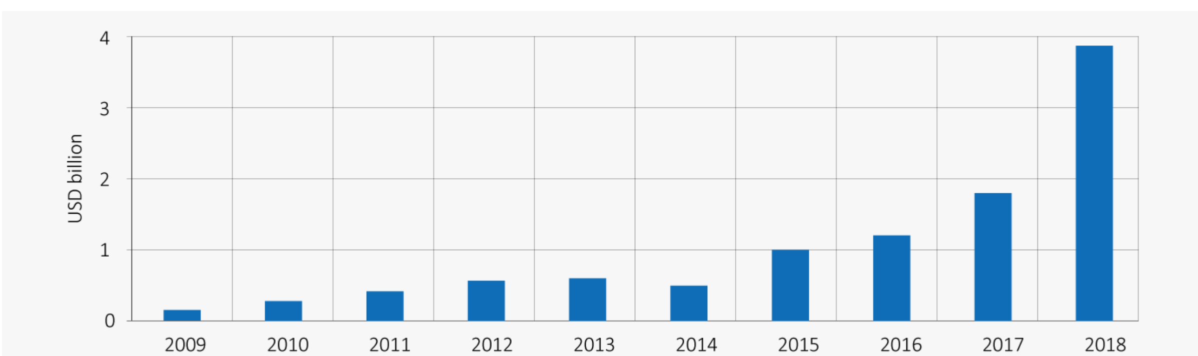
Business risks in the value chain

Bio-based value chains often find themselves in direct competition with fossil-based value chains. This represents a high hurdle, especially if bio-based products are to conform to the higher standards demanded by sustainability. Without attention to sustainability and carbon footprints, bio-based value chains will not be compatible with climate-change objectives.

Bio-based value chains are new and unproven. Although the technologies and ambitions of engineering biology are attractive, investors will look to the entire value chain. If weaknesses are apparent, from the feedstocks to the products and even beyond (e.g. end of life for bioplastics), investors may look elsewhere. This represents a "systemic business risk" (Marvik and Philp, 2020[29]). This risk is especially important in small countries: even small advanced countries can suffer from a lack of home-grown biotechnology, which has to be imported. Providing the public infrastructure described above is one way to address this, so that investors and the private sector are confident that a government is serious about promoting engineering biology in a sustainable manufacturing future.

That being said, global private-sector investments in synthetic biology have increased steadily year on year since 2009, with a significant acceleration in 2018 (Figure 7.5). Investments came from a variety of sources: established biotechnology firms like Bayer and Novartis, investment groups such as SoftBank and start-up accelerators.

Figure 7.5. Investments in the synthetic biology industry, 2009-18



Note: Figures for all of 2019 were not available. The investments for the first two quarters of 2019 showed a similar trend, amounting to just under USD 2 billion in total.
Source: Redrawn from Synbiobeta data, published in Cumbers (2019) https://www.forbes.com/sites/johncumbers/2019/09/04/synthetic-biology-has-raised-124-billion-here-are-five-sectors-it-will-soon-disrupt/#5f2492803a14 (accessed 14 September 2020).

The United States and the United Kingdom are the most prominent investors in synthetic biology start-ups, with over USD 12 billion invested so far (Clarke and Kitney, 2020[30]). To date, health-related biotechnology applications have dominated product commercialisation. Synthetic biology start-ups developing tools and services account for between 10% (in the United Kingdom) and 25% (in the United States) of private investment activity.

Around 20% of synthetic biology start-ups address industrial biotechnology targets, but they currently only attract around 11% in private investment, often due to the scale-up issue discussed above. While there exist some key technical barriers to scale-up, a number of policy interventions could help overcome some of the difficulties. (Clarke and Kitney, 2020[30]) cite the need for the various stakeholders to adopt a more networked approach linking specialists, infrastructure and ongoing research to de-risk the economic challenges of scale-up. If governments see this as part of the future of manufacturing, then an effective long-term funding strategy is needed, but one that addresses the outstanding scale-up issues. A promising field in this regard is cell-free synthetic biology as the presence of the microbial cell itself is responsible for some scale-up difficulties (Kelwick, Webb and Freemont, 2020[31]).[6]

Previous OECD work has highlighted that balanced measures on both the supply and demand side are needed in order to diffuse a technology (OECD, 2011[32]). Bioeconomy policies face this balancing act across diverse sectors, including industrial manufacturing, agriculture, forestry, marine resources and waste management. Many bioeconomy forums, including multiple OECD workshops (Philp and Winickoff, 2019[8]), highlight the need for a wide range of supply- and demand-side policies. Governments have traditionally preferred supply-side measures, yet demand-side measures, such as public procurement of bio-based products, would send strong signals to bioeconomy stakeholders.[7] This is not easy for various reasons. Public procurers are known to be cost-sensitive, and many bio-based products (such as bioplastics) still struggle to compete with their fossil equivalents on price. The United States Department of Agriculture (USDA) BioPreferred Program[8] is the only prominent example of a successful public procurement policy for bio-based products that specifies sustainability criteria. To date, the USDA has identified 139 categories of bio-based products for which agencies and their contractors have purchasing requirements. Each mandatory purchasing category specifies the minimum bio-based content for products within the category.

Policy co-ordination

All of the policy areas highlighted above need to be addressed to avoid value-chain weaknesses and failure. This is a whole-of-government issue that needs to be co-ordinated. A good approach might be to establish an independent advisory body, akin to the German Bioeconomy Council.[9] Such a body could help align diverse ministries and facilitate the interaction of government and industry. If a country possesses a synthetic biology or engineering biology roadmap, the advisory body could be asked to ensure that its milestones and deadlines are met.

Roadmaps themselves can also be used as policy co-ordination tools, although synthetic biology roadmaps are currently rare and have different intentions. Investments in centres of excellence and technology platforms, as well as in accelerating technology to market, are the most common steps being considered (Table 7.1).

Table 7.1. Most common recommendations from synthetic and engineering biology roadmaps

Recommendations	Australia	Finland	France	United Kingdom (2012)[10]	Engineering Biology Research Consortium (EBRC, 2019[33])[11]	European Union	(Le Feuvre and Scrutton, 2018[34])
Centres of excellence / technology platforms	✓		✓	✓	✓	✓	✓
Education/training	✓	✓	✓	✓		✓	✓
Safety/security regulation/governance	✓		✓	✓		✓	
Acceleration to market	✓	✓	✓	✓	✓	✓	✓
Public/stakeholder engagement	✓		✓	✓	✓		
International aspects	✓	✓	✓	✓		✓	✓

Public acceptance

Another important, but often overlooked, issue is public acceptance (OECD, 2017[35]); see Chapter 8 in this volume). As engineering biology applications become more entrenched in future markets, the representative organisations will become increasingly visible to the public. To avoid repeating past mistakes in communicating around genetically modified organisms, scientists, technologists, practitioners and policy makers need to work closely with biofoundry operators and the public to shape and guide future developments (Dixon, Curach and Pretorius, 2020[36]).

Digital security: An emerging threat for policy makers

There exist many ways to launch a cyberattack on a bio-production company. The convergence and integration of robotics, microfluidics, cell-free systems design, synthetic metabolic engineering and other technologies will reveal new vulnerabilities and offer new opportunities for nefarious actions (Richardson et al., 2019[37]).

The ability to separate design from manufacturing completely could heighten such threats. Ultimately, design will be possible from any location (including home), exacerbating potential threats to manufacturing facilities. Many different types of organisations are involved in bio-production security, from feedstock suppliers, through information technology professionals at law firms and IP offices, to customers. Digital security is only as strong as the weakest link in the overall system of protection, and calls for co-operation across many private and public institutions. Moreover, because attacks can also be launched by hostile governments, countries must act to develop the policy and infrastructure to prevent cyber-attacks (OECD, 2020[38]).

Future outlook

Given the current context of multiple sustainability crises and now the COVID-19 pandemic, science, technology and innovation (STI) systems are redirecting their efforts towards grand challenges, and reimagining in the process the ends and means of technological development (see Chapter 8). The health crisis has only accelerated the trend towards a greater mission orientation in the STI system, highlighting the importance of steering technology to address the most pressing problems. Clearly, many kinds of socio-technical solutions will need to be pursued simultaneously to address the uncertainties and complex challenges facing humanity.

This chapter has explored how engineering biology might contribute in time to novel approaches towards vaccine development and sustainability, given the new salience of mRNA approaches and the new-found convergence between the biotechnology and digital technologies embodied in the biofoundry. Significant policy and technological barriers exist, and will need to be addressed. The payoffs are potentially large: technological developments might open up new opportunities for manufacturing across a range of sectors and for a wide range of products, whether medicines, new materials or greener chemicals.

In the context of the current COVID-19 pandemic, this chapter has argued that engineering biology provides a model that is well-suited to overcoming the shortcomings of modern vaccine, diagnostics and antibody production. Looking towards the future, the opposite is also true. For a domain like engineering biology, in which the promise frequently outstrips the reality in terms of the actual economic and social impact, the COVID-19 crisis is an opportunity to realise the overall potential of the field. Such successes, if they can be accomplished, would bolster public confidence in these technologies.

