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Foreword

On 30 January 2020, the World Health Organisation declared the COVID-19 outbreak a Public Health Emergency of International Concern, which was the signal for an unprecedented mobilisation of the science community across the World. The pandemic has been not only a massive public health crisis but has affected all socio-economic sectors and all countries and changed many aspects of people's daily lives in a permanent manner. It has also changed many views on the roles of science and the way that it operates. Whilst the rapid development and deployment of effective diagnostic tools and vaccines has enabled most countries to emerge from the crisis and envisage a future living with COVID as another manageable endemic disease, there are many lessons that need to be learned to improve the long-term operations and resilience of science systems. The world is already in the midst of another complex global crisis that calls for rapid socio-economic transitions. New knowledge and new technologies are urgently required to address the challenges of sustainable development and environmental change.

This is the first of three reports, exploring how science was mobilised in response to COVID-19 and the lessons that we can learn from this for the future. This report focuses on 'policy for science' and how critical enabling elements of science systems – data and information, research infrastructures and public-private partnerships, responded during the crises. The second report focuses on 'science for policy and society' and key activities at the interface between science and other stakeholders – agenda setting, scientific advice and public communication and engagement. The third report explores cross-cutting meta-issues and discusses their implications for resilience and transitions. The three reports have been written so that they stand alone, although cross-referencing is included where appropriate. Each of the reports includes policy recommendations and options as well as case examples. The context in each country is different and so the priority attached to these recommendations and the specific details of how they might be implemented will vary. They are provided as an overall framework for science policy-makers and other actors, including research funders and research providers, to consider. They can also provide a starting point for national assessments of how science performed during COVID and how systems might be adjusted to respond more effectively to ongoing and future crises

The "Mobiising science in response to crisis: lessons learned from COVID-19" project was initiated in October 2020 – several months after the start of the pandemic – and was conducted under the aegis of the OECD Global Science Forum (GSF).

Acknowledgements

This work was overseen by an international group of experts from 12 countries (see annex 2) and drew on input from a broader group of experts from policy and research, who were directly involved in the pandemic response in different contexts and contributed to a series of virtual workshops (see annexes 3 and 4). Without these people, who made time to contribute in the midst of the crisis, this project would not have been possible. This report, and the other two reports in this series, were drafted by Jessica Ambler, working as a consultant to OECD, and edited by Carthage Smith, Head of the GSF Secretariat. The Expert Group and other members of the GSF secretariat – Frederic Sgard and Yoshiaki Tamura provided critical input and comments.

Executive Summary

The COVID-19 pandemic has presented an unprecedented global challenge. The urgent requirement for new knowledge and technologies to respond to the crisis has demanded much more than 'business as usual' from science. The response has revealed both the strengths and structural weaknesses of science systems when called upon to address urgent and complex societal challenges. The lessons learned, and good practices identified in this report relate specifically to three of the key elements of these science systems: access to data and information, research infrastructures, and academia-industry collaborations.

The broad impacts of the crisis, touching virtually all sectors of society, have required the integration, stewardship, and use of a diversity of data, ranging from census statistics to epidemiological, omics, clinical, and social sciences data. The ability and willingness to share data across scientific disciplines, sectors, and jurisdictions has been a critical determinant of the response to COVID-19. Prior efforts to improve access and use, including the adoption of Open Science policies and FAIR (Findability, Accessibility, Interoperability, and Reusability) data principles have been accelerated by new initiatives. However, structural barriers persist. Most notable amongst these are incentives and practices in academia and commercial publishing that conflict with the demand for timely access to research outcomes. These must be addressed to improve the development and accessibility of scientific knowledge.

During the pandemic, data access was challenged by unequal progress across scientific disciplines in the adoption of FAIR data principles. Much clinical and epidemiological data lacks universally recognised standards and coordinated systems for collection and dissemination, while the social sciences experience unique challenges related to standardising and integrating qualitative data from human subjects. Standardisation and interoperability issues hindered the generation of internationally comparative statistics. Confirmed cases, deaths, and recoveries, were often treated differently across countries or even sub-national jurisdictions, making it difficult to understand the evolution of the pandemic. It was important that collection, access, and use of sensitive data, including the results of clinical studies, patient records, or surveys, was aligned with – sometimes inflexible–- ethical and legal requirements that are not adapted to urgent crisis situations. Contact tracing apps have improved the ability to detect, monitor, and model disease transmission. However, it has been – and will continue to be – important that use of these and other novel digital technologies are governed transparently. There needs to be an onus on accountability and ensuring that data collection and use are inclusive, representative, and ethically appropriate, while accelerating safe access for research.

The pandemic demonstrated unequivocally that research infrastructures (RIs) can play a central role in crisis response. RIs have made a critical contribution to many areas, including the creation, validation, and dissemination of data and other resources. Tried and tested mechanisms were key to enabling RIs to adapt operations to address new priorities and accommodate new users. RIs had to rapidly adjust to a changing environment that called for operating at a distance and virtual access for users. In many cases, activities were constrained by a shortage of specialised personnel. Limited technical capacity required RIs to divert resources to training, not only for their own staff but alsofor the wider community. One unwelcome side effect of this was high rates of burnout and fatigue in RIs that were called upon to operate around the clock. There is a need to invest in the human and technological capacity required for crisis preparedness and response and ensure that RI operations can be quickly scaled-up, when necessary. This will require a shift in focus from short-term financial efficiency to long-term resilience.

Heterogeneity in the characteristics, contexts, and resources of RIs created a challenge for science policymakers. Policy action was focused largely on providing funding to biomedical and life science RIs and little additional support was provided to support other RIs in adapting their operations. Overall, a lack of connectivity or harmonisation between RIs limited collaboration across different disciplines and different stages of the R&D pipeline. In the few jurisdictions and domains that were able to leverage cross-infrastructural workflows, clusters, and other mechanisms that enable horizontal and vertical connectivity, these proved their worth. Looking to the future, the need for coordinated and interdisciplinary research

efforts is very likely to grow as new health and societal challenges emerge. This will require broad, inclusive, and connected RI ecosystems. Many societal challenges manifest at the international level, where there is an untapped opportunity for RIs to contribute more to regional and global coordination and cooperation.

Science-industry collaborations have played a significant part in the pandemic response. Science policy has a critical role in developing the conditions and incentives to facilitate such collaborations and enable their swift deployment during crises. Science-industry partnerships responding to COVID-19 spanned the research and development pipeline from fundamental and applied science activities to the production and distribution of science-based products. Collaborations occurred at the national and international levels, with bottom-up activities from individual researchers and research teams being important in catalysing partnerships with a variety of objectives, including the development of therapeutics, diagnostics, and vaccines. At the same time, international mechanisms, and top-down guidance, such as with the World Health Organization's novel Access to COVID-19 Tools Accelerator, were important to advance shared goals across countries.

While COVID-19 presented a cause for actors to rally around, many of the historical challenges characteristic of science-industry partnerships persisted in some form. Notably, these have included issues around resources, ownership, and the management of intellectual property (IP). In some instances, science policy provided valuable support to facilitate collaboration, while in others, it was apparent that traditional support mechanisms can be too slow or conservative. The swift mobilisation of pre-existing science-industry collaborations emphasised the need for science policy-makers to support these partnerships. In a similar vein, newly minted partnerships appeared more likely to adopt novel methods to quickly establish trust and mutual understanding. In some instances, this meant employing open or modular approaches to IP management. The pandemic response has stressed the value of agile and responsive funding and collaboration mechanisms and policy experimentation and learning needs to continue in this regard.

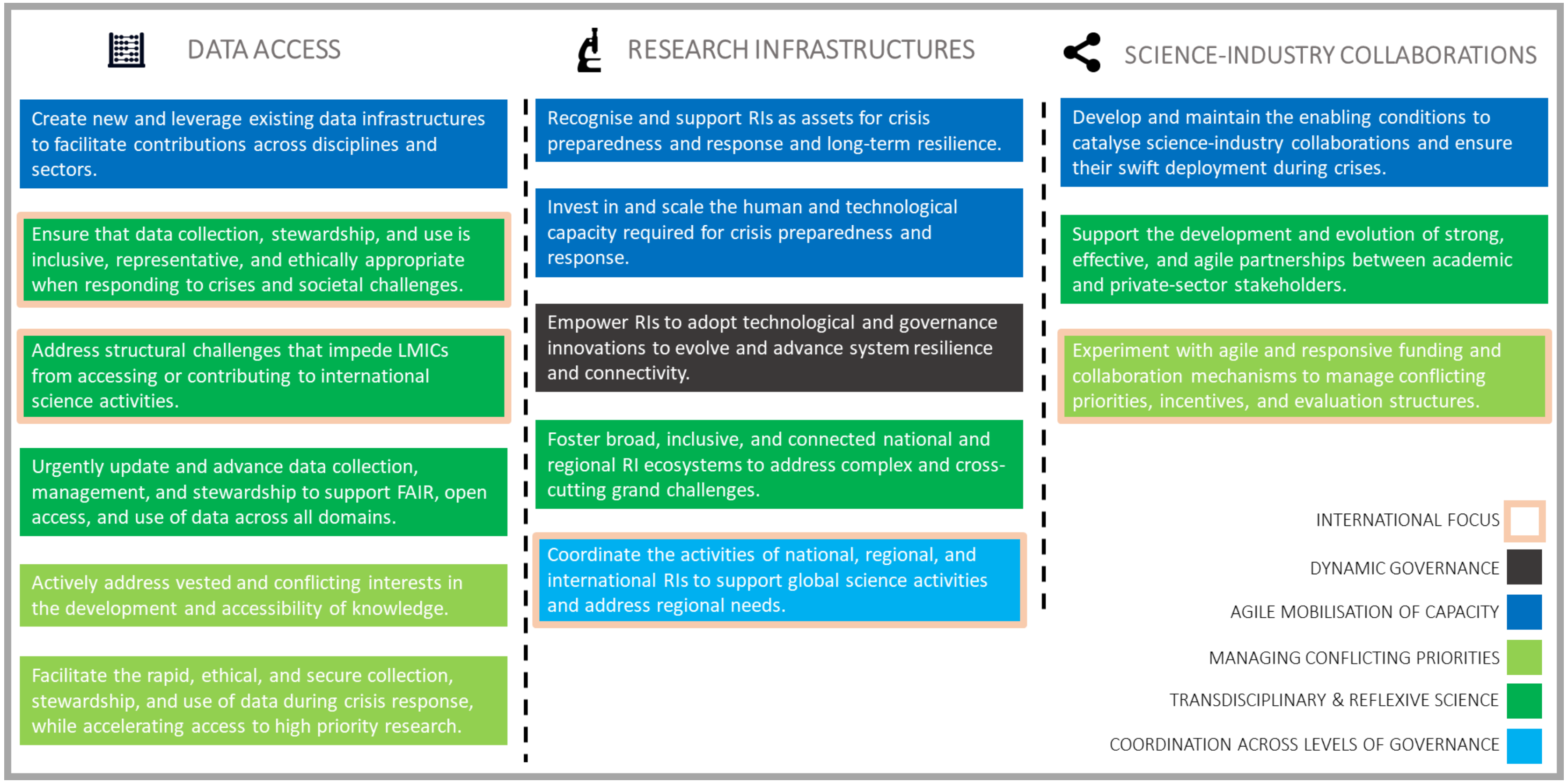
Recommendations

Overall analysis of the scientific response to the COVID-19 pandemic illustrates the significant and important interdependencies between 'policy for science' and 'science for policy and society' and the connectivity of actors across disciplines, sectors, and jurisdictions. Proactive, strategic, and long-term policy action and investments have been critical to ensure that capacity was in place to leverage in times of crisis. Prior investment in one domain often contributed to the functionality of others. A prominent example is the sweeping impact of digital technologies, which have been instrumental in the collection, stewardship, and analysis of data, in maintaining the continuity of RI operations through remote access, and in enabling new forms of collaboration.

Also evident across the three key key elements of science systems considered in this report - data, RIs, and science-industry collaboration - is the importance of inclusion. Governments and funders must act to ensure global preparedness through the full representation of disadvantaged or underrepresented populations in science activities. Many national responses were hindered by poor representation of certain demographics in data, which prevented the development of effective and targeted public health and social measures (PHSMs). At the international level, the scientific response in many low-and-middle-income countries (LMICs) has been constrained by weaknesses in their science systems. Despite diverse efforts prior to and during the pandemic, significant challenges persist in many LMICs, including deficiencies in data, infrastructures, and technical capacity.

Key recommendations that need to be implemented to address the main structural barriers identified in this report are summarised in Figure 1. More precise policy options for each of these recommendations are given at the end of each chapter and illustrative case studies are provided in boxes throughout the report. Although the challenges and key recommendations are broadly applicable across OECD countries, the national context differs considerably, and the applicability and importance of different policy options will vary accordingly. Similarly, the institutional responsibilities for implementing these options will differ across jurisdictions. A table listing all of the recommendations and policy options, illustrating how they relate to different stages of the crisis management cycle and to the 'science for policy and society topics' covered in the 2nd report in this series, is provided at Annex 1. These recommendations and policy options are provided to assist countries in advancing their science systems to prepare for, respond, and recover from health pandemics and other complex societal challenges more effectively in the future.

Figure 1. Policy for Science: Recommendations by elements of the science system and system-level themes



Note: This figure summarises the key policy recommendations for data and information access, research infrastructures, and science-industry collaborations and illustrates their alignment with the overall system level-challenges introduced at the end of this report (fig 6) and described in detail in report 3. Colours reflect principal connections between recommendations and system-level themes. It should be noted that there may be individual policy options under each recommendation (see tables at the end of each section in this report) that align with other or multiple system-level themes.

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Introduction

The mobilisation of science systems in preparation for, and response to, crises

The COVID-19 pandemic and resulting policy interventions have been a massive and prolonged disruptive force that has affected almost all aspects of a globally interconnected society. Responding effectively has required the rapid production of new scientific knowledge and tools and has served as a real-time test of science systems and their capacity to address a complex societal challenge. Even now many countries continue to respond to the pandemic as it evolves. However, looking back on how the pandemic response has unfolded up to this point provides already an opportunity to identify and address key factors that impede the ability of science systems to function more effectively in normal conditions and support them in developing the resilience that is required to respond in the future.

The project on Mobilising Science in Response to Crises: lessons learned from COVID-19 was authorized at the 42nd meeting of the Global Science Forum and the Terms of Reference were approved in October 2020 – several months into the pandemic. The overarching question that has guided the work is: *What can we learn from the scientific response to the COVID-19 crisis to help science policymakers improve the contribution of science in preventing, preparing for, and responding to future crises?*

The objective has been to develop actionable insights that will aid science policy-makers and the research community in preparing for and responding to future crises. These are presented at the end of each chapter as a suite of policy recommendations and policy options. Policy recommendations can be interpreted as critical actions with universal relevance to the capacity of science systems to prepare for and respond to crises. Policy options represent potential measures which might be taken to respond to the corresponding recommendation. Specific stakeholders, e.g., science policy-makers or funders, are named where relevant in policy recommendations, but it is recognised that roles and responsibilities will depend on the national context in which they are applied. It should also be noted that at the time of writing, in many parts of the world, the response to the COVID-19 pandemic is still ongoing and so the lessons to be learned at this stage are, to some degree, conditional on future events. To maintain a manageable scope, the project has focused primarily on the role of public science. The role of private sector research has been limited to issues at the interface with public sector research and broader innovation policy issues are the focus of other ongoing OECD analyses.

As the first report in the series, this document looks specifically at the mobilisation of three critical elements of national and international science systems – access to data and information, research infrastructures, and science-industry collaborations. It considers the interplays between policy, science, and other stakeholders across different geographic scales and different phases of the crisis management cycle (preparedness, response, recovery). The main focus of this report is on policy for science during crisis response. In this regard, policy for science refers to economic, regulatory, and information-based instruments introduced by governments to support science systems in producing science-based insights and products. This includes actions related to the development, operation, and redeployment of elements of science systems, as well as actions related to the governance of science systems, which are covered in more depth in the second report in this series. Learnings have relevance to preparedness and prevention of future crises and setting priorities for recovery and long-term resilience.

Methodology

The 'Mobilizing Science' project has been overseen and supported by an international Expert Group (EG) nominated by GSF (Annex 2). EG members have brought a diversity of national and institutional experience to the project and actively supported the development of international workshops through the identification of national information, case studies, and experts. The project's primary deliverable was initially proposed as a single report to capture challenges, learnings, and best practices identified during the workshop series. Due to the significant breadth and depth of the insights captured, this has been expanded to include a series of three reports, as described ahead in the 'Report Structure' section.

Six international workshops (Annex 3) were organized in partnership with other OECD working parties and organizations. These virtual workshops took place from April 2021 to April 2022, and focused on six key areas of interest related to:

1) **Policy for science**: access to data and information; research infrastructures; science-industry collaborations [the subject of this report]
2) **Science for policy and society:** priority setting and coordination; scientific advice; public communication and engagement. [the subject of report 2]

A symposium for research agency leaders was held also in October 2021 and provided valuable insights on the challenges faced by research funders and how they responded to these.

Workshops were designed to facilitate mutual learning and included a mix of case study presentations, expert panels, and moderated discussions. Background materials, including agendas, videos, and summary reports are available online at https://www.oecd.org/sti/inno/global-science-forum.htm. Information and insights gathered from the participants, most of whom were actively engaged in the science response to the pandemic, form the primary knowledge base for this study. Illustrative case studies and quotations from workshop attendees have been included in the reports to provide background context.[1] While quotations have not been attributed to individual contributors, a list of workshop presenters and panellists is provided in Annex 4. Workshop case studies have been supplemented with additional examples to expand on points raised during discussion and to broaden the geographical coverage, where necessary

The OECD Science, Technology, and Innovation Policy COVID-19 Tracker (https://stip.oecd.org/covid/) was launched in late 2020 as an open access resource that tracks the implementation of STI policy initiatives that address the pandemic. Currently, it includes over 900 policy initiatives from 56 countries and the European Union. The tracker was initially populated using a survey of STI policy responses to COVID-19 in October 2020 and has since been updated through the integration of targeted questions into the OECD's biennial survey of national STI policies (https://stip.oecd.org/stip/). This data has been used to provide additional context, in terms of the policy landscape, and has helped validate or supplement assertions and insights from the workshops. A detailed analysis of the OECD COVID-19 Tracker data upto the end of 2020 has been published previously (Paunov and Planes-Satorra, 2021[1]) (Paunov and Planes-Satorra, 2021[2]) and the Mobilising Science reports expand and deepen this analysis, from a science policy perspective.

In addition to the expert workshops and STIP COVID-19 data analysis, the 'Mobilising Science' project reports include references to other relevant OECD and GSF work on COVID-19, crisis response, and science systems more broadly. Additional academic and grey literature has been cited where appropriate. Due to the depth and breadth of related literature and the scale and speed at which it continues to expand, this report does not pretend to constitute a comprehensive review.