With the emergence of viable mRNA vaccine approaches against COVID-19, and other developments in biotechnology, it is clear how engineering biology could be leveraged to address significant global challenges – not only for vaccines, but also cancer treatment, personalised medicine, sustainable fuels and industrial chemicals, remediation of polluted environments and food supplies. But research is far from capitalising on its fullest potential.

Figure 7.4 outlines many tracks for future policy options. To develop the field, governments could:

- establish pre-competitive infrastructure and collaborative platforms, such as networked biofoundries and research consortia, by ensuring long-term and stable funding for engineering biology research and translational infrastructures, and accelerate its commercialisation by supporting the growth of an ecosystem of start-ups;
- address systemic business risk in bio-based value chains, e.g. by supporting translation and testing of technical scaling activities, including access to technical expertise and guidance, as well as equipment for start-ups and smaller businesses;
- support engagement of scientists, technologists, practitioners and policy makers with biofoundry operators, members of the public and stakeholder groups, to promote trust in (and trustworthiness of) the technology;
- support strong science-industry collaboration, e.g. by introducing support specific to these types of risky technologies, such as proof-of-concept funding, to determine whether larger-scale collaboration is warranted; and
- build multidisciplinary environments and transdisciplinary skills to promote convergence (as engineering biology extends beyond traditional discipline boundaries, drawing from engineering, biology, data science and physical sciences, and multidisciplinary environments are key to its success), and rely on people who can communicate across disciplines.

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[8] https://www.biopreferred.gov/BioPreferred/ (accessed 15 September 2020).

[9] https://biooekonomierat.de/en/ (accessed 10 July 2020).

[10] (UK Synthetic Biology Coordination Group, 2012[40])

[11] An example of a non-government initiative along similar lines is the EBRC roadmap (EBRC, 2019[33]). This very detailed technical roadmap, along the lines of industry roadmaps, consists of a matrixed framework that considers challenges, bottlenecks and other limitations observed or predicted in research, development and applications in engineering biology tools and technologies. This is done by combining a bottom-up approach, focusing on tool and technology innovations, and a top-down approach, focusing on how engineering biology can tackle national and global challenges.

8 Governance of science, technology and innovation for crisis and recovery

In contrast to the 2008-09 global financial crisis, science, technology and innovation is central to providing solutions to the COVID-19 crisis, and is clearly seen to be doing so. These solutions are shaped by the ways in which governments organise themselves, the sorts of relationships they have with other groups, including businesses and civil society organisations, and the resources they have at their disposal, including expertise and other capabilities. The chapter focuses on how various governance arrangements deployed by countries influence both their response to the current crisis and their scope for dealing with the challenges of the recovery phase. It covers governments' use of scientific advice to underpin COVID-19 policy, its use of digital tools to improve policy design and tackle the misinformation "infodemic", and its approaches to cross-government coordination. The chapter also covers governments' experiments with mission-oriented innovation policies and responsible innovation practices.

Key findings

- **Governments should reinforce public trust in policy through scientific advice**. Public trust is critical for ensuring support and compliance with policy measures, such as the wearing of masks and social distancing, and requires openness and transparency on the data and information underpinning these measures. Governments should carefully communicate uncertainties and provide a balanced presentation of potential scenarios. They should also draw upon multi-disciplinary advisory mechanisms to ensure they consider different types of expertise when developing policy.
- **Governments should link support for emerging technologies to broader missions that encapsulate responsible innovation principles**. This will help ensure an alignment of emerging technology development with the objectives of mission-oriented innovation policies. The responsible innovation approach seeks to anticipate problems in the course of innovation and steer technology to best outcomes, and emphasises the inclusion of stakeholders in the innovation process. This makes it well suited to mission-oriented innovation policies, which tend to target grand societal challenges, such as the 'green transition'.
- **Governments will need to renew their policy frameworks and capabilities to carry out a more ambitious science and innovation policy agenda**. Through their recovery and stimulus packages, governments have potentially more leverage to initiate a transition to more sustainable and equitable futures. Governments will also need to invest in preparedness measures, including technology platforms, infrastructures and collaborative networks that improve countries' abilities to respond effectively to a diverse range of risks. These roles and objectives require governments to acquire appropriate skills and capabilities to fulfil them, including dynamic capabilities that support learning and adaptability, which are needed for policy agility in times of great uncertainty.

Introduction

Countries' governance arrangements shape their research and innovation responses to the current COVID-19 crisis and will influence the contribution of science, technology and innovation (STI) to the recovery. These arrangements are broad in scope and include the ways governments set directions and choose priorities, their relationships with other actors in the innovation system, and the technologies they use to govern (including digital and social technologies).

The first part of the chapter primarily relates to how governments have responded to the COVID-19 crisis:

- One of the more visible – and most debated – aspects of this response is the use of scientific advice in designing policies. Previous OECD work has formulated guidelines on providing and using scientific advice in international crises like COVID-19. The chapter reviews these guidelines and considers how governments have followed them in their policy making.
- Governments are undergoing a digital transformation, which will profoundly change the ways they govern. The pandemic, its impacts, and responses to it all leave digital traces, which governments are increasingly exploiting to respond to the crisis. The COVID-19 crisis has led to unprecedented uses of new digital tools and data to inform policy, which could accelerate the digitalisation of science and innovation policy itself. This chapter highlights some of the initiatives put in place by governments to inform citizens of the latest developments on COVID-19 and tackle the "infodemic" of misinformation.
- Most parts of government are responding to the crisis in one way or another, leading to risks of duplication and insufficient scale if efforts are fragmented. Contemporary governance is highly distributed in most OECD countries, involving ministries and implementation agencies, as well as various degrees of subnational autonomy. This presents multiple co-ordination challenges for governments when responding to COVID-19. The chapter focuses on just one axis, horizontal cross-government co-ordination of STI responses to the pandemic. Most governments have set up mechanisms, for instance, to co-ordinate calls for research proposals. The chapter outlines the benefits and challenges, and highlights a few examples of how countries are trying to improve policy co-ordination.

The second part of the chapter focuses on STI governance arrangements for the recovery phase. It returns to a few of the big challenges already facing STI policy before the pandemic crisis hit, including whether and how to set directions in STI policy, how to account sufficiently for longer-term concerns in defining sound policies, and how to be inclusive in policy processes and outcomes to meet grand societal challenges. The chapter covers the following topics:

- Governments' ongoing experiments with "mission-oriented innovation policies" (MOIPs), which have tended to target "grand societal challenges", could feature more prominently in the STI policy mix, for instance as part of recovery packages targeting "green transitions". The chapter provides a simple typology of MOIPs and maps some MOIPs targeting health and healthcare.
- While science and technology will be essential to address challenges like sustainability and ageing, they can also raise societal concerns, as witnessed during previous waves of technological change. Indeed, many of the barriers to enabling emerging technologies lie not in the technology itself, but in technology governance. The OECD has developed an approach to "responsible innovation" that aims to enhance societal capacities to shape technology through its course of development, so that it might advance to market under conditions of trust. The chapter outlines how the OECD has applied this approach to the new OECD Recommendation on Responsible Innovation in Neurotechnology.
- A final section looks ahead to how STI governance and policy making may need to change if they are to play a role in redirecting economies and societies towards more equitable, sustainable and resilient futures. It considers how governments might adapt four key areas – policy goals,

frameworks, practices and capabilities – to meet the ambitious STI policy agenda that is now emerging.

Scientific advice in times of crisis

Science is informing the policy response to the COVID-19 pandemic and providing the greatest hope of a long-term solution. Even in where the role of experts has been questioned, policy makers find themselves turning to experts for advice. In some countries, the political leadership has even devolved much of the responsibility for communicating and explaining its policy choices to scientific experts. Different standing systems are in place for providing scientific advice to policy makers, often supplemented by additional ad hoc mechanisms in times of crisis. While most OECD countries rely on national expertise, many lesser-developed economies rely more on international sources of advice. As the pandemic has evolved, the requirements for scientific advice have become increasingly distributed across ministries and geographic scales – local, national and international.

The scientific evidence informing the policy response to COVID-19 is incomplete and conditional: as more data is collected, the scientific understanding of COVID-19 changes. This dynamic situation is a challenge for the scientific community, at a time when policy makers and the public seek assurances and certainty. Consensus is difficult to achieve, but communicating uncertainties and alternative views can undermine trust in scientific advice and related policies. In such circumstances, those providing advice need to be supported by an effective national (and international) scientific advisory system that complies with several basic principles (Box 8.1). Attention to these principles will both enhance the efficiency and quality of the scientific advice provided and help ensure the necessary trust between scientists, policy makers and the public.