Report structure

This report is the first in a series of three *Mobilising science: lessons learned from COVID-19* policy reports. This (first) and the following (second) reports target the functional components of science systems that enable their effective operation. Underlying components are grouped in terms of report 1) policy for elements of science systems – access to data and information, research infrastructures, and science-industry collaborations – and report 2) science activities for policy and society – priority setting and coordination, scientific advice, and public communication and engagement. The final report provides guidance and recommendations on system-level issues that cut across these different elements and activities (see Figure 6 at the end of this report). It should be noted that, while similar trends and challenges were experienced across many countries, national contexts are diverse. The effectiveness of science policy initiatives can be enabled or inhibited by a diversity of contextual factors and all national science systems have their own specificities. Illustrative case studies and policy options have been included in this report to support policy-makers in translating and applying recommendations to their local contexts.

1 Enhancing data and information access for research during crises

Key Messages

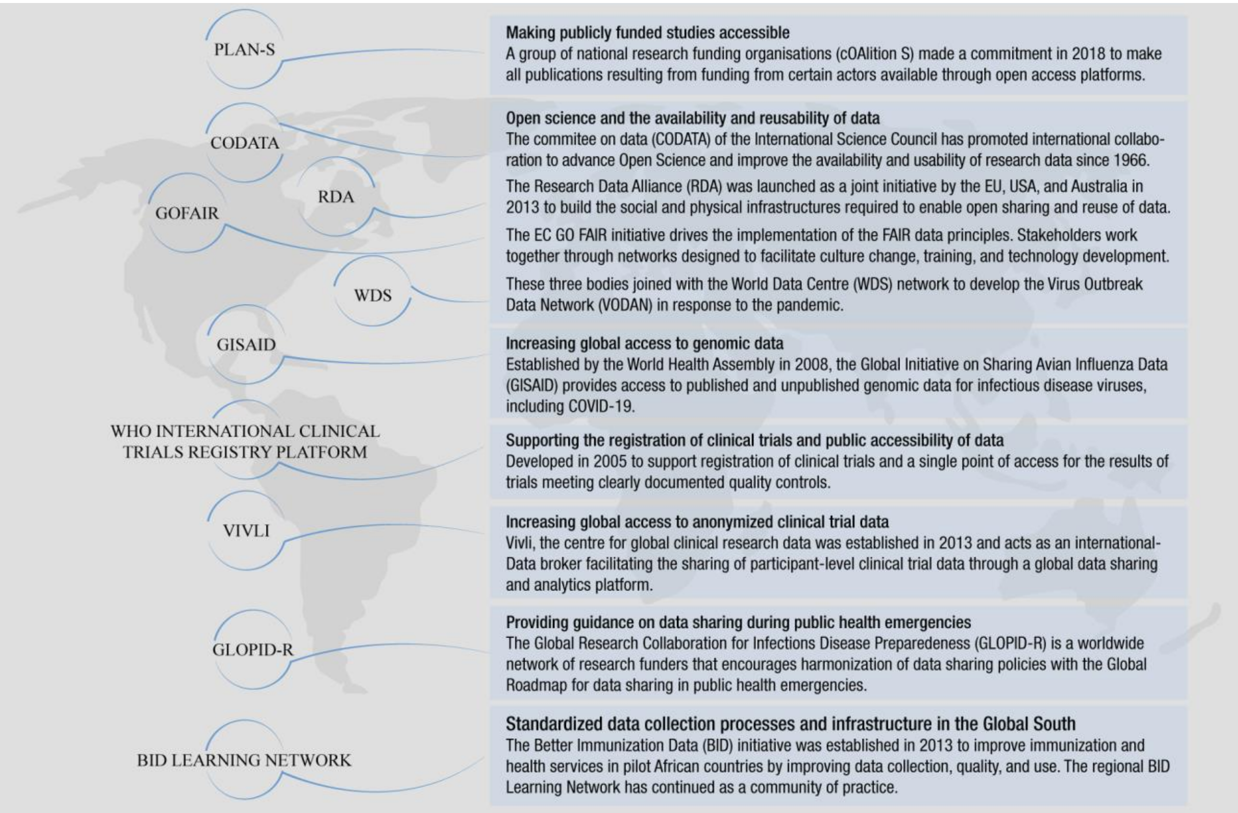
The breadth of the impacts of the COVID-19 pandemic posed an unprecedented challenge for science and policy actors in terms of the scope and scale of relevant scientific knowledge and data, requiring collection, stewardship, and integration.

- Improving international access to open and representative data first requires that trusted, inclusive, and adaptable data infrastructures, tools, and capacities are established. Longitudinal and disaggregated population data are critical to managing confounding factors inherent to social crises, which vary across different jurisdictions. Global preparedness will require targeted support for certain countries to overcome structural barriers to collecting and sharing such data.
- Different scientific disciplines have different requirements and practices for data management and access. During the pandemic response, these needed to be accommodated or adjusted to make data Findable, Accessible, Interoperable and Re-useable (FAIR) for the whole research community. Science policy-makers must tailor support to correspond to the progress of different domains for making their data FAIR.
- Realising the benefits of open data requires action to support users in navigating and curating information from disparate public and private sources and addressing heterogeneity in collection, storage, and analysis, which limits interoperability.
- While the COVID-19 pandemic provided an opportunity to positively advance Open Science, it is imperative that international efforts are made to prevent a reversion to 'business as usual' once the crisis is over.
- Open access publications are a specific aspect of Open Science that saw advancement during the COVID-19 pandemic response. At the same time, many stakeholders have cautioned that challenges remain, including the persistence of access constraints for the data and other research-relevant digital objects required to ensure the reproducibility of results.
- The COVID-19 pandemic has required scientists to work with and share sensitive data, which has been supported by the adoption of established good practices, such as the use of certified trustworthy data repositories. However, new challenges have emerged or escalated. For example, many governments have explored the use of advanced digital technologies to collect social and health data, which has required a careful balance between developing an effective front-line response and respecting ethical, legal, and social safeguards.

The ability of disparate actors to access data and the speed at which data are shared are important determinants of the rate of scientific advancement. As a result, the ability of national and international science communities to respond effectively to an emergent crisis is predicated, perhaps most fundamentally, on their ability and willingness to share and reuse data and other scientific outputs effectively. As the complexity and scale of a crisis increases and the scope of relevant scientific knowledge expands, this becomes more challenging and more critical. Responding to various phases of the COVID-19 pandemic required scientists and policy-makers to leverage and integrate data from across disciplines and countries. Many new science policy initiatives were implemented to try and address this (EC-OECD, 2021[3]). The release of a revised OECD recommendation concerning Access to Research Data from Public Funding, in January 2021 (OECD, 2021[4]) helped provide a general high-level framework for addressing many of the issues that came to the fore during the first months of the pandemic. A subsequent recommendation a few months later addressed issues around access and sharing of administrative and private sector data and helped extend this framework (OECD, 2021[5]). And several other international organisations made similar recommendations or declarations (see Figure 2 and 3).

The need for timely and transparent data sharing has been accentuated by the dynamic and changing nature of the pandemic. National response efforts were challenged by global connectivity and movement across borders, which was compounded, in turn, by the novelty of the virus and its rate of transmission and mutation. The result has been a speed and scale of change over the course of the pandemic that has been barely manageable for national governments. In this context, it was critical to be able to leverage and build on established mechanisms, policies, and processes to facilitate open science and the sharing of data across borders (See Figure 2).

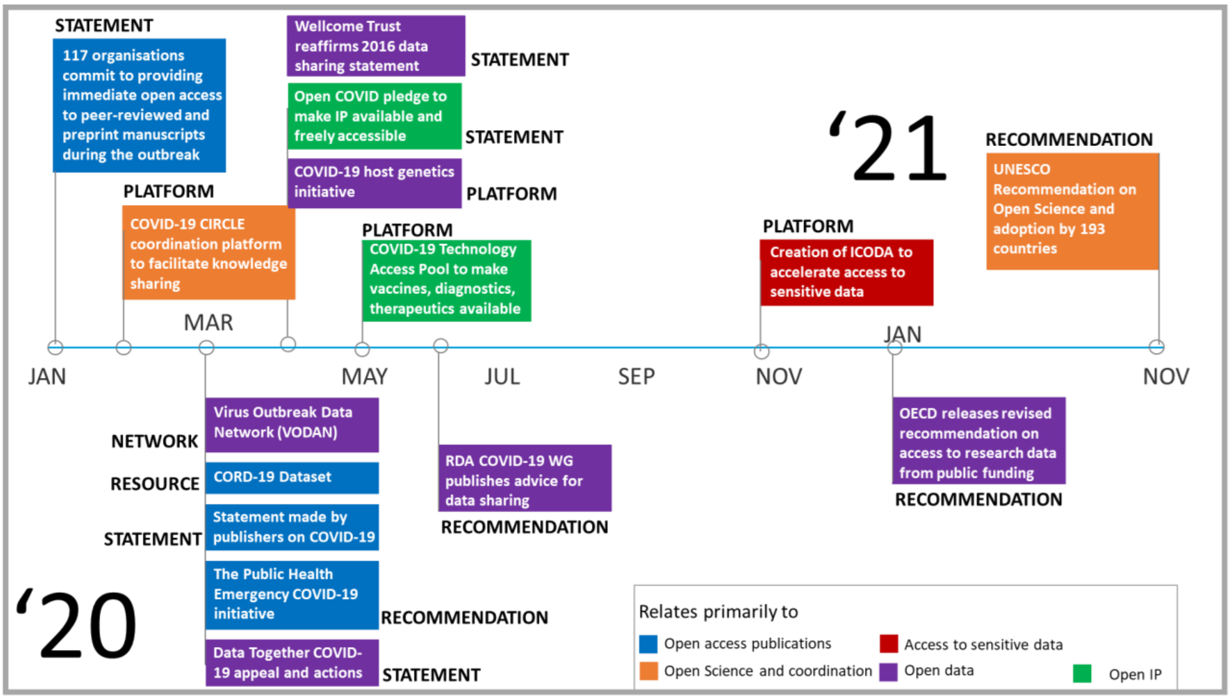
Figure 2. Established international data initiatives



Note: The initiatives are illustrative and are not a fully comprehensive representation of all established international initiatives that were mobilised to increase access to data or other research outputs during the COVID-19 pandemic response. Source: Adapted from Open science initiatives related to the COVID-1... |OECD

In many instances, increased visibility and awareness of existing and ongoing data science activities and resources improved both the efficiency and effectiveness of the scientific response: fostering collaboration instead of duplication; accelerating the advancement of knowledge and generation of new products and services; and increasing the quality of outputs through broader engagement and validation. Numerous analyses have cited the COVID-19 pandemic response as a catalyst for international sharing or open access to data, publications, and other scientific outputs (Besançon et al., 2021[6]) (OECD, 2020[7]). The crisis has motivated a robust and collaborative response from a number of public and private sector actors working to advance Open Science principles. Some of the main international pandemic data initiatives are represented below in Figure 3. At the same time, as response efforts have transitioned to recovery commentators have cautioned that persisting challenges must be addressed (Barbour and Borchert, 2020[8]). When the pandemic is finally over, international efforts will be critical to mitigate a historical tendency to revert to more closed 'business as usual' behaviours.

Figure 3. International data initiatives implemented in response to the COVID-19 pandemic



Note: The initiatives are illustrative and are not a fully comprehensive representation of all of the initiatives developed to improve international access to scientific outputs in response to COVID-19.

Source: Author's design.

1.1 Leveraging established data infrastructures during crisis response

> "For real-time public services data and analytic efforts, it's difficult to get grant support in a timely fashion. There is a lack of traditional incentives because this work is time consuming and does not count much towards promotional purposes"
>
> "Policies are needed to support the necessary funding platforms for sample and data collection"
>
> "COVID tracking was a volunteer effort. Incentives need to be re-thought"
>
> "Infrastructure support is needed for COVID data collection and harmonisation, to develop and maintain data dashboards and analytical tools and resources"
>
> "Community surveys need to be stood up at pace with ethical regulatory approval"
>
> "We don't have household surveys even now"
>
> "There needs to be discussion and consensus on what kind of data are needed. Are we missing data that is needed? Is the quality of the data being collected good enough or could/should it be better?"[1]

Source: A curated selection of significant quotations taken primarily from the 'Enhancing access to research data during crises' workshop held in April 2021. A complete list of workshop presenters and panellists is available at Annex 4.

Proactive and future-focused efforts are required to establish the data infrastructures, tools, and capacity needed to ensure that all relevant domains across government, healthcare systems, and research can contribute to addressing crises and other complex societal challenges. It is important that these capacities are considered as long-term strategic resources and supported accordingly. For example, where they existed, established longitudinal social or community-based surveys and enabling infrastructures have been critical for monitoring public attitudes, perceptions, and behaviours so that they could be integrated into the development and adaption of policy interventions. In this context, mechanisms for rapid ethical review that enable expedited changes to be made to census or other surveys were also important for the collection of relevant and timely data. However, tested processes and procedures to conduct appropriate social surveys did not exist in many countries prior to the pandemic. Other research domains were better prepared to respond both nationally and internationally. For example, while there are multiple types of clinical data (e.g., personal and health data) and these are also sensitive and governed according to ethical and legal frameworks, community standards exist to describe and structure most types and enable interoperability. Accredited data repositories have well established mechanisms to ensure that clinical data are appropriately preserved, documented, and reused in a secure, trustworthy, and efficient manner.

Another illustrative example is provided by the work done over the past 2 decades to establish national and regional networks of genomic data repositories and analytical services with the capacity to support research across scientific disciplines. In combination with global coordination structures, such as GLOPID-R and GISAID, distributed genomic data infrastructures were able to rapidly respond to the pandemic and played a critical role in supporting a wide range of research for understanding, monitoring and mitigating COVID-19. Whilst there is a strong open access ethos, dating back to the human genome project of the 1990s, which helped to drive development of genomics research, the pandemic has also required pragmatic adaptation of Open Science approaches to ensure that countries deposit and share sensitive data safely and securely (Naveed et al., 2015[9]). The specifics of sensitive data and their protection differ across domains; however, there are important lessons that can be learnt from how the genomics research community has organised itself internationally and the policy actions that have enabled this.

Box 1. Data Infrastructure

Leveraging established processes to collect and share timely, real-world data

Operational procedures in Korea's universal healthcare system enabled the responsible authority, the Health Insurance Review and Assessment Service (HIRA) to collect, process, de-identify, and store nationwide historical and COVID-specific patient data (Rho et al., 2021[10]). Through the COVID-19 International Collaborative Research Project, scientists were able to upload code for HIRA to complete analyses of time series healthcare use records for the entire population. These records included a 3-year patient medical history with data on patient demographics, treatment, diagnosis, and prescriptions.

Adapting existing tools to understand the impacts of COVID-19 on different demographics

Understanding Society is a UK community-based longitudinal study launched in 2009 to build on the British Household Panel Survey (BHPS), which surveyed 10,000 households from 1991-2009. It engages roughly 40,000 households, 8,000 of which are from the original BHPS (Institute for Social and Economic Research, n.d.[11]). From April 2020, participants were asked also to complete online or telephone surveys with content adapted with the evolution of the COVID-19 pandemic. General questionnaire content included: household composition, coronavirus illness, long-term health conditions management, general health questionnaire, loneliness, and employment. Data have been made available through a dashboard to allow secure analysis and comparison across different population groups.

1.2 Ensuring that data collection, stewardship, and use is inclusive, representative, and ethically appropriate

"Being invisible in datasets means not being recognized as a person and an inability to access, understand, process, manage, and leverage data"

"Limited age, sex, and race specific aggregated data makes for challenging analyses, especially for the purposes of policymaking"

"There are very concrete consequences as a direct result from lack of data access and lack of representation, such as racism"

"Basic level demographics data was very important but there was a gap between what was happening and where it was happening"

"When policy-makers make decisions based on data, they assume that people in danger will show up in the data, but these are calculated publics. This is an inherent problem in data production and existing datasets"

"We cannot only look at the proportion of people in the population who have had the vaccine and think of this as an indicator. We need an age-specific approach"

"Many of the datafied records of social life contain sensitive personal information and result from the 'power gaze' of datafication instruments and interest regimes" [1]

Note: a curated selection of significant quotations taken primarily from the 'Enhancing access to research data during crises' workshop held in April 2021. A list of workshop presenters and panellists is available at Annex 4.

Structural barriers persist regarding the representation of marginalised and under-represented groups in many population datasets. Accessibility of data for these same groups is also a challenge. Ensuring inclusion, requires, in the first instance, timely access to disaggregated information from national census data or other sources. Incomplete or non-representative data can exacerbate unfounded and harmful assumptions and biases, posing challenges for policy and science actors in understanding the experience of more vulnerable groups and targeting policy interventions appropriately.

'Invisible' groups, such as migrants, prisoners, or seniors are more likely to be overlooked by existing data collection methodologies and are thus more likely to be disadvantaged or alienated by resulting interventions. These same groups are likely to have limited capacity to assess, understand and leverage existing data sources. Novel approaches to data collection and governance are needed to improve inclusivity; however, in comparison with other areas, such as open access to publications, there appears to have been limited action from science policy-makers aimed at capturing or sharing disaggregated data or developing more inclusive data assets (EC-OECD, 2021[3]). In this regard, it is critical that community groups or representatives from target demographics are represented in solution development. Long-term action is required also to improve the overall data literacy and engagement of civil society in science activities. The COVID-19 pandemic has provided several significant examples of the importance of public engagement to understand the needs, perceptions, and behaviours of a diversity of demographics and to develop corresponding policies and countermeasures. [This is covered in more detail in the 'Public Communication and Engagement' section of the second report of this series.]

Box 2. Data collection

Engaging targeted demographics to facilitate inclusive and appropriate collection and use of data

The 'CARE Principles for Indigenous Data Governance' (Collective Benefit, Authority to Control, Responsibility, and Ethics), developed by the RDA's International Indigenous Data Sovereignty Interest Group in 2019, build on and codify earlier work (Carroll et al., 2020[12])[2]. The principles have implications for governments, institutions, and researchers in the design of studies and collection and stewardship of data. Their adoption serves to recognise and affirm:

1. Collective rights and interests of Indigenous Peoples in their data
2. Authority to access, control, and govern their data
3. Responsibility of users to interact respectfully with Indigenous Peoples from whom the data originates
4. Ethics of facilitating the ability of Indigenous Peoples to assess benefits, harms, and potential future uses through their adequate representation and participation in data practices.

Developing multivariate and multidisciplinary datasets to align policy with needs

Targeted government funding and the secure and confidential integration of large datasets have been important to facilitate interventions targeted to disadvantaged groups. For example, a Canadian study linking heath administrative data with historical immigration data has allowed policy-makers to better understand the extent to which racialised and immigrant communities in the region were subject to higher risk of contracting COVID-19 and poorer health outcomes (O'Neill et al., 2022[13]). These findings helped to inform COVID-19 policy interventions taken by the Ontario government to support specific demographics, such as with the development of accessible and mobile testing capacity. The need for integration of data from different sources was also necessary to shed light on different contextual factors that prevented the effective implementation of policy interventions. In the Canadian context this was demonstrated by affordable housing shortages that prevented people from quarantining safely.

1.3 Addressing structural barriers that prevent countries from accessing or contributing to international science activities

"There is a continued need to invest in and support Global South science, technology, and innovation capacities and ensure that networks are fully inclusive"

"Countries needed testing capabilities to identify COVID, but this was simply not the case of the large majority of African countries at the inception of the pandemic"

"Lots of valuable sequencing data is being generated and is available openly, but is… potentially not available to researchers in countries without the bandwidth to download or ability to retain it"

"What about the strains emerging in countries that cannot sequence samples?"