Box 8.1. Principles for an effective and trustworthy scientific advisory system

An effective and trustworthy scientific advisory process needs to:

1. Have a clear remit, with defined roles and responsibilities for its various actors. This includes having:
    a. a clear definition and – insofar as possible – a clear demarcation of advisory vs. decision-making functions and roles
    b. defined roles and responsibilities, and the necessary expertise for communication
    c. an ex ante definition of the legal role and potential liability of all individuals and institutions involved
    d. the necessary institutional, logistical and personnel support relative to its remit.
2. Involve the relevant actors, i.e. scientists, policy makers and other stakeholders, as necessary. This includes:
    a. using a transparent process for participation, and following strict procedures for declaring, verifying and dealing with conflicts of interest
    b. engaging all the necessary scientific expertise across disciplines to address the issue at hand
    c. giving explicit consideration to whether and how to engage non-scientific experts and/or civil society stakeholders in framing and/or generating the advice
    d. having the effective procedures necessary for timely exchange of information, and co-ordination with different national and international counterparts.

3. Produce advice that is sound, unbiased and legitimate. Such advice should:
    a. be based on the best available scientific evidence
    b. explicitly assess and communicate scientific uncertainties
    c. be preserved from political (and other vested-interest group) interference
    d. be generated and used in a transparent and accountable manner.

Source: OECD (2015[1]), "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. http://dx.doi.org/10.1787/5js33l1jcpwb-en.

The OECD has identified five key areas that are particularly important in providing and using scientific advice in international crises such as COVID-19 (OECD, 2018[2]):

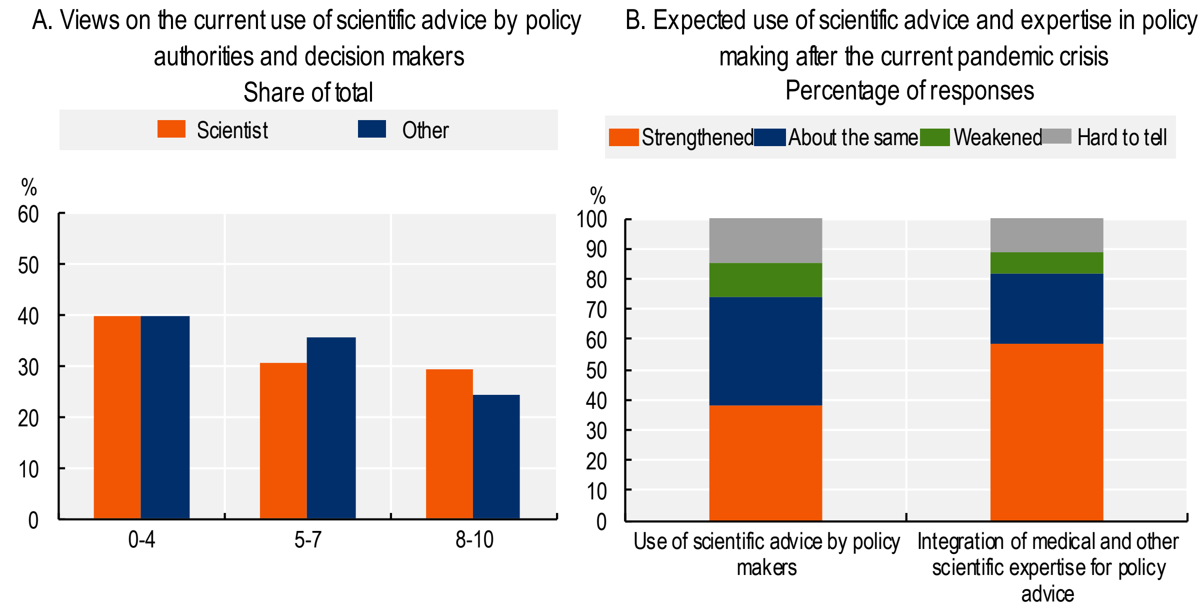
1. *Enhancing capacity to provide advice that fits the national context*: there exist differences in countries' capacity and structures, not only to develop and provide scientific evidence on the status and likely direction of a crisis, but also to provide evidence on the likely effectiveness of different policy interventions. Both aspects are important, but may require different types of expertise. Unless advisory systems are organised to bring different disciplines and perspectives together on an equal footing, there exists a danger that not all of the pertinent scientific evidence will be considered in developing policy. This is increasingly an issue in relation to COVID-19 as the longer-term effects of current policy actions, such as social distancing, become apparent. Certainly, many OECD countries do have multidisciplinary advisory mechanisms, but it is not clear that all countries are fully taking into account potentially useful scientific knowledge.
2. *International co-operation*: the World Health Organization (WHO) is the intergovernmental body with the remit to monitor and co-ordinate the response to global pandemics of infectious diseases (see Chapter 5). The WHO has its own scientific advisory mechanisms. It releases data, information and advice for all countries, which are publicly available and updated daily. The European Centre for Disease Prevention and Control also plays a co-ordination role and supports European countries with advice on responding to the epidemic. In addition, a variety of ad hoc co-ordination mechanisms have been implemented in response to COVID-19, including regular meetings of scientific advisors from Group of Seven and Group of Twenty countries. Most OECD countries consider the information emanating from international bodies as an important supplement to their own national advisory mechanisms, but certainly do not feel limited or bound by this advice (OECD, 2018[2]). The situation is somewhat different for lesser-developed economies, which are generally much more dependent on WHO advice – often in association with bilateral inputs from strategic partners. However, cultural practices and norms are critical for developing effective mitigation strategies. Policy interventions that are applicable in one country will not necessarily be as directly applicable or effective in other countries. International scientific research networks can play an important role in building and maintaining local scientific capacity that can be called on in times of crisis.
3. *Promoting mutual understanding and trust among people and networks*: promoting trust between different advisors and users of scientific data, information and advice is a long-term challenge. It requires appropriate support, mandates and incentives at the national level, and mechanisms for building mutual understanding at the international level. Openness and transparency regarding the data and information underpinning the scientific advice given in different countries is critical. This, in turn, entails support for international scientific networks and infrastructures that can complement and implement formal international frameworks – including, with specific regard to COVID-19, the WHO International Health Regulations.

4. *Being prepared and learning from past experience*: preparation for health pandemics ideally begins in times of calm, i.e. before crises occur. Most OECD countries do organise drills and exercises, involving their public health agencies and crisis management bodies, to rehearse possible scenarios during an actual crisis. Valuable as they are, such exercises may not always be given the priority they deserve and may not always engage all the necessary actors. They are more difficult to organise and more expensive at the international level – and unless conducted regularly, the turnover of individuals can mean that their value is reduced. Thus, establishing clearly defined structures with long-term responsibilities for crisis management and related scientific advisory processes is important for learning from the past to inform the present and future.
5. *Communication with the public*: no matter how good the scientific advice, and how well it is integrated into crisis management and decision-making processes, the manner in which it is communicated to the public will have a major impact on its effectiveness. This is clearly the case with regard to COVID-19, where the performance of political, medical and scientific leaders has been closely scrutinised and variously criticised or complimented. It is striking that in many countries, scientists have become national spokespersons, who are expected not only to provide scientific evidence, but also to justify policy actions. The reality is that in times of crisis, the distinction between advisor and policy maker can sometimes be blurred, and public debate about the scientific data and information accredited with determining policy can be intense.

How are countries meeting these challenges?

The available information suggests that the governments of OECD member countries are assessing and using scientific advice along the principles outlined above. However, to what extent they are meeting all of the conditions identified for optimising scientific advice varies considerably. Issues such as clarifying advisory roles vs. decision-making or communication roles and responsibilities vary across countries and over time, and are not always transparent. The engagement of many disciplines and non-academic experts in generating advice appears limited in some countries, although this may change as the public health imperative shifts to a fuller integration of socio-economic issues. Communication of uncertainties also seems to vary across countries. This is understandable in a situation where the scientific evidence is conditional, changing over time as more data and information become available. Nevertheless, when asked in the OECD Science Flash Survey 2020[1] how they would rate on a scale between 0 and 10 the way policy authorities and decision makers in their country have been using scientific advice, 40% of the responding scientists gave a score between 0 and 4 (where 0 corresponds to the worst and 10 is the best possible use) (Figure 8.1, Panel A). Two-fifths of survey respondents, however, expected the use of scientific advice and expertise in policy making to increase after the current pandemic crisis (Figure 8.1, Panel B).

Figure 8.1. Scientists' assessment of the use of science in policy making



Note: For Panel A, scoring on a scale between 0 and 10, where 0 corresponds to the worst and 10 is the best possible use, respondents were asked, "How would you rate the way in which policy authorities and decision makers in your country have been using scientific advice?" For Panel B, respondents were asked, "How do you expect the world of science to emerge out of the current crisis, in terms of (i) use of scientific advice by policy makers and (ii) integration of medical and other scientific expertise for policy advice?" Besides scientists, "other" respondents refers to science policy advisors (20%), professionals involved in science (15%), science communicators (10%) and individuals carrying out science-related administrative work (10%).
Source: OECD Science Flash Survey 2020, https://oecdsciencesurveys.github.io/2020flashsciencecovid/, (accessed 12 October 2020).

StatLink https://doi.org/10.1787/888934223555

Whether or not the policy actions currently being implemented in different countries to limit the effects of COVID-19 are ultimately judged optimal, they must be based on and reinforce trust across the science community, between scientists and policy makers, and within the public at large. Trust is critical to enhance support and compliance with policy measures such as the wearing of masks and social distancing. In the longer term, it will be important to garner solidarity and broad public support for interventions to ensure socio-economic recovery.

In the age of social media, openness and transparency are critical. Governments have been criticised for not providing rapid access to the primary scientific data and models underpinning their decision-making. Careful communication of uncertainties and balanced presentation of potential scenarios – including worst-case scenarios – appear to be broadly appreciated and understood by most of the public. The promise – and hype – associated with potential scientific or medical breakthroughs, such as reports of effective treatment with chloroquine, can also be managed with careful communication and explanation of scientific uncertainties by trusted experts.

Digital technologies and data for government decision-making

Digitalisation is profoundly affecting the public sector and the evidence base on which it formulates, implements, monitors and evaluates public policy. The STI policy field is no exception. In recent years, many countries have begun to develop initiatives around digital science and innovation policy to build a picture of the incidence and impact of their science and innovation activities, and formulate better policies.

The COVID-19 crisis has led to an unprecedented use of new data and digital tools to inform policy, possibly accelerating a process of innovation in policy making. For example, real-time granular data – such as daily evidence on COVID-19 cases, hospitalisations, deaths and scientific information on the COVID-19 pandemic – have helped inform policy actions. New data sources, e.g. data from job portals, have been used to provide quick information on the sectors and professions most affected by the COVID-19 crisis, while new tools from data science, computer science and machine learning are being used to automatically collect and analyse those types of data.

Such tools and data allow for entirely new policy approaches (OECD, 2020[3]; Paunov and Planes-Satorra, forthcoming[4]). The contact-tracing applications implemented in many OECD countries, which follow the movement of infected people and alert those who have come into close contact with them, are perhaps the most striking example. The rich granularity of the information collected (e.g. real-time data on the exact location of individuals), compared to typical statistical data, allows much more targeted evidence-based policy approaches, though it also raises challenges related to data quality and privacy (OECD, 2020[5]). Another prominent example is the proliferation of national COVID-19 portals that monitor the pandemic and its impacts, typically linking granular data from across government and providing information services on a variety of issues. In many cases, these portals include open-data application programming interfaces that allow other portals to download the data for other applications and analyses. Many of these portals have also been instrumental in tackling the torrent of misinformation and disinformation around COVID-19 (OECD, 2020[6]; OECD, 2020[7]) (Box 8.2).

Box 8.2. Tackling misinformation and disinformation on COVID-19

The global spread of COVID-19 has been accompanied by a wave of disinformation that undermines policy responses and amplifies distrust and concern among citizens. Online platforms are a key channel for this disinformation, but they can also play an important role in limiting its circulation (OECD, 2020[6]). At the same time, governments around the world are using various public communication tools to counteract disinformation and support policy (OECD, 2020[7]).

Centralising official information in a single website: most countries have created an official website to provide up-to-date information about COVID-19. Such websites are often a one-stop-shop where citizens can find official health-related advice (e.g. measures they can take in their daily lives to prevent the spread of the virus and how to react if they have symptoms.) and information regarding all the measures taken by national public authorities. Governments also issue statements about COVID-19 through social-media channels (e.g. Twitter, Facebook, Instagram). They also operate official websites on the coronavirus (e.g. in Australia,[2] Denmark,[3] Finland,[4] France,[5] Korea, New Zealand,[6] the United Kingdom,[7] Brazil,[8] Greece[9] and Italy).[10] Other information websites are operated by national or regional health services (e.g. in Finland,[11] Norway)[12] or organisations for science diffusion (e.g. the Danish Videnskab.dk and United Kingdom Research and Innovation's Coronavirus: the science explained).[13]

Fact-checking services to counter the spread of false information: some countries have created specific websites to alert the public to the spread of inaccurate and false information. In Germany, the Federal Ministry of Education and Research's webpage about fake news related to COVID-19[14] is updated regularly, and findings are diffused through social-media channels. In the United States, the Federal Emergency Management Agency has developed a Coronavirus Rumor Control website[15] to help the public distinguish between rumours and facts regarding the COVID-19 pandemic. Japan's Ministry of Health, Labour and Welfare[16] and the Flemish Agency of Care and Health[17] have also created fact-checking webpages.

Official chatbots, apps and other tools developed in collaboration with technology firms: the WHO launched the WHO Health Alert,[18] a free service on WhatsApp that answers questions from the public about COVID-19, as well as the "Verified" service offering prompt and reliable responses based on the latest official health information.[19] Several countries have developed (in collaboration with technology firms) automated chatbots on WhatsApp, e.g. "MyGov Corona Helpdesk" in India. Some governments have also launched their own COVID-19 app (e.g. Brazil's "Coronavírus-SUS" and Ireland's "HSE COVID 19") allowing citizens to monitor their symptoms and stay up-to-date on the latest official information and advice.

Source: Paunov and Planes-Satorra (forthcoming[4]).

The increasing public availability of project-level funding data, often set in the context of public transparency measures, is enabling related efforts looking specifically at data about R&D funding. It is currently very difficult to respond to requests for fine-grained information or categories of R&D funding that do not align with established classifications. This is manifest today with regard to COVID-19 research funding. It also applies to policy requests for information on research targeting particular technology fields (e.g. artificial intelligence) and grand challenges (e.g. the Sustainable Development Goals), where there exists widespread demand for data resources, tools and methods that help identify features of R&D funding. Funding organisations, and a growing number of commercial providers of research support services, have been not only compiling and offering access to data, but also providing semantic search and analytical functionalities using machine learning. However, this remains a fragmented landscape (OECD, 2018[8]; OECD, 2020[3]) and data could be better shared and exploited, both nationally and internationally.

Horizontal co-ordination to help fight COVID-19

The virtues of policy co-ordination are well-known and widely accepted. Whole-of-government co-ordination mechanisms – within and across levels of government – are essential to resolving discrepancies between sectoral priorities and policies. By concentrating resources towards common objectives, they also promote coherent and mutually supporting actions across sectors and institutions. Yet policy co-ordination and coherence remains one of the oldest and most prevalent challenges for governments, made even more difficult by multidimensional systemic problems such as climate change, ageing societies – or a pandemic. Such societal challenges involve institutions far beyond those responsible for STI policies.

Two factors are particularly detrimental to ensuring an effective policy response to the COVID-19 pandemic, making the need for policy co-ordination even more acute:

- *Uncertainty*: despite a wealth of information and scientific advice, there still exists little consensus on how the spread of the virus could evolve and how it may be treated. Policy makers must therefore take decisions amid changing – and at times conflicting – evidence.
- *Urgency*: when faced with an urgent need to react (as with the COVID-19 situation), decision makers across all sectors tend to act without sufficient consultation or exchange of information. Many research and innovation actors have reoriented some of their previously funded activities towards COVID-19, but often with little guidance from policy makers, or with different signals and incentives from different organisations.

Greater policy co-ordination within governments can enhance responses to COVID-19 by limiting the duplication of efforts, ensuring a sufficient scale of efforts, enabling a wider and more sustainable exploration of potential solutions, and providing greater visibility to initiatives that offer funding for COVID-19 (OECD, 2020[9]). Co-ordination of STI policies can be achieved in several ways, from top-down strategic co-ordination led by a cabinet office (as in Japan), to agency-level co-ordination (as in Norway). There exists no single best approach, and co-ordinating STI activities to tackle COVID-19 must be adapted to each country's specific governance structures.

Co-ordinating STI policy with other policy fields

While many countries have rightly allowed health authorities to lead the initial response to COVID-19, governments have followed the WHO guidance for national pandemic preparedness plans by establishing various cross-sectoral mechanisms to co-ordinate actions with other ministries. These have different activity portfolios aimed at containing, delaying and mitigating the virus, depending on the country's strategy and current public health situation.

Co-ordinating COVID-19 research initiatives

Many countries have also established specific governance structures and initiatives to co-ordinate activities within the STI system itself. One of the goals is to reduce silos between authorities overseeing research and innovation policies – including in the health area, which remains somewhat separated from the rest of the STI system in many countries. These efforts vary in scope and focus. They range from collaborative networks and working groups to integrated programmes and joint calls for research or innovation proposals, which are commonly used when two or more research agencies or councils pool resources to solicit and select proposals. These joint initiatives typically cover shorter research and knowledge-transfer horizons, with results expected in 3 to 12 months. A few are used to support later stages of the innovation process – for example, developing and rapidly manufacturing new technologies and services for detection and treatment. A notable example is the Accelerating COVID-19 Therapeutic Interventions and Vaccines (ACTIV) public-private partnership, led by the United States, which promotes a co-ordinated research strategy at the federal level to prioritise and speed the development of the most promising treatments and vaccines. This initiative is headed by the National Institutes of Health, together with other relevant US agencies, philanthropic organisations and biopharmaceutical companies. It is also linked with the European Medicines Agency for greater coherence with international efforts (see Chapter 5).