"Broadband can be an issue"

"Data are irregular in many developing countries. There is a need to provide resources for data collection"

"Sampling bias is created due to the expensive nature of sequencing" [1]

Note: A curated selection of significant quotations was taken primarily from the 'Enhancing access to research data during crises' workshop held in April 2021. A list of workshop presenters and panellists is available in Annex 4.

Low and middle-income countries (LMICs) face disproportionately high burdens from infectious diseases and often have limited capacity to monitor and respond to them (United Nations Publications, 2020[14]). On top of this, the COVID-19 pandemic revealed that data infrastructures in these countries are often impacted by additional funding constraints during crises, leading to delays or disruption of national census or other surveys. Even when data is available, engagement can be impeded by historical legacies, tensions due to economic or social inequalities, mistrust, or fear that data will be misused or exploited without appropriate credit being given to LMIC contributors (GloPID-R, 2019[15]). Limitations in the ability or willingness of LMICs to access or contribute to international science initiatives posed a critical challenge in responding effectively to the COVID-19 pandemic. Structural sampling biases and data gaps resulting from a lack of LMIC engagement can limit global preparedness for crises and the development of effective countermeasures and policy interventions.

Several challenges have come to light during the pandemic response with implications for the ability of LMICs to contribute to global collaborations. These range from limitations in foundational enabling infrastructures and processes, including broadband and data collection methodologies, to capacity more specific to the COVID-19 pandemic, such as genomic sequencing and medical diagnostics. Ultimately, there is a need for the international community to prioritise inclusivity in global science activities by continuing to invest in the development of STI capabilities in the Global South and by ensuring their representation and engagement in international collaborations and consortia. In this context, emerging economies with relatively strong scientific capacity, such as South Africa, can provide an important bridge between North and South.

Box 3. Data access

Catalysing regional collaboration to improve local data collection in LMICs

In response to the COVID-19 pandemic, the Africa CDC and a network of collaborators led a multi-pronged approach to address data gaps caused, in part, by limited local testing capacity (Ondoa et al., 2020[16]). Strategic actions included coordinating proactive regional procurement, decentralising testing, automating, and optimising workflows to increase diagnostics throughput, and increasing capacity and skills development. These efforts were critical in improving regional capacity to contain and address the pandemic, successfully expanding diagnostic capacity from 2 to 43 African countries from February to April 2020. The initiative has also improved representation of the African continent in the Global Initiative on Sharing all Influenza Data (GISAID) platform, which enables the design of targeted countermeasures, including therapeutics and vaccines, and improves global preparedness.

Developing the capacity for a global harmonized data infrastructure

The Virus Outbreak Data Network (VODAN, https://www.go-fair.org/implementation-networks/overview/vodan/) is an international initiative led jointly by the RDA, the Committee on Data for Science and Technology (CODATA), the World Data System (WDS), and GO FAIR. Its ultimate objective is to establish a federated global data infrastructure for the collection and analysis of data using artificial intelligence technologies. To ensure inclusiveness, several satellite initiatives have been created to support specific regions and countries. For example, VODAN-Africa was established in April 2020 and participating countries include: Ethiopia, Kenya, Liberia, Nigeria, Somalia, Tanzania, Tunisia, Uganda, and Zimbabwe. Three phases of work have been actioned since its inception. In the first instance, a Training of Trainers program was introduced to equip regional data stewards with relevant knowledge. The second phase of work has then focused more on producing FAIR, machine-readable observational patient data and advancing the analytical capabilities and ownership in local host facilities. Additionally, metadata architecture for clinical and research data has been augmented to align with local needs of participating countries, while adhering to the WHO's Smart guidelines.

1.4 Advancing policies and processes to support Open Science and FAIR, open data

"There is political will and willingness of investigators to share data during crisis…but we're running into challenges around governance and rules. It's difficult to do this during a crisis"

"Routine practices are needed to reduce barriers to open data and implement necessary science while protecting privacy"

"Build a global framework that can be adapted to localized settings"

"We need integration of disparate data sources for a complete picture. Do we have timely access to all the data needed?"

"Data and metadata can be highly situative and lose value or validity when taken out of context"

"There is a need for quality control and standardisation of data and sample collection"

"It is difficult to make data interoperable, but there can be a focus on interoperable systems"

"Data and information are being generated rapidly but how do we improve access to this?"

"Getting the right datasets together is the hardest part. Platforms can be built quickly"

"Involve everyone to discuss how to converge data policies"

"There is a lack of a rich knowledge base on data standards, data collections, sharing protocols and metadata standards"

"Data capturing systems have different levels of maturity and are built on a diversity of data models, definitions, and standards"

"We need to link epidemiological data with clinical and genomics data. These are not as powerful individually as they are linked together"

"Potential users of the data may not know details of the data" [1]

Source: A curated selection of significant quotations was taken primarily from the 'Enhancing access to research data during crises' workshop held in April 2021. A list of workshop presenters and panellists is available at Annex 4.

Pandemics are complex crises that are impacted by, and have implications for, a wide range of societal factors. This has been evident during the COVID-19 pandemic as effects of the crisis have been felt across almost all sectors of society. The ability of policy and science actors to integrate data and information from a wide breadth of different scientific disciplines and knowledge domains has been critical to national responses. The necessary inputs span from census statistics, to epidemiological, omics, clinical, and social sciences data. Open data and open science strategies have been critical to facilitating findability and accessibility, although having such strategies in place is not sufficient. Data access, generally and more specifically in relation to the COVID-19 response, varies considerably across sectors and scientific disciplines and access alone is not sufficient to ensure useability. For example, epidemiological models were critical for decision-making across all sectors of government during the COVID-19 response; however, there is no universally accepted international standard or coordinated system for collecting, documenting, and disseminating associated data and metadata, which makes international comparison very difficult.

Recognising the primary importance of open data to the COVID-19 response, several international initiatives have acted to accelerate the adoption of FAIR Data Principles (Findable, Accessible, Interoperable, and Reusable), a set of guiding principles proposed in 2016 to enhance the openness and reusability of data and other digital assets (Wilkinson et al., 2016[17]). In the early days of the pandemic, the Research Data Alliance (RDA) established the RDA COVID-19 Working Group, which developed into a major crowd sourcing activity, and published the COVID-19 Recommendations and Guidelines for Data Sharing for actors from across scientific disciplines (RDA COVID-19 Working Group, 2020[18]). The primary focus of the recommendations is making data FAIR and ensuring the reproducibility of research. They also explicitly address ethical, legal, and social issues such as access to indigenous data and participant consent. International community-led platforms, such as the RDA, proved to be an invaluable asset during the pandemic and yet they do not always attract the attention and support that they merit.

In a similar vein, the COVID-19 response has reinforced the importance of individual and international networks of trusted data repositories for findable and accessible data. To operate effectively, these networks need to be aligned through convergent governance frameworks and established data sharing agreements. In the best-case scenarios these repositories and networks were already in place before the pandemic, but in many scientific domains, notably in social sciences, their existence and connection with other disciplines was lacking. Beyond technological infrastructure, previous analyses of international data networks have also highlighted the importance of 'human interoperability' and cultural differences between disciplines, sectors, and countries (OECD, 2017[19]) In this regard, the COVID-19 response has, again, exacerbated existing barriers, underscoring the importance of addressing them to improve preparedness and response to forthcoming crises. Building common understanding and trust takes time and requires long term investment. It is very difficult to start de novo and produce an effective international data system during a crisis.

Box 4. Coordination of data activities

Coordinating data infrastructures to ensure completeness and consistency

In Canada, the VirusSeq Data Portal (https://virusseq-dataportal.ca/) was developed as a national open repository for all sequenced SARS-CoV-2 viral samples and associated depersonalised contextual data developed by the CanCOGen project (Stein and Katz, 2021[20]). The portal was developed in less than one month to address inconsistencies in how public health labs from different provinces were sharing data with international databases. A lack of standards for completeness and consistency, was resulting in only a fraction of available data being shared. VirusSeq operates as a centralised curator and ensures the automated harmonisation, validation, and submission of hosted data to international databases.

Improve findability and accessibility of regional COVID-19 datasets

The European COVID-19 Data Platform (https://www.covid19dataportal.org/) was launched in April 2020 as a collaboration between the European Commission and several member states and other partners to support scientists in accessing, sharing, and using COVID-19 data. The platform has three components: Data Hubs organise and provide open access to SARS-CoV-2 outbreak sequence data for use by European and global science communities; the COVID-19 Data Portal compiles and updates relevant datasets and tools; and, a federated archive provides controlled environment for researchers to share and access sensitive patient data. The platform's open standards allow researchers and systems to reuse and make reference to platform components to build other ecosystems adapted to local needs.

Once barriers to access are overcome, appropriate reuse and integration of data still requires harmonisation of the definitions and processes used in data collection and management. Progress has been made in establishing and implementing universal data standards in certain disciplines. However, in many areas there is an absence of commonly agreed standards for collection, documentation, and dissemination of data, code, and software, which introduces a major barrier to the use of data by third parties and its integration with other datasets. Longstanding challenges in reconciling different methodologies for data collection and interpretation across geographies, sectors, and scientific disciplines were amplified during the COVID-19 response. It was difficult for science and policy actors to understand the international context during the COVID-19 pandemic when statistics for confirmed cases, deaths, and recoveries were treated differently across countries. In some instances, the underlying methodologies were even subject to variability within countries (OECD, 2020[7]). Methodological inconsistencies can be intensified by distinct and differing purposes for data collection and by limited transparency regarding data quality and completeness (GloPID-R, 2019[15]). Throughout this project, scientists cited the importance of data being enriched to a certain standard to enable comparability and interoperability across studies and analyses. Data dictionaries and 'global, open, and unique identifiers' are important tools for researchers to reference digital objects unambiguously across scientific disciplines, improving interoperability and reusability as well as contributing to the findability of data.

Although the norms and culture for data sharing and reuse are diverse across scientific disciplines, social science research is subject to unique challenges. These stem from the diversity of social science disciplines and methods, dependence of research on human subjects and human interpretation, and the inability of scientists to standardise context-dependent data points without losing valuable information. Social sciences data are often not created for the purpose of research, and translation introduces additional risks of bias or misinterpretation. Even prior to the pandemic, concerns had been raised regarding a deficit in adequate infrastructure for sharing social sciences and community engagement data (GloPID-R, 2019[15]). Recent advancements in data repositories, which allow for the automatic connection of data contributors to hosted datasets and encourage communication between data owners and users might represent partial solutions by improving reusability, but more concerted international cooperation and strategic investment is also required.

Box 5. Traceability of Data

Connecting data owners and users to enable interoperability and appropriate reuse

Data repositories are increasingly adopting the practice of assigning digital object identifiers (DOIs) to research objects, such as datasets, which facilitate the consistent, unambiguous, and reliable identification and reuse across platforms (Bryant, 2013[21]). Their utility has been helped by the introduction of ORCID identifiers for individual scientists. For example, the ORCID DataCite Interoperability Network (ODIN), was a 2012 European Commission-funded collaboration to streamline the tethering of datasets to creators and users using interoperable metadata. Connecting owners and users of datasets and other interim research outputs also serves to address concerns regarding data quality and the appropriate allocation of credit to contributors. Data sharing initiatives developed in response to the COVID-19 pandemic have leveraged this work to ensure that data is being shared and combined in the most effective and transparent ways possible. For example, researchers are able to link data submitted to the EU COVID-19 platform with their ORCID accounts so that it's provenance is clear and it can be cited appropriately.

Facilitating communication between data owners and users.

Innovators Marketplace on Data Jackets (IMDJ) is a data sharing platform that facilitates wider sharing of data that may not be fully openly accessible. Data owners increase the visibility of their datasets with less risk of losing potential commercial value by filing a 'data jacket', or a "digest of a dataset, described as meta-data including the names (not the values) of variables in a dataset and other potentially useful information" (Ohsawa et al., 2015, pp. 47-48[22]). IMDJ has the potential to facilitate more appropriate reuse of data, allowing direct engagement between data owners and users and improving understanding of data prior to its use. It also informs the collection of new data by providing a forum for researchers to identify constructive research questions and potential gaps in existing data. During the COVID-19 response, close engagement between data developers and users enabled the development and design of new datasets to test emerging hypotheses and inform the creation of policy interventions in alignment with immediate need.

Mandating the accreditation and accountability of data users

The International COVID-19 Data Alliance's – ICODA's – operational standards set out the accountability of researchers in using the platform (https://icoda-research.org/). Users are required to complete onboarding and be ICODA accredited, ensure that data and outputs are created in line with project approval, and provide necessary documentation to ensure the understandability of outputs (ICODA, 2021[23]). As a social crisis requiring the integration and use of data from a diversity of sources and scientific disciplines, the pandemic response underscored the importance of development and use of data governance models and analytical approaches to ensure the reliability of inferences made by researchers. ICODA's governance structure includes a group of specialist advisors to inform the creation of data dictionaries, and a patient and public expert group to facilitate community engagement.

During the COVID-19 response, researchers and other data-users benefitted from the fact that data from a diversity of sources has been made available at a speed and granularity unprecedented for any pandemic or public health crisis to date. However, the sheer quantity of data has challenged the ability of scientists to complete important quality checks (Stoto et al., 2022[24]). Information sources are often dispersed and lack visibility due to disciplinary siloes and continuing preferences in some communities for sharing through informal, trust-based networks or for-purchase marketplaces. Data and knowledge curation has been a major challenge, although it appears that this has not been a significant focus of science policy during the pandemic, with only a handful of new initiatives being introduced specifically to support science and policy-makers in monitoring, understanding, and integrating novel scientific advancements into policy or knowledge development (EC-OECD, 2021[3]).

Many national governments and science actors have indicated that their ability to connect different data and knowledge sources in a useful way was challenged by systemic issues as well as by factors unique to the COVID-19 crisis. They have responded to this challenge in a variety of ways – from mobilising dedicated human capacity to the deployment of machine learning and other digital technologies. Some initiatives target data stewardship and the development of multivariate and multidisciplinary data, while others are focused on facilitating access to all relevant literature or synthesising new information. Common among them is the need to be able to leverage established efforts to make data and knowledge open, visible, and understandable[3].

Box 6. Open Scientific information

Improving the findability of open research outputs and incentivising reuse

Integration and reuse of data and knowledge can be facilitated by ensuring that open access publications are also submitted in globally accessible, machine-readable formats (i.e., XML). In the USA, the NIH has prioritised XML as an explicit requirement of their open access policy (NIH, 2022[25]). Additionally, in response to COVID-19, the institute has increased its engagement with downstream organisations, such as the Allen Institute, to develop resources and competitions that will promote and exploit open research. One such example is with the development of the COVID-19 Open Research Dataset (CORD-19), a living corpus of relevant machine-readable literature available for data mining, and its promotion through an associated Kaggle competition (Lu Wang L, 2020[26]).

Expediting systematic reviews for the real-time integration of new information

The novelty and rapid evolution of the COVID-19 pandemic translated into an ongoing deficiency in up-to-date systematic reviews to inform decision-making. In response, the Norwegian Institute of Public Health (NIPH) leveraged existing organisational expertise to establish a dedicated rapid review unit (Fretheim, Brurberg and Forland, 2020[27]). Simplified processes were designed to facilitate the expedited development of less formalised summary reviews within 1-3 days of request, improving the agency's ability to integrate real-time advances in knowledge into more timely science advice. The risk posed by the rapid process and the tentative nature of many of the inputs used i.e., preprints, was mitigated through transparency of the underlying methodology. [Additional lessons learned regarding the provision of science advice are included in the corresponding section in report 2 of this series.]

Curating scientific evidence in a comprehensive open repository

In response to the COVID-19 pandemic, the Chilean-based Epistemonikos foundation launched COVID-19 L·OVE (Living Overview of Evidence), an open repository and classification platform for COVID-19 evidence. The platform streamlines the access to scientific evidence by leveraging systematic methods and automation technologies to maintain the database and ensure its comprehensiveness (Verdugo-Paiva et al., 2022[28]). COVID-19 L·OVE accelerates access to a complete and trusted knowledge base, while preserving quality and enabling policy-makers to enact rapid, evidence-based interventions. This has potential implications for the general advancement of health-related science as well as crisis response.

1.5 Addressing vested and conflicting interests to accelerate access to critical research

"Too many established business models depend on the system being what it is. It will take time to change this"

"Knowing that there are commercial interests, it likely won't be open forever. How can we ensure that the public good is covered and continue to drive discovery by ensuring access to literature and data?"

"Balance is needed between protecting IP of data originator or provider versus developing licensing contracts and freedom to operate to enable research"

"It takes time to get through data governance constructs, particularly with big organisations and even when you are connected to people in upper management"

"It's important to respecting users and producers but also realise that the data producer may not be the one who analyses the data. We must credit the creator of datasets and actors who analyse and develop findings"

"There is variation in cycle times for contracts and data sharing of days, weeks, or many months. Delays are from publication lag and regulatory reviews as data sharing is contingent on publication, even with failed trials, because people want to be able to publish first."

"Experience from SARS, H1N1, Influenza, and Ebola: slow and inconsistent sharing, stealing due to exportation of samples without proper material transfer agreements, concerns about ownership and IPR, concerns about the possibility to publish data that was already publicly released, and lack of trust"

"Preparation and submission of data is not a priority because of a lack of resources. If a trial is positive, those who are involved are busy and if negative, they are reassigned"

"We need access to data and less fear about making data available for secondary analysis" [1]

Source: A curated selection of significant quotations that was taken primarily from the 'Enhancing access to research data during crises' workshop held in April 2021. A list of workshop presenters and panellists is available at Annex 4.

COVID-19 has been cited as a catalyst for open science, including open data (and software) and open access to publications (Besançon et al., 2021[6]). During the pandemic, many countries took policy action to promote open data, open access to publications, or both (EC-OECD, 2021[3]) (Paunov and Planes-Satorra, 2021[1]). In January 2021, the OECD adopted a revised Recommendation on Access to Research Data from Public Funding (OECD, 2021[4]) and in November 2021 UNESCO adopted a new Recommendation on Open Science (UNESCO, 2021[29]). Irrespective of these actions and intergovernmental agreements, there are persistent conflicts between academic and commercial incentive structures and Open Science principles. In academic settings performance evaluation, professional advancement, and the ability to attract research funding is largely dependent on the authorship of academic papers. Prior to publication, researchers are motivated to limit access to results and thus safeguard the novelty of their findings. However, publication in peer reviewed journals can take several months and can delay the accessibility of the research results and data, which are necessary for effective crisis response. Established incentives and biases towards positive results also often impede the publication or sharing of inconclusive or negative results, which can have implications for the trajectory of future research. From the commercial publisher perspective, removing pay-walls to provide open access to publications can threaten commercial viability, whereas increasing article processing charges may generate a discriminatory pay-wall for authors.

Tensions between academic and commercial actors with regards to access to scientific publications have been addressed to some extent by policies mandating that results from COVID-19 research must be made openly accessible. This has been complemented by a number of initiatives in which commercial publishers and public research organisations have come together to enable open access to COVID- related research articles (see Figures 2 and 3). It is an open question as to whether this increased momentum towards open access to publications will continue as the pandemic recedes. However, this is perhaps no longer just an issue for science: there has been enormous public interest in scientific information, and it is hard to imagine that the transparency which the public has demanded can be served by traditional limited access models for scientific publications.

Preprint platforms were widely adopted during the pandemic, with the number of submissions increasing exponentially in relation to pre-COVID levels and past response to emerging infectious disease (Johansson et al., 2018[30]) . While preprint platforms have been shown to be important tools in accelerating the communication of preliminary findings, enabling early feedback from peers, and ensuring appropriate attribution, their use during the COVID-19 response emphasised the need for appropriate safeguards (Sarabipour et al., 2019[31]). It is important that preprints are understood as preliminary, non-peer reviewed findings when used by the media, governments, and science actors. They must be interpreted and used with appropriate caution by all stakeholders and the public needs to understand their limitations relative to peer-reviewed scientific publications. It is also critical that researchers have access to the study design, methodology, and data to validate and reproduce findings. During the early stages of the COVID-19 response, less than half of related preprints made data openly available without restriction (Larregue et al., 2020[32]).

Box 7. Enabling open access

Mandating open access to publications through government legislation

In the USA, the NIH open access policy was initiated by Congress in 2004 and was first implemented as a request for grantees to make published works available in open access repositories (Suber, 2008[33]). Following a 4 percent adherence rate in 2005, it was made a legislated requirement in 2008. The policy requires that grantees make an electronic version of the final peer-reviewed manuscript available via PubMed Central within 12 months of official publication. During the COVID-19 response, this precedent enabled the NIH to leverage its established relationships with publishers, acting as a central point of discovery and access and enabling open access to 185,000 papers from the 1970s onwards.

Prioritising data collection and sharing in grant applications and funding requirements

The research data policy of the Bill and Melinda Gates Foundation (BMGF https://openaccess.gatesfoundation.org/open-access-policy/) requires that all data from funded research, with limited exceptions, be made publicly available at the time of publication. This includes disclosure of a Data Availability Statement providing the location of primary and meta-data and other outputs required to understand and reproduce the results. BMGF also covers fees for publishing in fully Open Access journals. Established policies to ensure immediate and open access to reproducible research results were critical to the pandemic response in that mechanisms and processes for data governance had already been tested and normalised. While not obligatory, grantees are encouraged to adhere to FAIR principles and to deposit submitted manuscripts and subsequent versions on preprint servers. Additionally, the BMGF requires applicants to submit data management plans outlining expected data outputs and proposed methodologies for collection, storage, and sharing. The foundation supports grantees in defining the type of data to be collected during project activities and the creation of data templates.

Conditional, partial, and time-restricted access to publications and related data are mechanisms that had been adopted prior to the pandemic to try and reconcile different interests but their limitations became clear in the midst of a global crisis. While there has been unprecedented openness during the COVID-19 pandemic in comparison to previous health crises, the extent to which this will be sustained remains unclear. Open access publications have largely been limited to a small core of knowledge directly linked to COVID-19 and lacked inclusion of the broader interdisciplinary context required to fully understand, contain, and manage the pandemic (OECD, 2020[7]) (Lariviere, Shu and Sugimoto, 2020[34]). In their roadmap for data sharing, GloPID-R points out the ambiguity around what constitutes a public health emergency (GloPID-R, 2019[15]). The need to 'switch on' open access measures can waste time and limit information access in the critical early stages of a crisis, as well as restricting the science activities undertaken during normal conditions to prepare for future crises. To be effective, particularly in preparing for and responding to crises, the international community must take action during 'respites' between crises to prioritise the functionality of science systems and their ability to generate and disseminate timely results for society. It is important that the positive progress made over the past 2 years is built on to ensure that open access to publications and data becomes a reality. [The need for policy and science actors to actively engage with conflicting priorities is covered in more detail and at the system-level in the third report of this series.]

1.6 Facilitating the rapid, ethical, and secure collection, stewardship, and use of sensitive data

"Key conversations are needed around privacy and a balance between where things can and should be open and promoted as such and when this is not possible"

"The datafied society as a new currency for governance allows us to know the pandemic better and faster but exposes some tensions"

"There are differences in policies associated with the data. Some datasets are too sensitive…and strictly available through specific infrastructures"

"In the biomedical field, there are data which need to be preserved for longer timelines than projects are lasting…This requires resources to properly preserve the data and liabilities for host institutions. We're not only storing our own data but data produced by people all around the world. This requires global action"

"There is a challenge of balancing between guardianship of data and stewardship and liberation to bring it forward to inform policy and advance research and training opportunities"

"Balance is needed between sustaining confidentiality of data as a legal requirement at the same time as making them available under challenging circumstances like COVID"

"It is very sensitive because there is indirectly identifiable data…it cannot be utilised with AI or Big Data workflows"

"Right now most of the data is not in public hands, it's in the hands of Big Tech"

"Only through emergency use operations could data sharing and approval processes be accelerated"[1]

Source: A curated selection of significant quotations was taken primarily from the 'Enhancing access to research data during crises' workshop held in April 2021. A list of workshop p,resenters and panellists is available at Annex 4.

In crisis response, there is a need to facilitate expedited and potentially remote access to sensitive data from different sources including clinical studies, patient records, surveys, and social science research involving human subjects, for a variety of purposes. Data controllers, repositories and other responsible science actors must ensure that sensitive data are collected and shared in line with ethical and legal requirements and that procedures for access are proportionate to the need for data confidentiality. Many of these issues are identified in a recent Recommendation of the Council on Enhancing Access to and Sharing of Data (OECD, 2021[5]). At the same time, there are unique challenges to ensuring the validation and reproducibility of findings based on sensitive data. During the COVID-19 response, deficiencies in current review processes resulted in the retraction of several significant studies, including the notorious Surgisphere Scandal, where anomalies in the underlying data and refusal of the firm responsible for a clinical database to submit to an independent audit led to retractions in several high-profile scientific journals and impacted public trust in science (Baker, Van Noorden and Maxmen, 2020[35]). While sensitive data cannot normally be openly shared, policy-makers, funders, and review boards need to put in place rigorous quality control measures, such as requiring that primary data be reviewed by an external trusted party, to validate research results. If not, then there is a serious risk that the 'social contract' which is necessary to enable the use of personal data in research will be withdrawn.

Data security poses a number of concerns, which relate primarily to the capacity of repositories and infrastructures to store, share, and facilitate the use of sensitive data, while preserving confidentiality and privacy. Integrating data from different sources can provide information and insights that are extremely valuable for crisis management, but this can also raise new questions regarding privacy protection. Whilst anonymised personal data is useful for many research projects and has traditionally been considered safe, once certain data sets are linked it becomes very difficult to conceal personal identities (OECD, 2020[36]). This was a particular challenge with the use of data from tracking apps during COVID. Continuous action is required from governments, data repositories, and other data holders to facilitate the evolution of data security and governance in line with technological advancements.

Box 8. Sensitive data

Preserving confidentiality while enabling the use of global multidimensional datasets

The International COVID-19 Data Alliance (ICODA, https://icoda-research.org/) was created in response to the COVID-19 pandemic to support scientists and policy-makers in leveraging health data for an effective global response. The consortium accelerates data access for high priority ‘Driver Projects’, which are then used to provide scientists with direct, controlled, and federated access to curated data and analytical tools. Data contributors can control access and authorisation approvals for their datasets and the location of the data, with data access requests managed through a dedicated platform (ICODA and Aridhia Informatics, 2021[37]). Data security is also maintained through malware scans of uploads and ‘secure airlock processes’ required to access and exit the secure ‘Workbench’ environment.

Using technical and governance innovations to streamline the security of sensitive datasets

The Ontario Health Data Platform (OHDP, https://ohdp.ca/overview/) was launched in July 2020 to support the provincial government’s COVID-19 response through Big Data analytics and machine learning. The platform is embedded within an established regional research computing ecosystem as a ‘federated high-performance computing environment’ with the capacity to link large health datasets from different organisations. OHDP hosts datasets that support different research in two different environments, OHDP-I and OHDP-Q. This allows the platform to streamline support based on high-performance computing and confidentiality requirements of the data and proposed research project. Access is expedited through a standardised one-window application overseen by a dedicated ethics board, which facilitates precise access to datasets aligned with project needs. The ethics board also ensures that users are trustworthy, accountable, and acting to preserve privacy and confidentiality.

Guaranteeing accountability to citizens

The authority of the Norwegian Institute of Public Health (NIPH) to establish preparedness registers was enshrined in legislation in 2012 (Elsrud and Lindman, 2021[38]). Preparedness registers are mechanisms through which the institute can collect and organise patient information to better understand the situation and inform the development of policy and countermeasures. Legislation requires that preparedness registers are terminated following crisis resolution. As such, the register established for COVID-19, Beredt C19, builds on existing national surveillance systems (Emergency preparedness register for COVID-19 (Beredt C19) – NIPH (fhi.no)). Data can only be accessed NIPH employees with designated approval and is limited to the data required to address clearly defined questions. While personally identifiable information is not stored in the preparedness registry, accountability is safeguarded by mechanisms that allow civilians to request information on which datasets contain personal information and how it has been used.

Use of advanced digital data technologies, such as geolocation and biometrics, has been an important feature of many national COVID-19 responses. Numerous new policies and programmes were introduced to accelerate the development of contact tracing apps or improve population surveillance capacities (OECD, 2020[39]). However, these initiatives come with risks to individual privacy and security. Concerns have been raised by several international organisations, including the UN, about the implications of these technologies for human rights if their adoption is normalised beyond crisis response (Bentotahewa, Hewage and Williams, 2021[40]). During the COVID-19 pandemic several countries introduced ‘extraordinary measures’, which required them to modify their normal regulations and processes for data collection. Based on an analysis of such measures during the pandemic, the OECD has recommended that their use be implemented with full transparency, accountability, and clear parameters for reversal (OECD, 2020[36]). Both privacy enforcement authorities (PEAs) and civilians should be engaged to ensure that appropriate safeguards are in place before the introduction of such extraordinary measures. There is an important role also for the research community, as both collectors and major users of such data, to be involved in the design and implementation of such safeguards.

Data Access Policy Recommendations

Recommendation[4]	Policy Options
1. Established data infrastructures should be leveraged and built on to enable stakeholders across disciplines and sectors to contribute to the response to crises and other grand challenges.	1.1. Proactively allocate the support required to develop infrastructures and tools for real-time data collection, management, and analysis across all relevant scientific domains. 1.2. Make additional strategic investments into institutional, disciplinary, sectoral, or national data infrastructures, taking into consideration economies of scale, flexibility, and resilience.
2. Policy-makers, funders, and research institutions must ensure that data collection, stewardship, and use is inclusive, representative, and ethically appropriate when responding to crises and other societal challenges.	2.1. Proactively fund science activities to address deficiencies in the availability of population data disaggregated by key demographic variables so that the tools, rules, and processes are in place to assess vulnerable groups, during crisis response. During crisis response, humanitarian actors should be engaged in data collection and management to ensure alignment with emergency operations and facilitate consideration of vulnerable and underrepresented communities 2.2. Develop mechanisms, tools, and skills to incentivise and support the engagement of community groups, patients, and the citizens in data science activities, from the co-design of projects to public-led citizen science initiatives. 2.3. Mandate or encourage the adoption of principles that promote the representation and engagement of 'neglected' population groups in the development of research and the collection, stewardship, and governance of associated data e.g., the CARE principles. 2.4. Implement and support long-term science and data literacy training through the established education system and ad hoc initiatives targeted to specific population groups, e.g., seniors, prisoners, migrants, and other key stakeholders, such as policy-makers and elected officials.
3. Policy-makers and funders must prioritise global preparedness by addressing structural barriers that impede low and medium-income countries (LMICs) from accessing or contributing to international science activities to prepare for and respond to crises.	3.1. Catalyse joint international partnerships and investments in LMICs to develop and strengthen infrastructures and local scientific capacities, including for the management and use of FAIR data. These initiatives should aim to ensure operational continuity of data infrastructures during crisis response. 3.2. Support established and emerging initiatives in LMICs to develop and host data assets and encourage international networking of repositories to provide equitable access to globally inclusive data. Material transfer and data sharing agreements should be in place prior to crises and prioritise the appropriation of benefits by LMIC partners in a way that does not impede collaboration. 3.3. Include and ensure that representatives from LMICs have a voice in international efforts to advance the adoption of Open Science policies globally.
4. Policy-makers, funders, and institutions must urgently update and advance policies and processes to support Open Science and FAIR data across all domains.	4.1. Facilitate the adoption of Open Science practices across scientific disciplines and tailor levels of support and guidance to the needs of different disciplines. 4.2. Broad and inclusive collaborations should leverage and build on established national and international efforts to develop, test, and advance Open Science and data sharing policies and resources. These initiatives should also engage and support relevant stakeholders in coordinating and harmonising activities across jurisdictions and expanding global participation. 4.3. Support connectivity and coordination between owners and users of related research outputs (e.g., peer-reviewed literature and preprints, datasets, and software) using tools, such as standardised, cross-disciplinary data dictionaries and digital communication platforms.

	4.4. Raise the visibility of open data and knowledge resources and facilitate and incentivise the stewardship, integration, and reuse of data to address targeted challenges. Established instruments, such as data sharing or material transfer agreements can be used to connect data repositories and other data holders. Innovative policy tools, such as competitions and hackathons can also be deployed to engage a diversity of stakeholders on targeted issues. 4.5. Data repositories and other data providers should drive the testing and adoption of enabling technology to facilitate and expedite the curation, recombination, and meta-analysis of existing knowledge (e.g., *machine-readable formats, linking to preregistration or open-source repositories, high-powered computing infrastructures, and artificial intelligence*).
5. Policy-makers, funders, and institutions should actively address vested and conflicting interests in the development and accessibility of knowledge to encourage accelerated and responsible sharing of research with importance to crisis response.	5.1. Registration of publicly funded clinical studies in international trial registries, and the open sharing of study protocols, should be mandated to reduce duplication and improve trial design. Subsequent publication of results should coincide with the release of relevant data, accepting there may be necessary limitations on access to this data. 5.2. Funders should facilitate and incentivise the creation and sharing of datasets as an outcome of funded research. Data collection can be enabled by requiring the submission of data management plans, defining data deliverables, and allocating grant funding to relevant activities at project conception. Evaluation structures should also be adapted to appropriately acknowledge novel and curated datasets as first-class research outputs and recognise the contributions of data creators and stewards. *5.3. Incentivise researchers to make publications and underlying data (including software and study design) from publicly funded research projects openly accessible. Open access policies can be used to mandate or encourage the submission of academic papers and data to open access journals and data repositories.* 5.4. *Access to important research results should be accelerated through a variety of avenues. Institutions and publishers can be incentivised to develop expedited, transparent, and trusted peer-review processes and capacity. Use of preprint platforms should also be encouraged to make preliminary outcomes openly accessible. However, safeguards, such as making supporting data available in conjunction with preprints, are important to ensure replicability.*
6. Policy-makers, funders, and research institutions should facilitate the rapid, ethical, and secure collection, stewardship, and use of data during crisis response, while accelerating access to high-priority research.	6.1. Promote the universal adoption of informed consent procedures and sharing agreements that enable ethical downstream sharing, reuse, and preservation of data. Particular attention must be paid to the acquisition, development, and reuse of social sciences data. 6.2. When extraordinary measures for data collection and analysis are adopted during crisis response, these must maintain full transparency and accountability and include clear parameters for reversal. A diversity of stakeholders, including scientists/data users, privacy enforcement authorities and civilians, should be engaged ex ante to ensure that actions are warranted, proportionate, and consistent with societal values. 6.3. Proactively engage with private sector actors with robust data or analytical resources and leverage these connections during crisis response. Good practice should be translated into policy that facilitates and incentivises ethical data sharing and preserves the constitutional rights of civilians. 6.4. Promote the use of federated safe computing environments to link large health datasets, whilst maintaining personal privacy and security. Data repositories should be supported in testing and adopting novel technical innovations and approaches to protect sensitive data and mitigate risks posed by cyberattacks. 6.5. Promote or mandate the use of certified trustworthy data repositories. Methodologies to ensure long-term data preservation, rigorous governance, and accountable use of data should be developed transparently in collaboration with relevant stakeholders, including repository users, policy-makers, and civil society representatives. Governance mechanisms can include the use of ethics boards, public inquiry channels, and mandated onboarding, training, and accreditation for researchers accessing sensitive data.

*Recommendations and policy instruments related to open access publications have been italicised

2 Mobilising and coordinating diverse research infrastructures

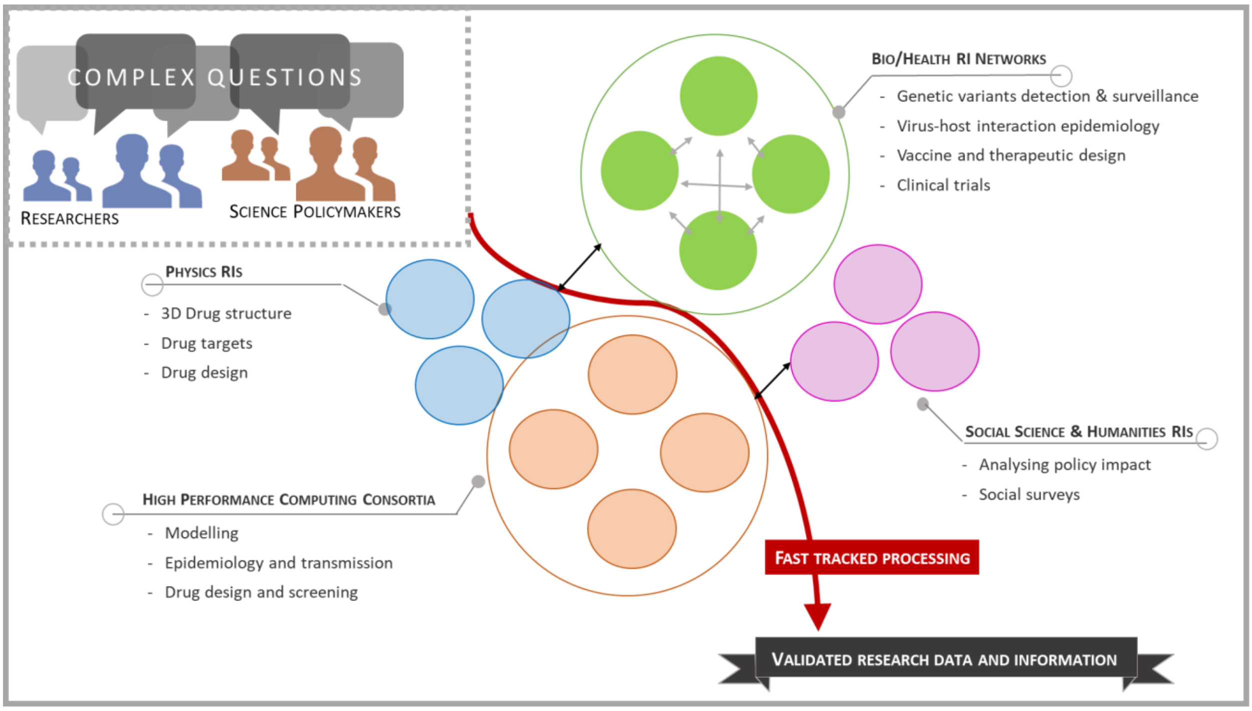
Key Messages

During the COVID-19 pandemic response, research infrastructures (RIs) were rapidly mobilised in the biomedical and life sciences, and across many other scientific domains. They played an essential role, as providers of equipment, materials, data and know-how and as an interface for interdisciplinary and international collaborations.