Co-ordinating efforts to communicate about funding opportunities

To complement these initiatives, governments have invested to communicate about research and innovation funding opportunities from different agencies. Initiatives include inventories and maps of relevant STI projects, as well as various online platforms and portals that list all the relevant information on COVID-related STI funding opportunities. Better collection and dissemination of such information facilitates formal and informal co-ordination across government. For example, the European Commission has launched the European Research Area (ERA) corona platform, a one-stop shop for information on coronavirus research and innovation funding (e.g. calls and funded projects). In France, the REACTing consortium monitors and encourages data sharing, promotes good practices and standardisation of data collection, and assembles and co-ordinates the French research actors working on COVID-19.

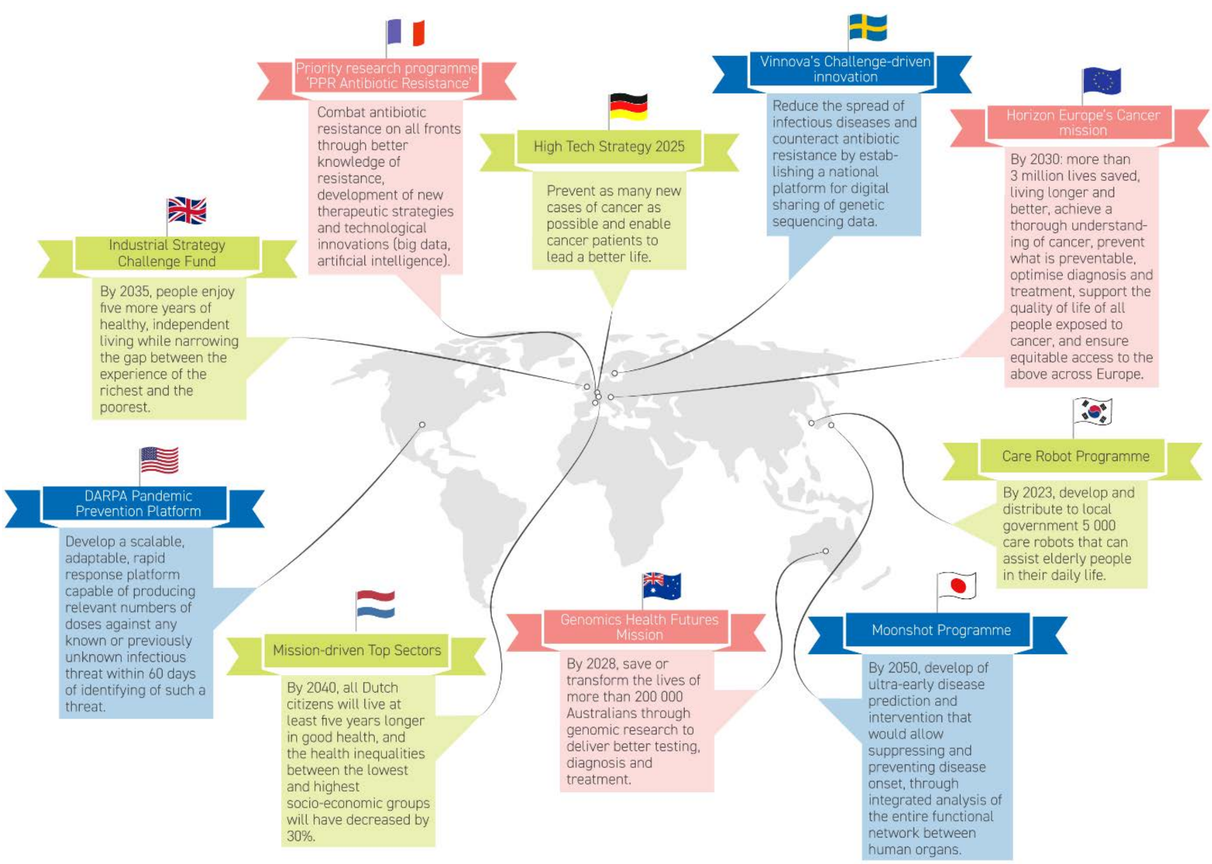
Governments leading collective action: Mission-oriented innovation policies

In parallel to co-ordinated early policy responses, more comprehensive approaches are needed to tackle COVID-19 in the longer run and prevent future pandemics. Governments' ongoing experiments with MOIPs could offer useful lessons in this regard. MOIPs bundle together a range of complementary public interventions to achieve ambitious goals for which traditionally fragmented STI policies have produced (at best) mixed results. These 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. They can mix supply-push and demand-pull instruments, and cut across various policy fields. Several countries are currently experimenting with different types of MOIPs to tackle a broad range of societal challenges. This section focuses on MOIPs targeting health challenges.

A range of tailor-made systemic policies for different missions

While some models have begun to emerge as countries learn from one another and emulate good practices, each MOIP is tailored to its objectives, most often combining imperatives to tackle selected societal challenges and strengthen national competitiveness in new growth areas. Several of these systemic initiatives are currently implemented in health and healthcare, in pursuit of various goals or mission statements (Figure 8.2).

Figure 8.2. International map of selected missions in health and healthcare



Note: DARPA refers to Defense Advanced Resarch Projects Agency and PPR refers to Programme prioritaire de recherche (research priority programme).

The mission-orientation imperative

The need for new approaches to better orient and co-ordinate health-related STI policies arises in the context of several specific challenges:

- Several intersecting transformations are affecting the sector, notably emerging or evolving threats such as the COVID-19 pandemic or issues related to an ageing population, the digital transformation of health and health care, and new trends towards personalised medicine. These transformations are driven in part by STI developments, but also demand directed STI responses.

- While health research and innovation is cross-sectoral, it is still often governed by its own "system" in many countries, with specific institutional structures and funding channels. The system itself is typically fragmented, with multiple actors operating at different stages of the innovation cycle and at different governance levels (national, regional or local) through a great variety of support measures and initiatives. This fragmentation is a challenge to co-ordinate efforts around national health strategic goals and missions.

The main MOIP models

Scanning the worldwide landscape of MOIP initiatives, two main models are apparent: "national mission-oriented strategic frameworks" and "challenge-based programmes". These are briefly summarised in Table 8.1.

Table 8.1. Basic characteristics of the main MOIP models

Type	Leadership	Missions	Examples
National mission-oriented strategic frameworks	• Centre of government (high-level committee, cabinet, prime minister)	• Multiple missions or mission areas • Pursue ambitious challenges, including transformative change • Long-term horizon	• Horizon Europe (European Union) • Mission-driven Top Sectors policy (Netherlands) • High Tech Strategy 2025 (Germany) • Moonshot R&D Programme (Japan)
Challenge-based programmes	• Policy implementation body (ministry, agency)	• Focused • Seek incremental or breakthrough results • Better fit for "accelerator" missions • Mid- to long-term horizon	• Pilot-E (Norway) • Industrial Strategy Challenge Fund (United Kingdom)

- *National mission-oriented strategic frameworks are broad initiatives launched at the highest level of policy making*. They provide concrete and ambitious targets within an overall strategic framework that helps co-ordinate actions among a wide array of public and private actors. In Japan, for example, the Moonshot R&D Programme was established in 2020 at the national level to solve six "Moonshot goals", including the development of ultra-early disease prediction and intervention by 2050. A characteristic of this programme is its multi-layered governance structure. At the overall programme level, it is governed by the Moonshot Strategy Council, which gathers different ministries and agencies to fund and implement the activities. A programme director is assigned to each goal and is responsible for all projects towards that goal, enabling portfolio management; project managers are in charge of designing the best team to carry out their project. At the European Union (EU) level, the "Conquering Cancer" mission – one of the five missions included in the future Horizon Europe Framework Programme for Research and Innovation (2021-2027) – has a target of saving more than 3 million lives, and living longer and better by 2030. A dedicated group of experts, the Cancer Mission Board, is engaged in extensive consultations with Member States, members of the European Parliament and several Directorates-General of the European Commission. One novelty of this initiative is its consultation and engagement of EU citizens, including cancer patients and survivors. This process resulted in a portfolio of European Commission and Member States actions to be implemented in five main intervention areas. The next step will be the design of a relevant governance and implementation framework for effective portfolio management that enables cross-sectoral and cross-institutional coordination. An important challenge for these overarching frameworks is to engage a wide range of actors without broadening or multiplying the missions, and enlisting high-level political actors without sacrificing the long-term time horizon and boldness of missions.