- Research Infrastructures are predisposed to act as critical assets that can be rapidly mobilised in national and international crisis preparedness and response; however, their ability to operate effectively in this capacity is dependent on the approaches taken by science policy-makers and funders.
- Secure, sustainable, and agile funding and governance are critical to supporting RIs in maintaining and scaling-up capacity, as well as enabling them to keep pace with the evolving technological landscape and the needs of the science system.
- The ability of science systems to address cascading crises and grand challenges will increasingly depend on connectivity and collaboration between scientists, industry, and other stakeholders. This needs to happen horizontally, across scientific disciplines, and at different stages of the R&D pipeline, and RIs have a critical role to play in catalysing these interactions.
- During the pandemic response, the activities of biomedical or life science RIs were primarily limited to the national or regional context with limited global collaboration (the notable exception to this being data management/access in fields, such as genomics, where accredited data repositories in international networks have well established mechanisms for data preservation, documentation, and reuse). There is an opportunity for RIs to better support international governing institutions, like the WHO, in responding to future global crises, by playing a more active global coordination and networking role.

As physical and digital sites of research activity, training, exchange, and collaboration, RIs and their services can be said to form the backbone of science systems. While RIs generally have resources and expertise that are applicable to many scientific domains and stages of research, they can be, and often are, segmented according to disciplinary focus. This became evident during the COVID-19 response when biomedical and life sciences RIs were immediately mobilised with high visibility, whilst a diversity of other RIs with indirect or unrelated mandates for health-related research also contributed but attracted less policy attention (Figure 4). Regardless of classification, the demonstrated capacity of national and international RIs to mobilise swiftly, effectively, and in coordination with relevant partners underscored the significance of their role in responding to crises and other complex societal challenges. At the same time, they are influenced by diverse and evolving financial, political, and historical contexts; difficult to define, characterise or group; and have a variety of governance and funding models (ESFRI, 2020[41]) (Larrue, 2022[42]). This heterogeneity can pose a significant challenge to science policy-makers in developing and leveraging RIs to their fullest potential[5].

Figure 4. Mobilising RI ecosystems in response to the COVID-19 pandemic



Note: The infographic is a conceptual representation of how the mobilisation of a variety of different Ris contributed to multiple aspects of the COVID-19 response.
Source: Authors' design.

Despite many analyses, there is a lack of clear consensus on where the boundaries lie between RIs and other science system facilities, such as public research institutes (PRIs), research and technology organisations (RTOs) and technology infrastructures. For the purposes of this document, the simple working definition deployed by the GSF in past analyses has been applied. Hence, RIs can be considered as *"organisational structures dedicated to delivering data or services for basic or applied research,* (OECD, 2017[43]). To accommodate heterogeneity in how elements of science system are developed and described across borders, this definition has been adopted to be inclusive. [Additionally, RIs dealing almost exclusively with data, such as data repositories, have been covered in the previous section on "Enhancing Data and Information Access"].

2.1 Recognising and supporting RIs as assets for crisis preparedness and response and long-term resilience

"COVID has been a vital catalyst for recognising and resourcing RIs to their fullest potential in response to crises"

"To prepare for crisis we need to stress-test with what is built and expand during moments when we're not in crisis"

"The ears of the funders are now open, but this will fade within 6-12 months"

"Ideally, funding would be provided for proactive efforts to expand infrastructure, build capacity through training, recruitment, fellowships of global experts, and develop rapid response networks"

"Networks and other RIs can become extensions of government in times of crisis. They should be officially recognised as assets in crisis planning with agreements and funding in place to maintain readiness to respond. This has not happened historically"

"Who's at the table in terms of boards of directors has significant

"RI projects need to cooperate with government and with each other through cocreation and co-ownership approaches"

"There needs to be a large diversity of RIs in the landscape as nobody can predict the expertise that will be needed in future crises"

"RIs have shown flexibility with readjustment of programming to align with existing socioeconomic needs"

"It is helpful to have crisis units set up in institutions to help face the crisis"

"The ability of RIs to respond depends on their state of readiness. It is critical that the right expertise, technology, data and analytics, and partnerships are already established"

influence on strategic plans for sustainability and preparedness…having those conversations is critical to the translation of activity into the policy domain"	"The institution faced a crisis in not belonging to a relevant research field, but any RI can contribute to any crisis"

Source: A curated selection of significant quotations was taken primarily from the from the "Mobilisation of Research Infrastructures" workshop held in May 2021. A list of workshop presenters and panellists is available in Annex 4.

Budgetary challenges have historically impeded the ability of countries to commit long-standing and secure funding to RIs. This has impacted the sustainability and effectiveness of science systems by preventing some RIs from simultaneously operating at the cutting edge of research (their primary mission) and fostering operational resilience. Yet, with the rising prevalence of complex global challenges and related, geopolitical tensions, there is growing consensus that this tension must be overcome (ICRI, 2021[44]). Effective integration of crisis response capabilities into the mandates of RIs will require a shift from the prioritisation of short-term financial efficiency (and an increasing dependence on short term project funding) to building strategic redundancies, resilience, and long-term effectiveness. However, secure and sustainable funding on its own will not be enough. As demonstrated by COVID-19, grand societal challenges cut across siloes between disciplines, sectors, geographies, and government domains. As such, the development and operation of elements of science systems, and in particular research infrastructures, deployed to address these challenges must also promote collaboration at the system level.

Box 9. Long-term investment and flexible design of RIs

Fugaku is a Japanese supercomputer designed to support the achievement of Society 5.0 and the protection of safety, comfort, and wellbeing. The initiative began as a collaboration between the public organisation, RIKEN and private firm, Fujitsu, in 2014 (Ishikawa, 2020[45]). Project partners adopted a cooperative design approach to ensure the functionality and alignment of supercomputer components. This approach instilled the flexibility to adapt to a wide range of applications and to accelerate timelines and bring the supercomputer online during the pandemic response. While software development occurred through ongoing collaboration since 2012 between RIKEN and Fujitsu, more recent stages of design also integrated insights from over twenty working groups targeting hardware, software, and applications. Close collaboration between application and system developers has been maintained from project inception to ensure mutual understanding of requirements for different aspects of the system.

During the COVID-19 response, Fugaku has been used to advance scientific knowledge related to the development of new drugs and treatments, as well as to model virus spread and contamination in various in-door and outdoor settings. Its use has been targeted to address specific events in Japan's national pandemic response. Results of the first completed study using the supercomputer related to the effect of partitions in offices and ventilation in commuter trains on the spread of the virus and were published following the first wave of infection when people were preparing to go back to work (Ishikawa, 2020[45]). The strategic direction and relevance of research activities during the COVID-19 response might be attributed, in part, to the transdisciplinary mix of organisations involved. In addition to the inclusion of RIKEN and several national higher education institutions, there is also representation from a foreign university, industry, and government representatives from across a range of sectors, including infrastructure, transportation, education, and municipal affairs.

During the COVID-19 response, many of the core characteristics of RiIs as research service providers contributed to their ability to adapt and rapidly align their operations with emerging scientific and societal needs. This occurred globally and across RIs within and beyond the biomedical and life-sciences domains, demonstrating their important strategic role as catalysts to mobilise and support the overall science system. It also emphasised their status as sites of collaboration between diverse and disparate partners and as focal points for the development and dissemination of unique and cutting-edge research and data.

Many RIs were challenged with having to rapidly change priorities and accommodate new users, while maintaining support for established projects and unrelated high-priority research. Even RIs operating in fields of direct relevance to the COVID-19 response faced challenges posed by capacity constraints. Tried and tested mechanisms are necessary to support RIs in rapidly adapting operations and reallocating existing and new resources outside of established funding cycles. Agility and flexibility can be improved through mandates that prioritise regular engagement and collaboration between RIs and other actors within and outside of science systems.

Box 10. Expanded RI mandates

Identifying and investing in national emergency response centres

The Canadian-based Vaccine and Infectious Disease Organisation (VIDO-InterVac, https://www.vido.org/) was founded in 1975 as an infectious pathogen containment facility, with the flexibility to meet advanced containment requirements. The institute was the first Canadian facility to isolate the virus and have a vaccine candidate in clinical development. However, because the scope of its operations is normally limited to the pre-clinical lab phase, outsourcing manufacturing activities resulted in significant delays. As a result, the Government of Canada agreed in April 2021 to fund an expansion of VIDO's mandate to become Canada's premier centre for pandemic research. Funding to construct Canada's only containment level 3 manufacturing facility will mitigate the institute's need to rely on external support for research, testing, and manufacturing.

Regarding system connectivity, VIDO has also served as a site of collaboration to address emergent community-based needs throughout the pandemic. An example of this is the collaboration that occurred between the institute and a fundamental science RI, the Canadian Light Source that provides a synchrotron light source to enable scientists to 'see' matter at a microscopic level. The partnership was formed to address a request made by the Saskatchewan Health Authority to mitigate a potential shortage in N95 respirators and other personal protective equipment (https://www.lightsource.ca/public/news/2020-21-q3-oct-dec/extending-the-lifespan-of-n95-masks.php).

Enabling RIs to innovate and contribute to crisis response.

Despite operating in a scientific field lacking direct relevance to COVID-19 or health crises, the Italian National Institute for Nuclear Physics (INFN) was able to contribute significantly to the national pandemic response. Several structures were put in place in the institute's initial response: 1) a crisis committee to manage the organisation's contribution and assist its leadership; 2) a statistics-focused working group, COVIDSTAT INFN, to use high-performance computing (HPC) assets to ensure openly accessible and current statistical analyses of daily government data; and 3) an internal channel for scientists to engage with each other and put forward project proposals (INFN, 2020[46]). INFN coordinated the development of a variety of initiatives to support medical research and the implementation of interventions to limit transmission. The success of these initiatives has been made possible by INFNs unique expertise and ready access to large-scale equipment and data analytics. INFN leadership has attributed the ability of the institute to contribute to the COVID-19 response to the importance of foundational competences, such as computer science, statistics, simulation, and data analysis to both fundamental and applied sciences, as well as the institution's strategic prioritisation of flexibility and open-mindedness. In addition, INFN was able to leverage a history of working with biomedical and pharmaceutical companies through applied interdisciplinary research programs and collaborations.

Most of the science policy initiatives introduced to support RIs in addressing the COVID-19 pandemic relate to funding in the biomedical and life sciences (EC-OECD, 2021[3]). A small number of initiatives were targeted to other areas, although, these were primarily limited to high-performance computing. In general, funding instruments were structured in one of three ways: as emergency transfers to RIs; funds to existing or novel programmes; or, funds to specific projects. Among these initiatives, there was a relatively even split between those with a broad set of objectives and those targeting specific outcomes. Much of the latter focused on surveillance, diagnostics, vaccines, and therapeutics, while only a small number included policy needs for scientific knowledge or the social sciences. In a handful of instances, policy initiatives were introduced to develop novel crisis response structures that ranged from dedicated response units and research institutes to national RI networks. At the same time, very few actions had been taken, up to the time of writing, to support policy and science actors in understanding the constraints of current RI systems. Only one was reported via the OECD STIP Compass survey: a whitepaper completed by the Korean National Medical Centre to analyse research resources available for the health and public systems' response and provide recommendations to improve the system and its governance structure.

2.2 Investing in and scaling up human capacity for crisis preparedness and response

"Operations can be made more sustainable through industry partnerships for training and recruitment"

"National centres focused on emerging diseases can act as fire departments with trained expertise and workers in place to respond quickly"

"We did ten times the volume of normal contract research, but this required a reallocation of resources and resulted in a shortage of manpower, fatigue, and burnout"

"The scale of work has been at the expense of human resources. A lot of people in research are at the brink of what

"Recognise the importance of training in research… one-third of researchers are grad students"

"Education and training of broad range of stakeholders and the next generation is key to ensuring preparedness"

"Had to find people willing to work 24 hours a day. Typically shifts in level 3 containment are 5 hours before a break"

"Ris should not have to go out to recruit people during the pandemic or crisis, train them, and get them to where they are working comfortably at level 3 or 4, which requires 4-5 months of intensive training"

they can do; they're operating in crisis mode"

"Hardcore work must be done on site in terms of training. This requires top-down direction to foster HR that will enable a bottom-up approach and then synergistic collaboration between the top and bottom."

"There will always be other aspects or uses than those you can think of. Too many users is trouble"

"RIs still have a normal group of scientists and users that want to work with the infrastructure and you cannot just abandon those. You must balance demand from both groups in the future" [6]

Note: A curated selection of significant quotations was taken primarily from the from the 'Mobilisation of Research infrastructures' workshop held in May 2021. A list of workshop presenters and panellists is available in Annex 4.

Human capacity is important for RIs in terms of their ability to contribute to advancing the cutting edge of science but also in their role as training sites, developing expertise both for internal operations and the broader science system. Challenges related to attracting and maintaining qualified scientific expertise, in addition to management and administrative staff have featured consistently in analyses of RIs over the past decade (OECD/Science Europe, 2020[47]) (OECD, 2017[43]). More recent analysis has also emphasised the precarity of research positions, which is a problem for science systems as a whole and RIs more specifically (OECD, 2021[48]). While staff shortages can critically impact the ability of RIs to contribute to a crisis response, science policy-makers can provide the support required to address talent scarcity proactively but this requires the prioritisation of resilience over financial efficiency. Ideally, RIs should have robust and evolving staffing policies in place to ensure that all staff categories are maintained at sufficient levels. However, the ability of RIs to attract, train, and retain staff depends on a variety of factors, including the national context, the international nature of the infrastructure and its legal status (OECD/Science Europe, 2020[47]). Flexibility to act independently or contribute to broader science policy discussions can help RIs in scaling internal capacity or deploying resources to address needs in the science system as a whole.

The speed, scale and intensity of the required scientific response to the pandemic exposed a deficit in specialised skillsets and expertise in some RIs, e.g., the skills required to work in a level 3 or 4 containment facilities. Despite deficiencies in capacity, very few policy initiatives were introduced to support RIs in employing new staff and those that were, appear to have been limited mainly to short-term fellowships (EC-OECD, 2021[3]). Personnel shortages required institutions to allocate scarce administrative capacity to find candidates willing to work under challenging and sometimes dangerous conditions. In the case of infectious agent containment facilities, these challenges were also compounded by the amount of time required for training, which can take several months under normal circumstances. At the same time, the urgency of the situation motivated many organisations and staff to adopt a high-intensity and, in the longer-term, unsustainable approach to work.

In addition to supporting RIs in mobilising human capacity to respond to crises, it is important that RIs are also recognised and supported as providers and enablers of training and education. The development of general and specialised skillsets, including the skills required for crisis response, requires a long-term strategic approach and corresponding funding commitments. Again however, the challenge is more than just funding. Depending on the specific context, not all training and capacity building initiatives will elicit equally positive or far-reaching effects. The integration of elements, such as labour mobility, industry partnerships, or multi-modal/digital training resources, have been shown in different contexts to result in important multiplier effects for capacity enhancement (see Box 11).

Box 11. A capacity building and training role for RIs

The Pirbright Institute provides the UK with the capacity to predict, detect, understand, and respond to livestock and zoonotic viral diseases. In addition to its national focus, the institute has significant expertise in surveillance and diagnostics from working internationally to address and prevent outbreaks, including African swine fever and foot-and-mouth disease. Training and capacity building are central to the organisation's mandate in both an international and a national capacity. The institute has several established training initiatives, such as Project SpirE, a five-year project to share critical infectious disease expertise to a global audience through a blended learning approach, which includes face-to-face, hands-on, eLearning, and Virtual Reality methods (The Pirbright Institute, 2020[49]). Established experience and training materials enabled Pirbright to support the National Health Services (NHS) in increasing its diagnostic testing capacity during the COVID-19 pandemic response. The institute supplied critical infrastructure, staff, and scientists, while also providing training to new staff on sample management, biosafety, and scientific diagnostic procedures (https://www.pirbright.ac.uk/covid19).

2.3 Empowering RIs to adopt the innovations required to evolve and advance system resilience and connectivity

"RIs have shown the ability to adapt to day-to-day changes and unprecedented conditions despite containment measures and pandemic restrictions"

"Because the organisation is a distributed e-infrastructure, it's designed in such a way that it could contribute solutions arising from challenges faced from lockdowns"

"Forced to change modus operandi to turn in-person operations to online rooms for discussion, training, etc. The nature of the infrastructure provides advantages that enable adaptation to new emergency situations but not all of these things can happen virtually"

"The team had to abandon the normal workflow of service provision to deal with cybersecurity issues. This required immediate attention, or it would have been fatal for the organisation"

"It's important to ensure the constant update of infrastructures"

"Virtual access was enabled to secure and confidential data. Historically this was only available physically"

"To share data, put it on the map and show what is where to ensure interoperability. The user doesn't care where it's coming from, but that they can find it and it is available with appropriate conditions"

"With meta-platforms of meta-platforms, it's only useful if there are many doors to reach the data relevant for researchers"

"Interoperability is also key. There are so many ways to facilitate or get access. This must come from top-down and bottom-up with a solid governance structure" [6]

Source: A curated selection of significant quotations was taken primarily from the from the 'Research infrastructures mobilisation' workshop held in May 2021. A list of workshop presenters and panellists is available at Annex 4.

Physical restrictions due to the transmissibility of the virus and corresponding public health and social measures (PHSMs), meant that the majority of RIs needed to adapt internal processes to maintain continuity through remote operations. Digital technologies have also been widely employed to expedite access to resources and data. While fast access options were in place in some RIs prior to the COVID-19 pandemic, it was not uncommon for access to take several months (OECD, 2017[43]). In many national contexts, limited or no additional funding was provided to support RIs in adapting operations, which therefore required the reallocation of 'ín house' funding from other budget areas (EC-OECD, 2021[3]).

Adapting to a changing environment is not a new issue for RIs, which are used to having to anticipate and react to technological innovations (OECD, 2017[43]). In the case of COVID-19, the major technological innovation was the very rapid shift to virtual working and remote access, which significantly impacted the business model and services for many RIs. A disconnect between challenges faced and support provided, underscores the importance of maintaining engagement channels between science policy-makers and RI managers in times of crisis. Good communication between different stakeholders is critical, particularly when there is high pressure on science to deliver results.