- *Challenge-based programmes focus on solving specific problems and are implemented by dedicated agencies or programmes*. They often pursue ambitious technological or even scientific challenges, in line with their narrower scope and focus. One of their main objectives is to embed support for selected projects throughout the innovation chain, from research to market introduction, to increase the chance of innovation success and accelerate development through closer linkages between researchers, business firms and users (including patients). Several of these programmes are implemented by funding agencies and draw on the well-known experience of DARPA in the United States. An early application of this model in the health area took place in the early 1990s, when USD 300 million were allocated to the Department of Defense to fight breast cancer. Rather than apply a bottom-up, curiosity-driven research approach, the Department of Defense used a directed approach, with significant participation of patient-activists in the planning process and the final selection of the scientific projects to be funded. The programme funded research that is credited with developing drugs and therapies considered among the most important advances in breast cancer treatment in recent decades (Sarewitz, 2016[10]). In a more recent example, the United Kingdom's Industrial Strategy Challenge Fund targets four health-related challenges. These include inventing new ways of detecting and preventing the development of diseases, and the "healthy ageing challenge", which asks industry and researchers to develop products and services to help people remain independent, productive, active and socially connected for longer. Each challenge mobilises a tailor-made range of instruments to reach its objectives. In Norway, building on the experience of Pilot-E, a cross-agency integrated scheme aiming to accelerate the development of sustainable energy solutions, the government plans to set up a Pilot-H scheme to co-ordinate focused and joined-up interventions in the health area. As of today, many agency-led challenge-based initiatives are experimental pilots. To have a significant transformational impact, they will need to be evaluated appropriately. There also needs to be political willingness to scale them up and elevate them to the national level. Countries such as Austria, Norway and Sweden are currently at this pivotal stage.

Several of these ambitious systemic policies are created out of a sense of urgency related to the challenge to be solved, enlisting the high-level political support that is essential to create initiatives of such scale and scope. However, designing and endowing these policies with the proper resources and governance structures takes time. The outbreak of the COVID-19 pandemic has not been the best time to establish MOIPs, beyond the co-ordinated responses identified in the previous section. Nevertheless, as government recovery packages embrace longer time horizons, some MOIPs have turned to COVID-19 and post-COVID-19 challenges. In response to the COVID-19 pandemic, Japan's Moonshot programme added a seventh goal in July 2020, namely, establishing a sustainable medical and care system to overcome major diseases by 2040, and living until the age of 100 without health concerns. The programme has also launched a consultation in September 2020 to create a new Moonshot goal to tackle the challenges facing society and the economy in post-crisis Japan.

Technology governance

Science and technology will be essential to increase resilience and address the challenges of our time, such as pandemics, sustainability and ageing. Yet they also raise societal concerns, as witnessed during previous waves of technological change in industry and current debates around nuclear power, gene editing, neurotechnology and artificial intelligence. Traditional means of governing science and technology, whether through institutionalised research ethics, government regulation or market mechanisms, are increasingly ill-equipped to capture the pace and depth with which innovations are reshaping societies.

Developments in emerging technologies have triggered a global debate about the consequences of the resulting commercialisation and the potential need for new oversight mechanisms (Jasanoff and Hurlbut, 2018[11]). Under conditions of uncertainty, traditional regulatory instruments – e.g. risk assessment, product-based standard-setting, export controls and liability – tend to focus on managing the immediate or readily quantifiable consequences of emerging technology, or are put into play only after key decisions about technology design have been made. Yet many of the issues raised by emerging technologies are more fundamental and long-term.

The governance of emerging science and technologies poses a well-known puzzle: the so-called Collingridge dilemma holds that early in the innovation process – when interventions and course corrections might still prove easy and cheap – the full consequences of the technology, and hence the need for change, might not be fully apparent. Conversely, when the need for intervention becomes apparent, changing course may become expensive, difficult and time-consuming (Collingridge, 1980[12]). Uncertainty and lock-ins are at the heart of many governance debates. What is needed is a novel approach to technology governance that anticipates concerns early on, addresses them through open and inclusive processes, and steers innovation trajectories in a socially desirable direction. Alternatives to the existing paradigms of governance must emerge alongside a form of innovation that is more responsible and responsive to the needs of society.

Several new approaches in science and technology policy seek to overcome the Collingridge dilemma by addressing concerns with technology governance upstream. The key idea is to make the innovation process more anticipatory, inclusive and purposive, injecting public good considerations into innovation dynamics and ensuring that social goals, values and concerns are integrated as they unfold. Process governance shifts the locus from managing the risks of technological products to managing the innovation process itself: who, when, what and how. It aims to anticipate concerns early on, address them through open and inclusive processes, and steer the innovation trajectory in a desired direction.

Reaping the benefits of emerging technologies while preventing or mitigating their potential negative effects is a critical challenge for science and society today. Many of the barriers to emerging technologies lie not in technology itself, but in technology governance. 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. It can consist of norms (e.g. regulations, standards and customs), but can also be operationalised through physical and virtual architectures that manage risks and benefits. Technology governance pertains not only to formal government activities, but also to the activities of firms, civil society organisations and communities of practice. In its broadest sense, it represents the sum of the many ways in which individuals and organisations shape technology and conversely, how technology shapes social order.

Responsible research and innovation

A persistent but misguided view is that resistance to technology stems mostly from public ignorance about the benefits of particular technologies or innovation in general. Social science research shows that such resistance might be steeped more in basic value conflicts, distributive concerns and failures of trust in governing institutions, such as regulatory authorities and technical advisory bodies (Gaskell, 1999[13]); (Bauer, 2009[14]). As a general rule, governments and innovators should take into account inasmuch as possible social goals and concerns from the beginning of the development process.

Neurosciences and neurotechnology are a case in point: they have dramatic potential for promoting human health and well-being. At the same time, they raise complex ethical, legal, and policy questions, including on (brain) data privacy, cybersecurity, human enhancement, the regulation and marketing of direct-to-consumer devices, the vulnerability of cognitive patterns for commercial or political manipulation, new inequalities of access, and implications for human rights (Ienca and Andorno, 2017[15]; Wexler and Reiner, 2019[16]). Such questions do not exclusively pertain to the field of science: policy choices around innovation and regulation will also steer these technologies. Thus, science and society more broadly must address these issues together in order to realise the full potential of neurotechnology.

Drawing from country practices around responsible research and innovation (Stilgoe, Owen and Macnaghten, 2013[17]) and "ethical, legal and social implications" frameworks, the OECD has been developing an approach to responsible innovation, culminating in the Recommendations on Responsible Innovation in Neurotechnology (OECD, 2019[18]) (Box 8.3). The Recommendation embodies a "responsible innovation" approach, drawing inspiration from the field of science and technology studies (Stilgoe, Owen and Macnaghten, 2013[17]) and recent work funded by the European Union (European Commission, 2020[19]). This approach seeks to anticipate problems during the course of innovation and steer technology to best outcomes, involving many stakeholders in the innovation process (OECD, 2018[20]). The OECD has also published the Recommendation on Artificial Intelligence (OECD, 2019[21]), which promotes artificial intelligence that is innovative and trustworthy, and that respects human rights and democratic values.

Box 8.3. OECD Council Recommendation on Responsible Innovation in Neurotechnology (2019)

1. Promote responsible innovation
2. Prioritise safety assessment
3. Promote inclusivity
4. Foster scientific collaboration
5. Enable societal deliberation
6. Enable capacity of oversight and advisory bodies
7. Safeguard personal brain data and other information
8. Promote cultures of stewardship and trust across the public and private sector
9. Anticipate and monitor potential unintended use and/or misuse

Source: OECD (2019[18]), OECD Recommendation of the Council on Responsible Innovation in Neurotechnology, https://legalinstruments.oecd.org.

Good governance can actually enable, rather than constrain, technology. This insight, focusing on governance from the perspective of innovation, is a touchstone of the Recommendation. In creating a responsible innovation system, at least five overarching elements stand out: (i) directionality, (ii) inclusivity, (iii) anticipation, (iv) deliberation, and (v) the role of the private sector. Each is gaining traction in innovation policy.

- *Directionality*. The Recommendation responds to calls to better align research, commercialisation and societal needs. In other words, it promotes "mission-oriented" and "purposive" technological transformation to better connect innovation to mental health.
- *Inclusivity*. Discussions about inclusive innovation usually focus on technological divides and access inequality. The Recommendation highlights further forms of inclusivity, i.e. how the inclusion of stakeholders, citizens, and systematically excluded actors within the innovation process can help drive innovation (OECD, 2018[20]).
- *Anticipation*. From an innovation perspective, end-of-pipe-approaches can be inflexible, inadequate and even stifling. In the realm of technology governance, governments and policy makers are currently experimenting with test beds, sandboxes, new technology assessment methods and foresight strategies.