While some RIs, including distributed international e-infrastructures and data repositories, were well positioned to accommodate heightened demand for remote access during the pandemic, the action required of others managing physical facilities or sensitive data was much more significant. Nonetheless, COVID-19 has had a catalysing effect. A series of surveys by the European Research Forum found that whereas pre-COVID remote access made up only 20% of all access to RIs, this had shifted to 60% by October 2020 (Kolar, Andrew and Florian, 2021[50]). At the latter date, the majority of RIs had returned to regular operations suggesting that the shift is likely to be permanent. Accelerated digitalisation catalysed by the pandemic response has contributed to the overall ability of science systems to continue to function during crises and should continue to be prioritised as a means of building further resilience, although it requires increased attention to cyber-security. At the same time, it has been noted that not everything can be done virtually and certain activities, such as training, engagement, and empowerment of staff and younger workers, require physical interaction.

Many RIs produce and provide access to large amounts of research data. During the COVID-19 crisis, all RIs, and not just e-RIs or data repositories, had to respond to the need for accelerated diffusion of data and research results. When combined with the requirements of open science and FAIR principles, as described in chapter 1, this drove RIs to work together to share data (e.g., use of the European COVID-19 Data Platform in Europe). RIs played a critical role in ensuring data quality, balancing the need for rapid data access with requirements to ensure that data is fully described and understood.

Box 12. Streamlined RI access

Advancing novel digital innovations to enable remote operations and co-creation

LifeWatch-ERIC (European Research Infrastructure Consortium) was in a unique position to contribute to the COVID-19 response. The consortium is tasked with harnessing insights from international experts' large-scale data management and epidemiological modelling services. This e-RI launched an initiative in 2019 to develop next generation virtual research environments (VREs), which enable data to be imported from different sources and analysed using HPC and Cloud technologies. A Blockchain system ensures data integrity and fidelity of attribution, (Vaira, 2021[51]). Together, the VREs and Blockchain system represent a powerful data integration and analysis tool to address complex societal challenges, like COVID-19.

Coordinating and accelerating access to scientific resources through centralised application processes

The European Alliance of Medical Research Infrastructures (AMRI) is a novel collaboration between three biomedical and clinical research infrastructure consortiums. The alliance aims to streamline use of scientific services, expertise, and tools and facilitate the transition of projects through different phases of the biomedical pipeline, from pre-clinical to product development. In response to the COVID-19 pandemic, the three RI consortiums partnered to establish the COVID-19 Fast Response Service to coordinate and accelerate access to facilities, services, and resources (AMRI, n.d.[52]). A centralised, digital contact point is used to manage access requests and provide guidance to users on relevant services and suppliers in accelerated timelines. The service requires that users have already secured funding for their projects, although resources are available for use by applicants in preparing grant proposals.

Advancing science and innovation by private sector access to research infrastructures

During the COVID-19 pandemic response, the Government of Korea developed the COVID-19 Response R&D Support Council, a collection of major government-funded research institutes and universities (EC-OECD, 2021[3]). The council is designed to support start-ups and small and medium-sized enterprises (SMEs) in accessing specialised equipment, expertise, or infrastructures required to undertake R&D for the development of COVID-19 vaccines or therapeutics, such as Biosafety Level 3 facilities.

Note: For additional insights on engagements between Ris and private industry, please refer to the VIDO and Fugaku case studies provided above or the section of this report corresponding to academia-industry interface.

The growing number and diversity of RIs has served an important purpose in terms of addressing a variety of needs within science systems and broader society; however, this trend has also increased the complexity of science systems, making their navigation more difficult for users. The first critical step in supporting users in accessing RIs is often collecting, analysing, and disseminating information on what RIs exist, what they do, and how they can be accessed (OECD, 2017[53]). Novel virtual environments have already contributed significantly to the ability of RIs to enable broad and inclusive collaborations. Digital platforms proved to be critical in facilitating the visibility, connectivity, and use of data, knowledge repositories, research infrastructures, and other assets during the COVID-19 pandemic. Social media and dedicated websites also supported science actors in navigating and identifying relevant resources and services. At the same time, digitalisation has exacerbated risks to cybersecurity, with many RIs noting that monitoring and addressing cyber-attacks has required dedicated resources and expertise and, at times, the suspension of normal workflows during the pandemic.

Box 13. Visiblity of RIs

Establishing a catalogue of COVID-related resources

The European Strategy Forum on Research Infrastructures (ESFRI) has existed since 2002 to support advancement of RI policy in Europe. In response to COVID-19, the organisation developed an online catalogue of

COVID-related services and resources(https://www.esfri.eu/covid-19). There have also been initiatives established to improve the visibility of European RIs more broadly. For example, RI-VIS was established in 2019 as a consortium of stakeholders across the biomedical, environmental, and social sciences (https://ri-vis.eu/network/rivis/Home).

Using meta-platforms to increase the findability of scientific data and resources

BBMRI-ERIC (Biobanking and BioMolecular Resources Research Infrastructure – European Research Infrastructure Consortium) connects more than 600 biobanks over 20 countries to facilitate access to human samples in accordance with scientific and privacy standards. BBMRI acted to improve the findability of COVID-related data and samples through development of a novel COVID-19 search function and a map of relevant biobanks. Throughout the pandemic response, metadata descriptors have been continuously updated to include COVID-relevant attributes based on feedback from biobanking communities. Findability was further boosted through connectivity with aggregation services like Google dataset search and FAIRSharing.org.

2.4 Fostering broad, inclusive, and connected national and regional RI ecosystems to address complex challenges

"Clustering RI services could be a good way forward to ensure dynamic maintenance, sustainability, access to data"

"RIs shouldn't be viewed as standalone installations but facilities providing knowledge, expertise, technologies to public and private stakeholders to address grand challenges"

"RI action can be expedited through higher levels of vertical integration to facilitate in-house access to broad capacities and avoid the need to develop new legal agreements"

"We were initially missing coordination and synergies with other RIs and institutions, but this was built up with some difficulties"

"Utilising cross-infrastructure workflows was essential to success"

"RIs recognise their own interfaces of collaboration as trading zones, the most fertile areas for research development and new science and innovation"

"Tight collaborations with industry are important to realise design of experiments compatible with industry needs"

"Industry has a different skill set from research and this is important…It's important to get this perspective early on in developing vaccines. You can have great ideas at small scale but if you cannot scale-up, it won't make it"

"50 percent of co-operations already existed in other areas… there was trust that they would do the right thing as the agreement was being finalised and signed because there was already a partnership foundation"

"You must collaborate in order to build on what you have and adapt in times of crisis" [6]

Source: A curated selection of significant quotations was taken primarily from the from the 'Mobilisation of Research infrastructures' workshop held in May 2021. A list of workshop presenters and panellists is available at Annex 4.

Historically, structural siloes and procedural bottlenecks have posed a significant challenge to effective collaboration between RIs and, more broadly, with potential users or partners operating in different disciplines and at different stages of the R&D pipeline. This came to the fore during the COVID-19 response when established connectivity between system actors, including those operating in basic, applied, and industrial research was critical to accelerating the advancement of scientific solutions. The complexity of the crisis highlighted the value of cross-infrastructural workflows for projects, such as drug repurposing, that require the services of multiple RIs The need for coordinated and interdisciplinary efforts will only continue to grow as new health and societal challenges emerge. In the area of infectious diseases, it is estimated that 70 percent of emerging pathogens are zoonotic and addressing these will require joint action across several research fields (WHO, 2022[54]). New research has also surfaced the critical link between climate change and the increasing prevalence of novel infectious diseases (Carlson et al., 2022[55]). Meaningful global progress for health security will require the development of more inter- and trans-disciplinary initiatives focused on the interface between humans, animals, and the environment and RIs can play an important role in facilitating and supporting this.

There are a variety of ways to increase the horizontal and vertical connectivity or integration of science systems. Some countries have benefitted from system connectivity fostered through structural mechanisms designed to limit the duplication of research and maximise complementarities. Rather than compete, RIs and research groups with similar or complementary funding applications are required to coordinate their activities (OECD/Science Europe, 2020[47]). For example, the Netherlands uses a cross-ministerial "Inventory of Memberships of RIs" to ensure that funding is not duplicated. In other national or international contexts, where this kind of connectivity has not been well established, it may be necessary to define common challenges and best practices as part of a broader long-term strategy for RI cooperation to support the research community and society in addressing complex societal challenges (see Box 14).

Box 14. Connectivity between RIs

Coordinating regional efforts to address complex societal challenges as they evolve

Analytical Research Infrastructures of Europe (ARIE, https://arie-eu.org/), is a consortium of 7 European research networks collaborating to resolve targeted missions identified by the Horizon Europe program (ARIEs, 2020[56]). The consortium has created several transversal platforms to facilitate agile and proactive advancement of fundamental, applied, and industrial multidisciplinary research from 'bench to bedside'. ARIE has enabled coordination of European efforts for different aspect of the COVID pandemic response, from identification and analysis of the virus to treatment and prevention. Through its delivery of services, data, and knowledge, the consortium has supported an interdisciplinary community in excess of 40,000 stakeholders from academia and industry and a diversity of scientific domains.

Managing decentralised clinical trials through a network of networks

The Collaborating Network of Networks for Evaluating COVID-19 and Therapeutic Strategies, NHLBI CONNECTS (https://www.nhlbi.nih.gov/science/collaborating-network-networks-evaluating-covid-19-and-therapeutic-strategies-connects) was formed in the US in response to COVID-19. CONNECTS promotes rapid and efficient collaboration by integrating all major NHLBI clinical trial networks into a central adaptive platform with established master protocols. The NHLBI Biodata Catalyst provides a secure, cloud-based ecosystem for scientists to share, access, and work with digital resources and data. Critical points along the clinical spectrum, including exposure and initial symptoms to hospitalisation and recovery are targeted. Paired with the adaptive design of CONNECTS, this allows agile action to be taken to remove ineffective therapies, advance promising treatments, and adjust research as knowledge and the clinical landscape evolve. Rather than testing single treatments within single networks of clinical trial sites, researchers across sites are able to simultaneously analyse a variety of interventions, share data, and identify the most and least promising avenues of research to continue or suspend.

Note: In addition to national efforts to coordinate COVID-19 vaccination platforms, there have also been a variety of initiatives at the regional level, such as the EU-based VACCELERATE and TRANSVAC networks. These complement efforts at the global level, to identify and track clinical trials, such as the WHO's International Clinical Trial Registry Platform.

2.5 Coordinating the activities of national, regional, and international RIs to support global efforts

> "What we lacked at the national level is international coordination. This needs a transparent, accessible and correct vision"
>
> "We need better management systems at the European, regional and global levels… cross border collaboration is fundamental"
>
> "The proposal for international architecture is valuable but how and who? It's not only health; it's wider than this"
>
> "Infrastructures to produce vaccines should be kept running. There is plenty of work to do to control infectious diseases and neglected diseases"
>
> "The wheel turning is important; having infrastructures in place and already being used, and people trained to use them…"
>
> "We need to involve low and middle-income countries much more than is being done" [6]

Source: A curated selection of significant quotations was taken primarily from the from the 'Mobilisation of Research infrastructures' workshop held in May 2021. A list of workshop presenters and panellists is available in Annex 4.

There is an increasing number of international collaborations or consortia centred around data and data infrastructures, such as repositories. In 2019, EPI-BRAIN (https://www.epi-brain.com/) was conceived as a partnership between the WHO and the World Economic Forum to support the analysis of large datasets for global emergency preparedness and response. During the COVID-19 response, the WHO Hub for Pandemic and Epidemic Intelligence (https://pandemichub.who.int/) was launched in Berlin, with a mandate to prioritise data and analytics, connecting networks, and developing collaborative tools to develop disease outbreak solutions. Nevertheless, strategic initiatives to connect biomedical or life sciences physical or e-infrastructures, beyond the regional level, are limited.

A lack of global focus was evident in the RI-related initiatives introduced by national science policy-makers during the pandemic response. Of the few actions that had an international focus, most were bi- or small multi-lateral partnerships, or regional networks (EC-OECD, 2021[3]). Established and novel international collaborations did contribute significantly to the global pandemic response, but the universal scope, disruptive scale, and unprecedented speed of the virus' evolution and impact underscored the need to improve on current levels of global cooperation. Barriers to broad and inclusive collaboration are compounded by the need for significant, sustained, and flexible funding commitments. Addressing this will require the engagement of funders with heterogeneous and diverse priorities and different financial and scientific resources (ICRI, 2021[44]). There is potentially an important role for hybrid funding mechanisms that combine public research funding, philanthropic funds, commercial funds and, in the case of LMICs (see below), official development assistance (ODA).

Box 15. RIs and international coordination

Coordinating international activities for vaccine discovery and development

In 1997, the United Nations Development Programme established the International Vaccine Institute (IVI, https://www.ivi.int/) to advance global health through discovery, development, and delivery of affordable vaccines. The institute is headquartered in Korea but collaborates with and coordinates activities of 160 global partners from the international scientific community, public health organisations, governments, industry, and other intergovernmental organisations, such as the WHO, the World Organisation for Animal Health (WOAH), and the Coalition for Epidemic Preparedness Innovations (CEPI). During the COVID-19 response, it was critical to the IVI's mission to protect the most vulnerable populations from vaccine-preventable illness by continuing to develop vaccines for different emerging infectious diseases as well as established illnesses, such as cholera and typhoid. As a result, the institute did not attempt to develop a COVID-19 vaccine internally but focused on providing global support through early-stage clinical trials and epidemiological studies, as well as developing vaccine evaluation systems and COVID-19 vaccine adjuvants. The organisation has taken on additional activities with the specific focus of supplementing LMIC RI capacity during the COVID-19 pandemic as well as supporting longer term preparedness in several Asian and African countries, including the Philippines, Nepal, Ghana, and Mozambique.

Connecting RI users and expertise across the globe to address critical needs

CERN, the European Organisation for Nuclear Research, is the world's largest particle physics laboratory but also acts to coordinate activities of a community of over 18,000 researchers from more than 100 countries. The organisation established a task force in March 2020 as a mechanism to gather and align research activities being actioned by its user base, which ranged from the deployment of technological infrastructure for local support to global contributions. The initiative has enabled global collaboration between national physics laboratories to address ventilator shortages, with resulting designs made openly accessible via the CERN Open Hardware License to maximise their impact. CERN was also able to draw on a 2011 agreement, as a framework for collaboration with the WHO.

Effective global action on crises will require science stakeholders to act to correct a lack of effective and sustainable engagement with LMICs. In the context of pandemics and other health-related crises, this is needed to address the higher prevalence of public health risks common to these areas and foster global preparedness. More inclusive representation of LMICs in global science efforts has been stressed by the WHO as one of the most critical future priorities for the international community (WHO, 2022[54]). While engaging LMICs has been the focus of a small number of COVID-19 policy initiatives in OECD countries, it appears that these have largely been limited to short-term, reactive action and have not included more ambitious aims to develop infrastructures or capacity (EC-OECD, 2021[3]). Immediate action can be taken to integrate LMIC researchers into international RI networks, but more significant long-term action is required to address the concentration of major RIs in the global north. The International Conference on Research Infrastructures (ICRI) that was held in 2021, in the midst of the pandemic, recommended that the global science community reconsider current investment approaches to prioritise the development of RIs and related capacity in alignment with the needs of developing regions and countries (ICRI, 2021[44]). While it is outside the scope of the 'Mobilising Science' project, learnings from the COVID-19 Vaccines Global Access (COVAX) initiative have stressed the need for international action to be taken to extend manufacturing and logistics infrastructures in the Global South to support the equitable distribution of science-based countermeasures and improve vaccine security.

Box 16. Combining public and private efforts to build capacity in developing regions

Launched in 2019 with funding of US$100 million, the Africa Pathogen Genomics initiative (PGI) is an integral component of the Institute of Pathogen Genomics, based in Ethiopia and a collaboration between the African and US CDCs, Microsoft, Illumina, and Oxford Nanopore Technologies (Makoni, 2020[57]). The initiative responds to a need identified by the Africa CDC to improve and expand laboratory and bioinformatic capacity across the continent. It has been designed to integrate genomics and bioinformatics into public health surveillance, complete outbreak investigations, and improve regional disease control and prevention. The primary focus of the initiative has been investing in public health institutes and training African scientists to use genomic sequencing innovations. During the COVID-19 response, these activities were built on with the launch of a regional COVID-19 genome sequencing laboratory network through which twelve reference laboratories committed to providing sequencing, data analysis, and technical services nationally and to neighbour countries and sub-regions. The new capacity is expected to support African countries in monitoring and managing localised or imported transmission and developing vaccines and therapeutics that correspond to the local context.

Note: For additional insights on private investment into the science systems of developing regions, please refer to the section of the report corresponding to academia-industry interface.

Research Infrastructure Policy Recommendations

Recommendation[4]	Policy Options
1. Governments must recognise and support research infrastructures as assets for crisis preparedness and response and long-term resilience.	1.1. Adopt a systemic approach when making STI investment decisions to incentivise and promote the development of infrastructures, and the capacities and relationships required to address cross-cutting grand challenges and optimise resilience. 1.2. Engage relevant research infrastructures and user communities in developing strategy and policy for addressing crises and complex societal challenges. 1.3. Establish long-term agreements and secure funding commitments, with national RIs to enable the proactive integration of emergency response activities into their operations. Such activities might include the development of internal crisis response units or the development of emergency response procedures and protocols. 1.4. Designate selected RIs as national or regional crisis response centres to be supported by policy-makers and funders in coordinating the crisis response activities of disparate infrastructures and supporting the strategic mobilisation of national science capacities. 1.5. Prepare RIs to contribute to crisis response by supporting activities outside of their set mandates. This will require established decision-making and approval mechanisms, capacity, and governance frameworks to expedite the adaptation of operational priorities to accommodate new demands.
2. Policy-makers, funders, and research infrastructures must invest in and scale-up the human and technological capacity required for crisis preparedness and response.	2.1. Develop and implement long-term strategies for development, attraction, and retention of expertise, including scientific, management, and administrative capacity. 2.2. Reflect the critical roles played by RIs in training, education and public engagement in their mandates and funding allocations. 2.3. Advance partnerships with public and private sector research providers to facilitate training and labour mobility and increase the connectivity of national science and innovation systems.
3. Policy-makers and funders must ensure that research infrastructures are empowered to adopt technological and governance innovations required to advance system resilience and connectivity.	3.1. Learn from COVID-19 and proactively consider how emergencies might alter regular operations. RIs need to have the technological and human capacity required to be resilient in the face of ongoing and future crises. 3.2. The proactive integration of digital and other enabling innovations into the operations of RIs should be encouraged and supported. This is key to ensuring sustained collaboration, security, and resilience and will require specific training and resources. 3.3. RIs must develop governance and technological solutions to streamline flexible, secure, and accelerated remote access to data and other assets, while addressing corresponding challenges, such as cybersecurity. 3.4. Invest in and support tools and infrastructures, such as digital platforms, to increase the visibility and awareness of RIs with potential users.
4. Policy-makers must foster broad, inclusive, and connected national and regional RI ecosystems to address complex and cross-cutting grand challenges.	4.1. Interdisciplinary RI clusters and cross-infrastructural workflows can reduce administrative obstacles and improve interoperability across infrastructures. They are also important for improving coordination across scientific disciplines and enabling broad and inclusive collaborations, e.g., for advancing a global One-Health approach. 4.2. Physical and e-infrastructures should be empowered as collaboration switchboards tasked with engaging actors from across disciplines, sectors, and geographies and supporting them to develop joint research activities. 4.3. Science policy-makers and funders should encourage and incentivise RIs to engage industrial users and build trusted relationships.
5. Governments and funders must coordinate the activities of national, regional, and international RIs to support global science activities and address regional needs.	5.1. International agencies and national governments should increase their support for cooperative mechanisms, such as international vaccine platforms, to facilitate and accelerate the development of coordinated, collaborative research. 5.2. Governments and funders in OECD countries should consider broadening the mandates of national RIs and provide support for them to actively participate in international networks and support international organisations as appropriate. 5.3. Invest in high-priority regional infrastructures critical to the abilities of LMICs to respond effectively to future crises and complex societal challenges. In some instances, private funding or industry partnerships can be leveraged to achieve this.