- *Deliberation*. More demanding than public participation, deliberation implies an iterative exchange of views in hopes of achieving reasoned discourse and even finding common ground. The approach requires enhancing societal capacities to understand, communicate on and shape technology through the course of development so that technology might advance under conditions of trust, enabling their development to market. A good example of public engagement and deliberation is the process followed by the Human Fertilisation and Embryology Authority (HFEA) in the United Kingdom during its examination of a controversial technology (Box 8.4).
- *Role of the private sector*. Whereas many ethics of technology codes place duties on scientists and clinicians, the Recommendation also advances an institutional approach directing guidance to funding agencies, oversight bodies and companies. Firms in particular have a critical role to play in governance. They are on the front lines of product development, regulation, diffusion and marketing, and should commit themselves to a responsible innovation framework.

Box 8.4. An example of deliberation and technology uptake: The Human Fertilisation and Embryology Authority

The HFEA was established in 1990 to license and monitor in vitro fertilisation and insemination clinics throughout the United Kingdom, as well as institutions conducting embryonic research and storing gametes and embryos (Jasanoff, 2005[22]). In 2007, the HFEA launched a public consultation to explore the public's views on whether or not research scientists should be allowed to create embryos containing animal DNA (HFEA, 2007[23]; Starza-Allen, 2007[24]). The programme, entitled Hybrids and Chimeras, was supported by Sciencewise, a programme currently run by UK Research and Innovation, which aims to assist policy makers in conducting public engagement activities.

The consultation ran from April to July 2007 and involved a range of approaches to consultation. A public opinion poll gathered the general views of a representative sample of the public. Public deliberations expanded upon these general findings and opened up new questions, focusing on the effects of deliberation and new information on participants' views. A written consultation and a public meeting then took place. The HFEA analysed the results of the public consultation and decided that cytoplasmic hybrid research should be allowed to move forward, with caution and careful scrutiny (HFEA, 2007[23]).

More recently, the HFEA conducted a public consultation and submitted a proposal to the UK Parliament on whether to allow mitochondrial replacement in embryos intended for implantation. The parliament accepted the recommendation, with high public approval.

Participatory technology assessment

Technology assessment is another mechanism enabling responsible innovation. Initiated in the 1960s, technology assessment has been increasingly adopted in many countries and has evolved over time, based on the lessons learned. Innovation policy in many OECD countries is now guided by forms of societal technology assessment carried out by a mix of actors, including national ethics committees and other government bodies charged with considering wider social effects, and health and safety risk assessment. Some of these assessments are more broadly participatory, and include procedures involving stakeholder and public input (Durant, 1999[25]).

These societal technology-assessment processes involve formal risk analysis. Beyond the immediate health and safety risks, they can also be mindful of the longer-term social implications of technological adoption. Questions to consider relate to the distribution of the possible benefits and costs, the consequences of intellectual property in the field, the existence of particular pathways of greatest social benefit, the sources of uncertainty in assessing the technology, and the potential benefits of innovation.

Generally speaking, there has been a shift from more expert-based forms of assessment to more participatory models (see below). Born out of controversies around technologies like nuclear energy, technology assessment in the United States initially focused rather narrowly on providing objective, probabilistic knowledge about future trajectories of emerging technologies. Over time, it was increasingly recognised that framing assumptions (e.g. problem definitions, scope and methodologies) shaped the conclusions of technology assessment (Wynne, 1975[26]; Ely, Stirling and Van Zwanenberg, 2011[27]). In particular, an overemphasis on technical consequences could overshadow important issues associated with the social, ethical and political impacts of technologies. For these reasons, countries began to shift towards more inclusive, open and deliberative forms of technology assessment.

Some mechanisms of technology assessment involve formal public procedures that feed directly into innovation policy and governance decisions, particularly through consultation with expert advisory bodies. One approach consists in relying on scientific academies or regulatory authorities to assess the more technical aspects of emerging technologies; another is to establish public advisory bodies. Examples of these approaches include the Danish Board of Technology Foundation, the Nuffield Council on Bioethics in the United Kingdom, and presidential bioethics committees in the United States. Such groups might be charged with gathering evidence on particular technologies through research and public testimony, and writing reports that can inform public reasoning. Other methods include using public surveys and stakeholder interviews to assess emerging technologies and gauge current opinion, as well as holding hearings to collect input from various publics and inform regulatory agencies.

Recent efforts to introduce participatory technology assessment have variously been termed “constructive technology assessment” (Schot and Rip, 1997[28]), “participatory technology assessment” (Guston and Sarewitz, 2002[29]) and “real-time technology assessment”, among others. These approaches emphasise the value of engaging citizens and stakeholders alongside experts, based on the notion that technology assessment is inherently value-laden and citizens should therefore have a voice in the process. There is also growing recognition that non-experts and other stakeholders possess relevant knowledge that would otherwise be missed.[20]

More participatory modes of technology assessment recognise that the public is more likely to accept assessments of which they have been a part, and that the knowledge produced during these assessments will likely be more robust if diverse stakeholders are engaged. These approaches might include socio-technical mapping, which combines stakeholder analysis with plotting of recent technical innovations; early experimentation to identify and manage unanticipated impacts; greater dialogue between the public and innovators; public opinion polling and focus groups; and scenario development (Guston and Sarewitz, 2002[29]).

Future outlook

This chapter has reviewed a diverse range of issues facing the governance of STI. It has touched on lessons learned from recent OECD studies and highlighted outstanding policy challenges. Looking ahead, periods of crisis can offer opportunities to revisit existing policy goals, models and practices, as well as redirect economies and societies towards more equitable, sustainable and resilient futures. This final section explores some of the options available to countries when pursuing such policy goals, using currently underutilised policy frameworks and theories to guide policy action. It discusses policy practices in light of the pandemic crisis, and highlights the importance and challenges of developing the capabilities within government to successfully implement the ambitious STI policy agenda that is now emerging.

Revisiting policy goals

In contrast to the 2008-09 global financial crisis, STI is clearly central to providing solutions to the COVID-19 crisis. It is playing a prominent role in shaping policies to contain the virus through scientific advice, and the race to develop effective vaccines and therapeutics is drawing on the latest cutting-edge medical research and innovation. Such highly visible contributions could play a decisive role in the positioning of STI in the future.

The pandemic crisis has pushed the issue of "resilience" (i.e. the ability to recover from and adapt to disruption, and if need be, shift towards transformative paths) centre stage in policy agendas. While STI policy may need to adjust to this new emphasis, STI already makes important contributions to socio-economic resilience, by generating new knowledge and furthering its applications through innovation. In the COVID-19 context, new technology platforms are facilitating the development and production of vaccines and therapeutics at a rate that would have been unimaginable only a decade ago (see Chapter 5). The emphasis on resilience may therefore bring with it increased attention on supporting flexible platforms such as these and furthering collaborative partnerships that provide STI systems with greater agility to respond to future challenges.

It also seems likely that STI policy will continue to lean towards a more proactive "systems transformation" orientation, particularly to address the challenges of the climate emergency. While this shift has been under way for some time in several OECD countries, it could well accelerate in response to COVID-19 and the ambitious goals (e.g. green transitions) contained in many countries' recovery and stimulus packages (OECD, 2020[30]). Similarly, STI policy agendas may emphasise more the need to ensure an inclusive recovery (OECD, 2017[31]). Given that the COVID-19 crisis has had highly unequal effects, with a higher impact on many vulnerable groups in society and on some regions more than others, working towards greater inclusiveness could become as important a goal for STI policy as supporting national competitiveness and growth (Paunov and Planes-Satorra, forthcoming[4]).

Revisiting policy theories and frameworks

Reorienting policy goals towards sustainability, inclusiveness and resilience in the recovery period will require altogether different policy frameworks and practices. In their efforts to "build back better", STI policy makers and analysts could usefully deploy a range of novel and emerging frameworks and concepts. Some of these are well established in other policy fields, but largely overlooked by STI policy. Others have been at the fringes of STI policy for a decade or more, but have yet to be mainstreamed. The socio-technical transitions multi-level perspective (MLP), which emerged in sustainability research in the 2000s, is a prominent example. MLP underpins much contemporary discussion around the need for a new "transformative STI policy" (Schot and Steinmueller, 2018[32]) and is increasingly being promoted by international organisations (OECD, 2015[33]; European Environment Agency, 2019[34]; Pontikakis et al., 2020[35]) as an encompassing policy framework to promote sustainability transitions. However, despite many notable examples over the last decade (e.g. the Challenge-driven Innovation and Strategic Innovation programmes operated by Vinnova in Sweden, the Academy of Finland's Flagship initiative, the Pilot-E programme in Norway, and the Grand Solutions programme in Denmark), the framework has yet to be widely applied.

Such transformations call for system-level interventions to enact "systems innovations" – which, in turn, have highlighted the complexity of systems and the need to shift away from "command-and-control" notions of policy intervention (Hynes, Lees and Müller, 2020[36]). Furthermore, the COVID-19 crisis has exposed both the strengths and vulnerabilities resulting from strong interdependencies across countries and sectors, where changes in one component may directly or indirectly shape impacts in other parts of complex systems. Thus, the pandemic has emphasised the relevance of designing and implementing policies as components of a complex system (Paunov and Planes-Satorra, forthcoming[4]). As with MLP, while policy discussions of complex systems are more prominent than ever, there remains a sizeable gap in putting this thinking into STI policy practice.