3 Partnerships at the Academia-Industry Interface[6]

Key Messages

Science-industry interactions have been essential to accelerate development and deployment of science-based countermeasures during the COVID-19 pandemic. However, there are persistent barriers that need to be overcome for such interactions to realise their full potential in addressing future crises and complex societal challenges.

- Strategic and sustained investments are required to support various types of engagement between science and industry actors, including knowledge transfer, co-design of research, and co-production of knowledge. The design of effective policy depends on a range of factors, including the existing policy mix and national context.
- Jurisdictions in which concerted and sustained effort had been made to establish and strengthen science-industry collaborations were able to mobilise partnerships quickly to respond to the pandemic. Intermediaries, digital platforms, and other policy tools were critical to the development of novel partnerships across sectoral, disciplinary, and geographic siloes and helped to mitigate constraints posed by lockdowns and social distancing interventions.
- The urgent, significant, and pervasive nature of the COVID-19 pandemic eased some of the challenges typical to science-industry collaboration. However, government policy was still important to catalyse novel partnerships, incentivise the development of public goods, and address conflicting priorities. Judicious policy action will be required to leverage the positive momentum and lessons from the pandemic response to address other complex societal challenges.
- Global convenors, such as the World Health Organisation (WHO) and more targeted collaborative platforms have been important to ensure the coordination of already established and new multi-stakeholder partnerships and the inclusion of low- and middle-income countries (LMICs). Vaccine development and production (and to lesser extent, access), benefitted from existing partnerships and frameworks and good practices should be applied to other fields e.g., therapeutics and diagnostics, in the future.

Leveraging diverse insights and expertise from academia and industry is important for the development of the robust, and innovative solutions needed to respond to crises and other grand challenges. There are many ways of achieving this and a variety of terms have evolved to characterise cooperative or collaborative activities in STI systems, including:

- *Knowledge transfer*, such as through IP licensing, is where academia is the producer and industry is the receiver and user of knowledge, (Kreiling and Paunov, 2021[58]).
- *Public-private partnerships* (PPPs) lack a universally recognised definition but are often characterised as long-term contracts between a government and private-sector partners where the government shares risk and provides funding to the private partner to design, construct, finance, operate, or manage a 'capital asset' required for service delivery and/or the delivery of a service to the government or public (OECD, 2012[59]). In theory, PPPs can span the breadth of the R&D pipeline, from research design to knowledge application, but traditionally occur in the application of knowledge through public procurement.

- Knowledge co-creation can be defined as the process of joint production of innovation between industry, public research, and possibly other stakeholders (Kreiling and Paunov, 2021[58]).
- Transdisciplinary research can be defined as the co-design of research and co-production of knowledge between different scientific disciplines and non-academic stakeholder communities, often including industry (OECD, 2020[60])

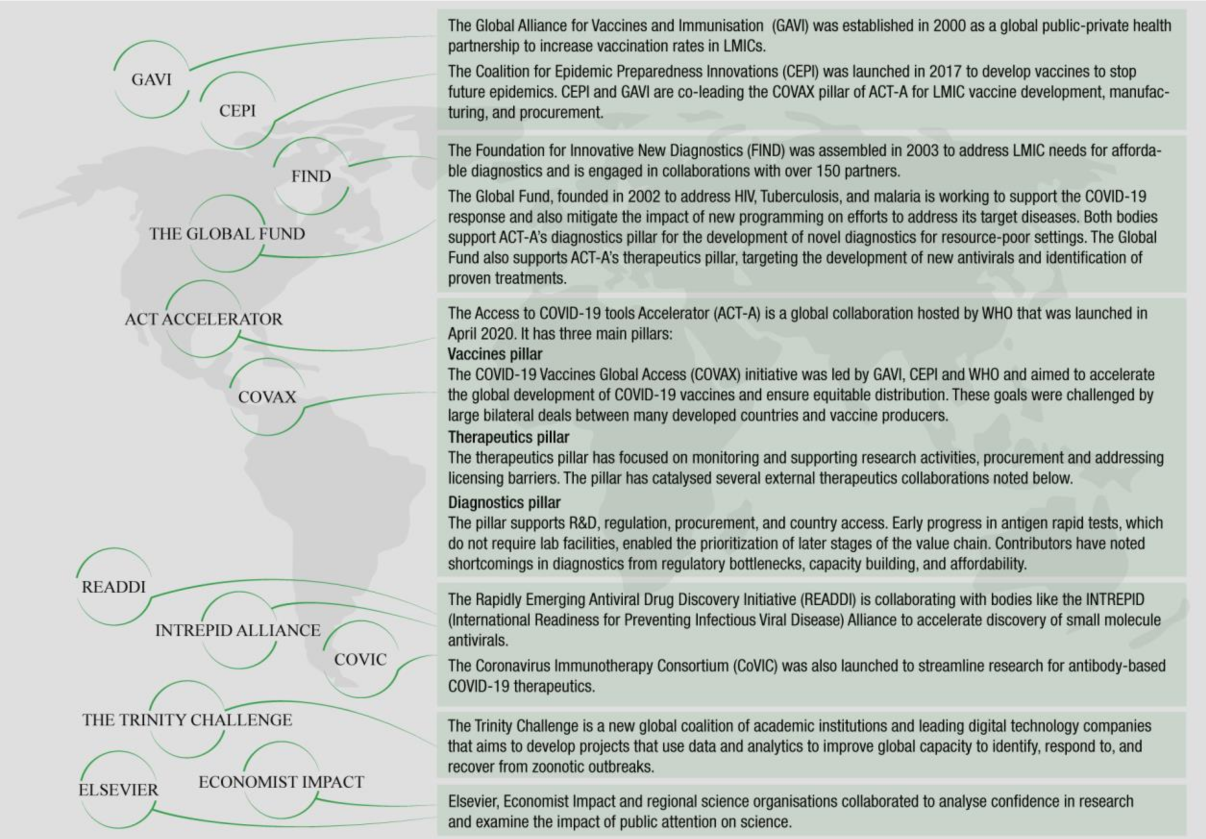
Knowledge transfer policies and mechanisms generally aim to translate public research results for use by industrial actors and enable downstream development, deployment, and/or commercialisation. Policies often focus on licensing or improving access to IP, as this represents the most significant way in which knowledge is 'locked down'. However, even when the transfer of codified knowledge between partners is successful, lack of engagement and transfer of more tacit knowledge can limit effectiveness. Analysis suggests that only a small proportion of traditional knowledge transfer projects have a significant impact on economic outcomes like jobs and income (Guimón, 2019[61]). Nevertheless, policies specifically targeted to knowledge transfer were a key element of the strategies taken by many governments to respond to the COVID-19 pandemic. Novel initiatives to promote knowledge transfer more broadly tended to relate to the development of digital platforms to facilitate cross-sector discussion or centralised infrastructures to share data (EC-OECD, 2021[3]) (Paunov and Planes-Satorra, 2021[1]). A handful also provided direct financial support to researchers to make research results openly accessible or to share results with private sector actors.

Deeper engagement is generally characterised by collaborative activities in which science-industry interactions may be only one dimension. For example, co-creation and transdisciplinary projects can often engage a variety of public and private sector partners and civil society in problem definition and research design as well as knowledge production and transfer. However, challenges and functions that are unique to research partnerships between science and industry actors warrant special consideration from policy-makers. Analysis of the COVID-19 response has underscored the importance of such partnerships in leveraging and mobilising the financial, technical, and technological resources of industry partners to address societal challenges. Accelerating and scaling-up these collaborations has benefitted from government intervention in the form of policies, frameworks and funding models. Science-industry partnerships targeting joint knowledge development can occur with various objectives and scales. Previous analyses have delineated partnerships in terms of increasing length, complexity, and scope, from individual projects to broader mechanisms, and institutional level arrangements (Kreiling and Paunov, 2021[58]). Targeted projects were used to address specific COVID challenges, such as vaccine development. Broader mechanisms and institutional arrangements were more likely to be deployed at the national and international level to facilitate connectivity and engagement.

During the COVID-19 response, science-industry partnerships spanned the R&I value chain, with actors engaged beyond their normal remits in fundamental and applied research activities, as well as the production and distribution of science-based products and public health and social measures. Collaborations occurred at the national and international levels for the research, development, and deployment of countermeasures. They also played an important role in addressing a variety of other topics that have been critical to crisis management including, the production of personal protective equipment, medical equipment, and surveillance and monitoring. However, analysts have noted that the most significant efforts have been made in the field of vaccinations, asserting that additional mechanisms focused on therapeutics and diagnostics are required to improve preparedness (OECD, 2021[62]).

Much of the collaboration that occurred in response to the COVID-19 pandemic has been initiated from the bottom-up by individual or groups of scientists (OECD, 2021[62]). At the same time, the response has required international top-down action to prioritise the alignment and joint use of data, research results, infrastructure, skills, and other resources. The World Health Organisation has played an overall convening role in this respect, while other specialised global partnerships have also been important. A number of partnerships and mechanisms to facilitate science-industry collaboration were established de novo in response to COVID-19. Others were mobilised, adapted, or even re-instated after being withdrawn following the conclusion of past emerging infectious disease outbreaks. A selection of key international initiatives is shown in Figure 5. Many of these are large-scale public-private partnerships involving institutions and designed to facilitate project-level science-industry or broader transdisciplinary collaborations.

Figure 5. International science industry collaborations responding to Covid-19



Note: These initiatives are illustrative and are not a comprehensive representation of all of the established international initiatives mobilised to support the joint development of knowledge by science and industry actors during the COVID-19 pandemic response.
Source: Adapted from initiatives presented in several documents (National Academies Press, 2020[63]) (Dalberg Advisors, 2021[64]) (G7 Chief Scientific Advisers, 2021[65]).

3.1 Developing the enabling conditions to catalyse science-industry collaborations during crises

"Open data, data sharing, and infrastructures were important to enable collaboration and became the platform for developing co-creation partnerships"

"Fellowship programmes work well to place young people in science careers both in public and private sectors"

"Barriers to mobility are created by perceptions that transferring to industry is unidirectional. We need to create opportunities for crossing barriers so the act of crossing and co-creating is more widely taken up"

"The pandemic created new social needs and demands for different solutions. Collaboration between academia and industry through new activities will be important to address these"

"The project tried to raise initial funds with an emergency grant submission but was unsuccessful. They reached out to the crowd via twitter and it snowballed into a serious discovery project with many contributions"

"You cannot do it alone and you need to be prepared. The EU and the world needed to act together. Industry and other stakeholders needed to be involved early on"

"It helped that the appeal for collaboration was raised by credible institutions, which had been funded over the long-term"

"It's important to remember that co-creation is only one part of the policy mix in knowledge exchange and policy instruments to enable knowledge transfer, such as licensing and greater access to data and publications, are also important"

"Funds were raised from various institutions, primarily through their pandemic allocations, and contributed to experimental work"

"Government support with timely allocation of additional funding was useful to scale cocreation activities" [7]

Source: A curated selection of significant quotations was taken primarily from the from the 'Improving academia-private sector interactions' workshop in September 2021. A complete list of workshop presenters and panellists is available at Annex 4.

The deep and reciprocal relationships that characterise effective science-industry collaborations are often enabled at the system-level by having clear channels for knowledge transfer. Collaborations are also shaped by the specific attributes of different STI systems. General and COVID-specific analyses have identified a number of important enabling conditions that facilitate science-industry collaboration, including:

- **Long-term investment in discovery research** is important for ensuring that the science system can contribute pioneering and disruptive scientific knowledge when engaging with industry partners. This has been strongly confirmed during the COVID-19 response with the translation of decades of work on mRNA technology into effective vaccines that have been an essential part of the global response (Dolgin, 2021[66]).
- **Data sharing infrastructures, processes, and culture** play a key role in enabling the rapid dissemination and utilisation of research results. The pandemic response illustrated the need to incentivise academic and industry collaborators to openly share data assets and analytical capacities.
- Public **research institutions and infrastructures** act as major sites of collaboration, spill-over, and cross-fertilisation. Reputable institutions and infrastructures contributed significantly to bringing different actors together to respond to COVID-19. They also supported actors in leveraging existing and new resources, including technological and human capacity, research, and networks.
- **Novel digital platforms and technologies** have been critical facilitators of data sharing and access, providing remote access to research infrastructures, and enabling collaboration between public and private actors.

Box 17. Long-term academia-private sector partnerships

Leveraging established programmes to expedite crisis response activities

The Innovative Health Initiative (https://www.ihi.europa.eu/)is a public-private partnership that is jointly funded between the EU and the European life science industries. The primary goal of the initiative is to pioneer a more integrated approach to health research. The initiative was approved in 2021 to consolidate several iterations of the Innovative Medicines Initiative (IMI), which was started in 2008. This continuity has allowed members to carry forward established best practices and lessons learned. Significant changes between the two programmes have included expansion from the pharmaceutical industry to a cross-sectoral focus, which includes medical technology, biotechnology, digital health, and vaccines to align with the increasingly interdisciplinary nature of health research and healthcare. The governance structure has also been revised with the creation of an advisory board, which ensures that decision-making is informed by representatives from the broader scientific and health communities, including patients and end-users.

Prior to its transition, IMI supported several collaborations developed in response to the COVID-19 pandemic. For example, the CARE (Corona Accelerated R&D in Europe) consortium (https://www.imi-care.eu/)received funding to operate from 2020-2025, engaging a variety of partners from industry, public research organisations, and funders from several EU countries, USA, The People's Republic of China (hereafter "China"), UK, and Switzerland. The project aims to repurpose established therapeutics and deliver new pharmaceuticals to treat COVID-19 and other coronaviruses. Collaborators are using of established methods, such as cryo-electron microscopy, in new ways to identify vulnerabilities of viral spike proteins and predict the impacts of new mutations.

Accelerating crisis response through flexible operation of established partnerships

The Center of Innovation (COI) programme (https://www.jst.go.jp/tt/EN/platform/coi.html) was launched as a major new funding initiative by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2013 and is managed by the Japan Science and Technology Agency to establish and support collaborative teams of industry and academic actors to tackle important interdisciplinary challenges. The programme was developed specifically to serve as a catalyst for vision-driven transdisciplinary innovation. Governance of COI sites is shared between 'Project Leaders', representing both industry and academia to supervise the overall management of the site and R&D activities, and 'Research Leaders', who are responsible for daily operations and strategy. Partners have the flexibility to provide financial, human, and other in-kind resources throughout the project depending on their expertise and interests. 18 COI sites were able to immediately launch projects in response to the pandemic, leveraging established and trusted networks of industry, science, and civil society stakeholders, and collaboration procedures, including standardised IP and technology transfer agreements. COVID-19 projects included:

- Sharing of 3D data through GitHub to facilitate the rapid production of face shields by SMEs,
- The development of wearable devices for medical check-ups to reduce physical contact

- Development of portable devices to support telemedicine for pregnant women

Studies and trials that were established through bottom-up action taken by researchers could be rapidly scaled-up due to the shared vision, values, and understanding, which already existed among site partners.

A variety of instruments can be used to incentivise and support specific science-industry collaborations. 21 specific instrument types, classified as either financial, regulatory, or soft policies, have previously been identified (OECD, 2019[67]). While funding programmes made up the significant majority of new initiatives, there were also a handful of other instruments introduced during the pandemic, including platforms to facilitate matchmaking, and support collaborative networks of experts (EC-OECD, 2021[3]). Policy-makers need to consider a variety of factors in designing a policy mix to effectively mobilise science-industry collaboration. The optimal approach is often dependent on the national context, including historical investments in academic-industry partnerships in different areas.

Having a diversity of flexible funding mechanisms has supported the ability of governments to prepare for crises and respond to COVID-19. Established collaboration-focused policy instruments were important in enabling and incentivising science and industry partners to develop and advance collaborations as an aspect of normal operations. Long-term trends in OECD countries have indicated that grants requiring public and private collaboration are among the most popular innovation policy instruments and are particularly valuable for addressing defined priorities or missions (Guimón, 2019[61]). This is also reflected by the data collected on national STI policies introduced during the COVID-19 pandemic. A variety of existing and novel funding instruments have been deployed, including: core institutional funding, flexible emergency funds, challenge-based funding programmes, debt financing, and procurement. Most initiatives targeting science-industry collaborations provided direct financial support, either through competitive funding programmes or for the development of individual projects (EC-OECD, 2021[3]).

Box 18. Funding academia-industry collaboration

Using a diversity of funding initiatives to create environments that are conducive to collaboration

Science Foundation Ireland (SFI) has established a variety of policy instruments focused on the academia-industry interface, from knowledge transfer and network development to the joint development of knowledge. The diversity of tools employed over the long-term allowed the foundation to mobilise funding effectively and flexibly and leverage established connections between industry and academia through their COVID-19 Rapid Response Funding Call. Examples of supporting policy tools include:

1) The Research Centres Programme – Launched in 2012, the programme establishes centres to support the development of a dynamic and evolving research ecosystem aligned with the changing needs of industry and society. The centres consolidate research activities across public institutes to create a critical mass of expertise in strategic areas and attract industry investment and partnerships. Academic actors are incentivised to actively pursue partnerships with industry as SFI funding has to be leveraged against industry funds and other competitively won sources. According to an academic study completed in January 2022, the programme has been successful in motivating industry partners to redirect R&D budgets towards more scientific research activities, improving the potential for disruptive innovation (Mulligan et al., 2022[68]).
2) The Industry RD&I Fellowship programme – The programme supports academia-industry interactions and industry development by enabling academic researchers at the faculty or postdoctoral level to spend up to two years in industry at the national or international level. Fellowships are flexibile in structure, and duration, and can facilitate a variety of activities, including knowledge translation, capacity development, and collaboration.

SFI leveraged this foundation of external collaboration in launching the COVID-19 Rapid Response Funding Call and adopted similar collaboration principles internally. To streamline and accelerate application processes, Irish agencies came together to manage a single application portal so that project selection and funding allocations could be determined at the back end in line with the established mandates of the different agencies.

Rapidly scaling-up established research funding programmes

In response to the COVID-19 pandemic, Business Finland, a funding agency which primarily acts to accelerate the sustainable growth of industry, introduced a temporary co-creation funding service. Under the programme's guidelines, research organisations were able to apply with joint project plans for funding of up to EUR 240,000, or 80% of a total project cost of EUR 300,000 to support pilots, experimentations, validations, and applied public research related to the development of solutions specific to the COVID-19 crisis or the renewal of impacted industries. Funding amounts were scaled from the agency's normal first-stage co-creation funding, which only provides support for 60% of total project costs of EUR 100,000.