Transformations and transitions create winners and losers. They can threaten powerful incumbents, who may seek to maintain some semblance of the status quo (Geels, 2014[37]). Power is ubiquitous in science and innovation, yet tends to be predominantly framed in narrow competition terms. Other policy fields, such as developmental aid (Whaites et al., 2015[38]), use broader concepts of power, deploying tools like political-economy analysis to better understand and map the drivers of change, and using these insights to design policies with greater chances of success.

The significance of values informing policy choices, including in the STI policy field (Bozeman, 2020[39]; Mazzucato and Ryan-Collins, 2019[40]), and the role of narratives and collective mobilising visions (Jasanoff and Kim, 2015[41]) in enacting transformations are increasingly recognised, yet rarely considered or mainstreamed in STI policy. STI should be a source of "collective hope" for societies (Mulgan, 2020[42]), but existing techno-economic visions will likely need to be renewed to serve a positive, sustainable and fairer socio-technical transition. While strategic foresight exercises can contribute to building such visions, these alone will be insufficient. Sustained, multifaceted and multi-stakeholder actions will likely be required, involving government, civil society organisations, the media and business.

Revisiting policy practices

The COVID-19 crisis has obliged governments to engage in "forced experimentation", from organising new ways of working from home, to using new data, policy tools and partnerships to formulate, design and implement policies. It is difficult to assess the long-term impacts these experiments will have on policy practice, but some will no doubt be scaled-up and diffused more widely. The new emphasis on building greater socio-economic resilience to dynamic change and future shocks means that various preparedness measures – including support for public-private networks, platforms and infrastructures that improve countries' abilities to respond to diverse risks – will likely be designed and implemented.

Ambitious recovery and stimulus packages may give policy more leverage to initiate a transition towards more sustainable and equitable futures. For example, the aviation and automotive industries require public subsidies as part of the recovery, which could be tied to various sustainability targets. Initial steps in that direction have already been taken. The bailout package for Air France requires the company to cut its emissions on all flights by 2030 (OECD, 2020[43]; Paunov and Planes-Satorra, forthcoming[4]). Thus, the crisis may strengthen the role of governments in both shaping the recovery and signalling the direction of desirable socio-technical transitions.

On the other hand, whether and to what extent ambitious recovery packages spur structural change remains uncertain. Government intervention needs to be affordable, which will be a major concern for many countries as the pandemic raises costs to the economy. Government debt for all countries is unprecedentedly high, far above the levels reached during the global financial crisis. Such unfavourable fiscal conditions could severely restrict the scope and scale of STI policy, reducing its ambition (see Chapter 1). Fiscal constraints will also leave STI policy facing some hard choices about the research and innovation areas and activities it should prioritise. Given the current pandemic crisis, more resources are likely to be directed towards health research and innovation. But if the total amount of funding remains unchanged or even decreases, this implies a decline of public resources for other research and innovation areas (see Chapter 2).

If STI policy is to apply some of the frameworks mentioned above, particularly MLP and systems approaches, an even greater use of new digital tools and data would be highly beneficial. Big-data analytics and artificial intelligence can help map entire systems at granular levels and in real time, allowing a better capture of system dependencies and improving understanding of how policies targeting one area can affect others. However, as with approaches to technology governance, such mapping and assessment activities should be performed with citizen and stakeholder engagement. Stakeholders and non-experts possess different types of knowledge and values that are relevant to STI policy. Even if it were technically feasible to capture or model such knowledge and values, the act of engaging stakeholders and citizens at different stages of the policy cycle brings process benefits that will make STI policies more robust and effective.

Revisiting government capabilities

The governance topics covered in this chapter, from using scientific advice and big-data analytics, to driving mission-oriented policies and governing technology, assume that sophisticated capabilities exist within the public sector. This section has highlighted the possibility of establishing new goals, new frameworks and new practices for STI policy, which will require expanding such capabilities. Beyond the skills of public servants (important as they are), organisational capacities and routines will also be needed. 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.

Developing the capabilities to deliver on a more ambitious policy agenda will become an increasingly significant concern for STI policy. Increased policy emphasis on building resilience, which calls for policy agility, highlights the need for governments to possess "dynamic capabilities", which (Teece, Pisano and Shuen, 1997[44]) define as the "ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments". Dynamic capabilities are distinct from the ordinary routines and capabilities organisations possess to exploit existing strengths and opportunities. They refer to an organisation's ability to adapt and learn, essential traits for effective governance.

Dynamic capabilities need to be distributed across the public sector, rather than focused in just a few agencies or innovation labs. Non-governmental actors, such as businesses, universities and civil society organisations, also possess knowledge and competencies that governments will need to leverage in order to fulfil ambitious policy agendas. This calls for developing both co-ordinative and absorptive capacities, to understand and act on knowledge generated by others. This can be challenging, particularly in leading-edge technologies like artificial intelligence, where the public sector competes against higher-paying businesses to hire technical experts. Government capacities have also been somewhat "hollowed out" in many OECD countries over the last decades, and some countries may need to rebuild them.

Thus, building capabilities in governments to meet the challenges ahead will be a major challenge in itself. While it has been beyond the scope of this chapter to explore this challenge in any detail, it is common to all governance topics covered here, and deserves greater attention in STI policy agendas.

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Notes

[1] This survey has been implemented through an online open-link questionnaire, inviting scientists or any other individuals with an interest in science or science policy on the impact of the COVID-19 crisis from a science perspective. The survey has been initially promoted through the network of the OECD Committee for Scientific and Technological Policy and former participants of the 2018 OECD International Survey of Scientific Authors (ISSA). It is being carried out in collaboration with the Inter-American Development Bank. As of 12 October 2020, over 2 600 responses from nearly 100 countries had been collected. 45% of responses correspond to individuals that identify themselves as scientists, with the rest comprising science policy advisors (20%), professionals involved in science (15%), science communicators (10%) and individuals carrying out science-related administrative work (10%). The survey does not request any information that can identify the respondents. As a result, results cannot be considered to be representative of a well-defined population and should be treated with extreme caution and considered as a complementary view to other evidence.

[2] https://www.australia.gov.au/.

[3] https://politi.dk/corona/.

[4] https://valtioneuvosto.fi/en/information-on-coronavirus.

[5] https://www.gouvernement.fr/info-coronavirus.

[6] https://covid19.govt.nz/.

[7] https://www.gov.uk/coronavirus.

[8] https://coronavirus.saude.gov.br/.

[9] https://eody.gov.gr/neos-koronaios-covid-19/.

[10] http://www.salute.gov.it/nuovocoronavirus.

[11] https://thl.fi/en/web/infectious-diseases/what-s-new/coronavirus-covid-19-latest-updates.

[12] https://helsenorge.no/.

[13] https://coronavirusexplained.ukri.org/en/.

[14] https://www.bmbf.de/de/faktencheck-zum-coronavirus-11162.html.

[15] https://www.fema.gov/coronavirus-rumor-control.

[16] https://www.mhlw.go.jp/stf/seisakunitsuite/bunya/0000164708_00001.html.

[17] https://www.gezondheidenwetenschap.be/dossiers/coronavirus.

[18] https://www.who.int/news-room/feature-stories/detail/who-health-alert-brings-covid-19-facts-to-billions-via-whatsapp.

[19] https://shareverified.com/en.

[20] Toxicological risks are a good example. It is the users of potentially toxic substances in their places of work that are well positioned to provide knowledge of how workers might become exposed in particular workplaces, given normal habits, etc. To give another obvious example, an assessment of the risks of pesticides would have to take into account the everyday practices of field workers, for example, whether protective clothing is in fact routinely used.

OECD Science, Technology and Innovation Outlook 2021

TIMES OF CRISIS AND OPPORTUNITY

In immediate responses to the COVID-19 crisis, science and innovation are playing essential roles in providing a better scientific understanding of the virus, as well as in the development of vaccines, treatments and diagnostics. Both the public and private sectors have poured billions of dollars into these efforts, accompanied by unprecedented levels of global cooperation. However, the economic crisis that is currently unfolding is expected to severely curtail research and innovation expenditures in firms, while debt-laden governments will face multiple, competing demands for financial support. These developments threaten to cause long-term damage to innovation systems at a time when science and innovation are most needed to deal with the climate emergency, meet the Sustainable Development Goals, and accelerate the digital transformation. Governments will need to take measures to protect their innovation systems as part of their stimulus and recovery packages, but should also use these as opportunities for reforms. In particular, science, technology and innovation (STI) policy should shift towards supporting a more ambitious agenda of system transformation that promotes a managed transition to more sustainable, equitable and resilient futures.

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