Flexible funding is critical to maintaining and strengthening successful partnerships before, during, and after crises. The ability to swiftly adapt or pivot funding instruments has accelerated and optimised cross-sectoral collaboration during the pandemic. In some instances, such as with Finland's adaptation of an existing co-creation funding service (Box 18), governments used established mechanisms to get funding quickly into the hands of project partners. However, difficulties in initiating new collaborative projects have emphasised that traditional funding mechanisms are often too slow or conservative to support partnerships at the science-industry interface, particularly when unconventional approaches are being proposed. This was true of both for funding of individual projects via emergency response programmes and support for institute-facilitated collaborations where public funding could often not be deployed quickly enough to get things started.

To deploy scientific expertise in response to crises and grand challenges, it is important to ensure that policy and bureaucracy do not impede process innovations or novel ways of doing things. In this respect, willingness to cooperate across established siloes has allowed science policy-makers and funders to act swiftly and efficiently in response to the pandemic. Some national agencies have taken action to address shortcomings in solution-oriented initiatives by engaging with a diversity of stakeholders in developing new policy instruments. Such consultations can support STI policy-makers in proactively addressing aspects of policy that otherwise might not align with how beneficiaries operate and/or unintended implications that may impede the effectiveness of policy instruments.

3.2 Supporting the development and evolution of strong, effective, and agile partnerships between academia and the private sector

"It is almost impossible to start new collaborations during crisis, but you can start new projects if there is a foundation of trust or established legal agreements"

"Many connections were already in place because the biopharmaceuticals sector is small"

"There is a need for trusted facilitators, brokers, or coordinators. This would help with academic-industry collaboration, but these have traditionally been missing from cocreation projects"

"Tight collaboration with industry is important to design experiments which are compatible with industry needs"

"The private sector plays an important role but comes in at a later stage. Research institutions play a critical role in early research and then it is licenced by industry to develop and commercialise it"

"Partnerships should build on the strengths of contributors, such as strengths of academic institutions in analysing data, private sector in developing visualisation tools, and public health labs in generating data"

"Industry has different skillsets and these are important. Relationships are needed with major multinational enterprises over the long-term."

"Regular confidentiality agreements for mutual engagement can provide early site of work and improve understanding of whether a technology is likely to be commercially viable and scalable before significant effort and funding has been committed"

"The project snowballed because it was visible and it was obvious that something was happening with what was being contributed, which kept momentum going. Goals and intentions were simple and clear – that the project would be open – and people knew what to expect"

"Actors have been anyone: national institutions, volunteers from across the biopharmaceutical industry, with intellectual contributions donated or provided at cost" [7]

Source: A curated selection of significant quotations was taken primarily from the from the 'Improving academia-private sector interactions' workshop in September 2021. A list of workshop presenters and panellists is available at Annex 4.

Emergencies and urgent situations often result in reactionary responses, making novel collaborations or partnerships more challenging and unlikely. As with the other elements of science systems, it was important to have the foundations of science-industry partnerships in place to respond to the COVID-19 crisis. Methodologies, mechanisms, and skillsets developed, tested, and adapted over time were critical for the cultivation of projects during the pandemic. In some contexts, strong and sustained relationships had been facilitated through long-term engagement of industry representation in the management of public research institutes and infrastructures, including in the development of in-house projects. Studies show that long-term partnerships between academia and industry are an increasing trend, with industry participation in the governing boards of universities and research and innovation councils in 74 and 84%

of OECD countries respectively (OECD, 2019[67]). Additional actions can be taken by policy-makers to facilitate the engagement of industry and civil society in the governance of scientific institutions; however, it is important to actively manage potential conflicts of interest in doing so. Stronger industry engagement in public science must be carefully balanced with the need to maintain autonomy and public trust (discussed in relation to science advice and public communication and engagement in report 2).

The pandemic and resulting public health and social measures (PHSMs) created an additional dimension of complexity for new and established partnerships by limiting the ability of people to travel or meet in person. Having partnerships already in place allowed actors to leverage established trust and/or contractual agreements to accelerate project development and streamline administrative processes. There is a long history of close engagement in the biopharmaceutical industry, which by its nature is very research and technology intensive. This was instrumental in the rapid mobilisation of this sector. In addition, the majority of policy support for science-industry collaborations was targeted the development of medical countermeasures i.e., vaccines, therapeutics, and diagnostics (EC-OECD, 2021[3]) (Paunov and Planes-Satorra, 2021[1]) or to general biomedical research. Not all sectors benefitted from similarly favourable conditions. Much less focus appeared to be placed on academia-industry partnership in other areas, although there were a handful of additional programs related to personal protective equipment (PPE), surveillance, and social science research.

Box 19. Engaging industry stakeholders in RI and programme governance

Industry engagement in science activities was not only limited to the project level. There are several examples of mechanisms and institutions that benefitted from long-term representation of industrial stakeholders in governance functions or in the development of internal projects. Development of the Fugaku supercomputer in Japan is one example (see Box 9), where private sector actors have engaged as co-developers of the infrastructure, including software and hardware components, since 2014, as well as in the development of projects targeted to COVID-related challenges. Representatives from a range of sectors, including infrastructure, transportation, education, and municipal affairs have been included on the board of directors to ensure that the projects prioritised during the COVID-19 response aligned with the downstream needs and operational protocols of industrial (and policy) actors who would make use of fundamental and applied science outcomes. Similarly, the Japanese Center of Innovation Programme (Box 17), engages private sector actors in its leadership and governance structures.

Limitations to in-person engagement increased the importance of digital tools and platforms during the pandemic response, with their use ranging from providing access to health technologies to creating open innovation communities and sharing open-source solutions. Platforms were used to increase the visibility of initiatives, enabling the development of new - and expansion of existing - partnerships. New forms of online collaboration, such as communities of experts, hackathons, and crowdsourcing or crowdfunding were particularly useful in responding to the COVID-19 pandemic as they can, in some situations, enable more intense collaboration and mitigate some of the challenges of traditional collaboration approaches (OECD, 2019[67]) (Paunov and Planes-Satorra, 2021[2]). Not only do they bring together diverse actors, but they also align with and facilitate Open Science practices to make research results freely accessible.

In addition, digital infrastructures and tools have provided important support to the activities of previously established cross-border partnerships, supporting actors in overcoming constraints on physical mobility, while ensuring agility and responsiveness. Effective collaboration requires flexibility and fluidity, which is particularly true when responding to crises. Over the course of the COVID-19 pandemic, the situation changed often, swiftly, and radically. A variety of compounding and confounding variables influenced this evolution, and these differed in their nature and impact across countries. As a result, it was challenging for partners (and policy-makers) in different countries to predict or fully appreciate the changing situation and potential implications. Virtual collaboration helped partners to engage regularly and transparently. Building trust was crucial for mutual understanding, joint decision-making, and rapid action.

Intermediary organisations, such as research infrastructures, have often played a valuable role in the development of new large-scale partnerships, or consortia. Mechanisms to select complementary project contributors and match them with project needs are important to ensure that knowledge, skills, and resources are combined effectively. This is particularly true of science-industry partnerships as public- and private-sector actors often contribute different expertise and resources and may also play different roles, depending on the stage of the R&D activities. Respected and trusted intermediaries can be valuable in negotiating the potentially conflicting priorities and expectations of partners.

The early involvement of industrial stakeholders in response efforts accelerated knowledge production, technological development and innovation during the COVID-19 pandemic. For example, many European countries have noted that private sector capacity was important for supplementing government and public sector capacity, which was not sufficiently equipped to respond (Tille et al., 2021[69]). At the same time, it is important to consider the development of science-based solutions through a broader lens. Policy and science actors must consider challenges or barriers to adoption for downstream users, sectors, or disciplines. Early engagement of potential users is important to expedite and anchor results and ensure not only their applicability, but also feasibility of implementation. This has been evident with the COVID-19 response, as the uptake of research results has been challenged in numerous countries by the chronically underfunded public healthcare sector and outdated infrastructure (Wells Kocsis et al., 2022[70]) as well as by public attitudes.

Box 20. Combining expertise across sectors

Matching partner expertise and resources with project needs

The Canadian COVID-19 Genomics Network (CanCOGen) was established in April 2020 by Genome Canada as a pan-Canadian, cross-agency initiative targeted to understanding the origin, transmission, and mutation of the COVID-19 virus and to and inform critical policy decisions. The network includes membership of federal, provincial, and regional health authorities and associated partners, academia and research institutes, hospitals, and industry and encompasses two initiatives to sequence and share 150,000 viral samples from positive COVID-19 tests (VirusSeq) and the genomes of up to 10,000 patients diagnosed with COVID-19. Rather than a research project, the initiative represents activity initiated by public health labs to invest in developing and sharing data assets to support other actors in undertaking related research.

Since inception, priorities of the consortium have evolved in response to pre-existing challenges to the effective, rapid, and timely sharing of data across Canada and internationally. Within the network, an additional partnership was formed to develop data portals, engaging four universities, provincial labs, and companies providing cloud services and expertise for dashboard development and data visualisation. For the effective function of the partnership, it was important that contributors were able to build on and leverage strengths that different actors brought to the project: public health labs generated data, academics contributed analytical capacity, and the private sector developed visualisation tools. Transparent and open communication was recognised as a critical aspect of cross-sector collaboration when advancement of the project encountered resistance from public health labs because of the involvement of industry. To a certain extent, there were mistaken perceptions among some project actors regarding industry benefitting from access to project data and associated privacy and security concerns. In reality, project data was already openly and internationally available.

Unlocking private sector data to improve the development, evaluation, and adaptation of government strategy and public health and social measures

In response to the COVID-19 pandemic, the Chilean Ministries of Health and Sciences, the Institute of Complex Engineering Systems (ISCI), researchers from the University of Chile, and the Entel telecommunications company collaborated to prioritise the development and use of innovative tools for data analytics. The collaboration allowed academic actors to leverage large volumes of anonymised cell phone data in their models to understand the evolution of the effects of countermeasures and policy interventions at the local level and tailor the allocation of limited supports to areas of critical need ((n.a.), 2022[71]). Officials estimate that the use of analytics to guide the response has saved more than 2,800 lives and US$200M and avoided more than 65,000 infections in the region (Hurtado, 2021[72])_. Tools, such as the COVID Analytics platform, were used to: understand the effectiveness of lockdown measures in reducing mobility; develop additional systems to distinguish asymptomatic people in high-risk areas; monitor antibody responses to different vaccines; and, align patient demands with capacity across the national hospital network. Effectiveness of the cross-sector collaboration has been recognised with the award of the 2022 Franz Edelman prize by the Institute for Operations Research and the Management of Sciences.

3.3 Managing conflicts between academic, commercial, and societal priorities, and incentives.

> "Traditional drug discovery is synonymous with playing the lottery. There is potential to get a lot of money back but there need to be alternatives to this kind of funding. Some drug discovery needs to be commissioned and funded more like public infrastructure through a tender process"

"In a pandemic situation, getting intellectual input was not a problem"

"People did not contribute for the publications and there was no preconception that the publication was the end goal. A pre-publication was done last year as a Google document of

"The science is very robust and there has been excellent steering from people with industry experience, but the challenge is that there is no proven model for taking the project through all the processes needed to get to the clinic"

"Guided altruism was important from governments and funders"

"There have been successful projects in the private sector but then stocks crash and projects are discontinued when it's clear that they won't make money"

"A modular approach is required where project contributors first agree on outcomes and set expectations for IP. When IP rights are on the horizon, then you need to stop and make another kind of contract"

"Lots of people only want a salary and they will do the work. Don't foist legal things on these people but allow them to work these things out later. The only people who care about the IP are investors" names with no ranking"

"People were able to see results in real time due to openness of the data and this generated a lot of enthusiasm"

"Companies approached project developers with intellectual contributions without the need for contracts and the project moved because this was not required. In some contexts, this would have been devastating, but in this project, it was crucial"

"Academic actors had preconceptions about industry motivations, and it was assumed that there would be a conflict of interest in industry motivations. Some actors questioned whether it was 'right' that industry would capitalise on their involvement in the project"

"Enabling public-private partnerships requires experimentation. There is the issue of linking incentives and institutional conditions and constraints with how people and researchers act out of different motivations" [7]

Source: A curated selection of significant quotations was taken primarily from the from the 'Improving academia-private sector interactions' workshop in September 2021. A list of workshop presenters and panellists is available at Annex 4.

Tensions inherent to science-industry partnerships are rooted in the differing priorities and circumstances of actors operating in different sectors. Science or public health officials operate with public funding to develop new knowledge or improve societal outcomes, whereas the actions of industry stakeholders are largely motivated by the need to maximise shareholder returns (Wells Kocsis et al., 2022[70]). Despite the heightened altruism of many actors in responding to the COVID-19 pandemic, many challenges typical of science-industry collaborations persisted. Various national and international initiatives were introduced to incentivise the development of countermeasures that lacked a short-term business case. Some leveraged standard grant funding mechanisms, while others employed alternatives, such as commission or tender processes. Additional action was also required to address conflicts of interest related to the generation and use of project outcomes, such as data, publications, patents and intellectual property (IP). Patents and IP are integral to the dominant business model for the translation of research into clinical therapies by the pharmaceutical industry, which played a central role in the crisis response (Paunov, Borowiecki and El-Mallakh, 2019[73]). However, there have been several calls for more enlightened approaches to IP management and licensing based on experience with COVID-19, in particular with regards to access to vaccines and development of anti-viral therapies (Gold and Edwards, 2022[74]).

Avenues taken to address or mitigate challenges common to science-industry collaborations differed, in many cases, from typical models. Much of the established analysis of science-industry partnerships posits that detailed agreements and contracts are necessary to establish roles and responsibilities, division of labour, financial and in-kind contributions, and rights to project resources and outcomes, including technology, facilities, human capacity, and data (Kreiling and Paunov, 2021[58]). However, many COVID-specific partnerships and projects were established rapidly, leveraging pre-existing relationships that allowed contributors to benefit from streamlined administrative and legal processes and established rapport and way of doing things. In the development of novel partnerships, innovative approaches, such as intentionally building new relationships using established contacts and the use of digital platforms to facilitate regular communication (see the section on Transdisciplinary Science in report 3) were used to accelerate the development of trust, rather than formalising agreements through contractual arrangements.

Box 21. Mitigating potential conflicts through innovative approaches to collaboration

The COVID Moonshot project began in March 2020 as an international open-science consortium of scientists, academics, pharmaceutical research teams, and students to develop readily available oral therapeutics for LMICs and vulnerable communities. It arose through spontaneous virtual collaboration, which was initiated and fuelled through Twitter, following the inability of several contributors to raise money through emergency grant competitions. The project has been facilitated by key players, including the University of Oxford, the NIHR Oxford BRC, and UK synchrotron Diamond Light Source, but has also been supported by upwards of 200 collaborators, including national and international academic and industrial groups. Moonshot partners have maintained informal and flexible work arrangements by making it clear at the outset that IP and publications were not the primary objective of the project and that key scientific outcomes would remain openly accessible. Following the identification of several promising anti-viral compounds, the initiative eventually succeeded, in September 2021, in securing GBP8 million from the Wellcome Trust to support testing in clinical trials. In addition to research funding, collaborators have raised the need for support from a diversity of stakeholders to develop and implement a business model that supports affordable worldwide access. Moonshot is a pioneering effort to employ Open Science approaches to address unresolved tensions with pharmaceutical business models, which are primarily driven by large returns on private investment. The Moonshot initiative has certainly been enabled by the scale and urgency of the COVID-19 response, but it raises important issues about promoting public private partnerships for global public good.

An alternative way of working has been adopted by the **Finnish Fast Teams initiative,** which aligns different partner expectations using an iterative modular approach. In this way formal elements of collaboration, such as the development of IP agreements are negotiated only as and when they are needed. Similar to the Moonshot project, the Fast Teams methodology leveraged digital platforms to connect project contributors; however, initial engagement was primarily driven through established relationships. Existing social capital and trust were utilised initially to maintain flexibility, with the understanding that contractual arrangements would be established as necessary once research activities had progressed to a stage where commercialisation was 'on the horizon'. (Due to the extensive trans-disciplinary nature of the Fast Teams COVID-19 initiative, it is covered in additional depth in the third report of this series in the section on 'Transdisciplinary and Reflexive Science').

It is notable that both these initiatives run counter to the normal practice for academia-industry collaborations, whereby issues around ownership and IP are negotiated up front. Having clear contracts and binding cooperation agreements in place as the start of a collaboration may be desirable but agreeing these can take several months and in an urgent crisis such a delay is not acceptable.

Governance practices that prioritised and enabled open and regular communication were crucial to establishing trust and common understanding between partners. Social capital appeared to be key in the evolution of open or modular approaches to the ownership and use of project outcomes. For example, while 'open' drug discovery efforts are often cited as being slow, coordinators of the Moonshot project (Box 21) were successful in accelerating their work by establishing a clear and transparent vision that all partners bought into from the outset (von Delft et al., 2021[75]). Subsequent visibility and openness of project results generated additional enthusiasm and buy-in among partners and potential participants. Flexibility in the absence of binding contracts can enable the engagement of diverse partners. In circumstances where partners are less flexible, an iterative approach can be used to allow project activities to move ahead with limited delay. In this case, legal or contractual arrangements are negotiated up-stream once development of a commercially viable product is on the horizon. IP waivers and other more rigid alternatives may be applicable to specific circumstances but can be limited in terms of their adaptability to evolving activities or situations.

Adapting standard processes has contributed to the speed and flexibility of the pandemic response and demonstrated the ability of actors to collaborate across sectors despite uncertainty and time constraints. It is not currently clear how these adaptations have impacted other essential aspects of collaboration, such as accountability, fairness, and efficiency (Tille et al., 2021[69]). Preliminary analysis of the COVID-19 response has shown that one outcome of reduced bureaucracy and expedited action has been an increase in the amount of risk that governments and public science actors have taken on through public-private partnerships, investing more significant funding with higher uncertainty of returns. At the same time, it has often been the case that neither public nor private sector actors were able to undertake complete risk analyses or formalise risk-sharing agreements. Additional analysis is warranted to better understand potential trade-offs between bureaucracy that might optimise and safeguard some elements of science-industry engagement, such as accountability, while reducing agility and more immediate action.

Policy-makers and funders also have a significant role to play in prioritising the inclusive and equitable development and allocation of research outputs from science-industry collaborations. International initiatives such as the People's Vaccine Alliance (https://peoplesvaccine.org/) and Access Campaign (https://msfaccess.org/about-us) have brought attention to vaccine inequality and the challenges that this presents for public and privates sector actors. Whilst many of these issues extend beyond the remit of science policy makers, concerted and coordinated action is required to ensure that LMICs are represented in, and benefit from, global science activities. As has been evident during the pandemic response, it is important that mechanisms to enable this are established prior to crises as national actors have vested and potentially conflicting interests in prioritising local outcomes during an ongoing emergency.

A variety of prominent global platforms have been adapted or newly created to respond to COVID-19; many of these under the aegis of the WHO. These include the Access to COVID-19 Tools Accelerator (ACT-A, https://www.who.int/initiatives/act-accelerator) and its various pillars of work. As a complement to the activities of ACT-A, several multinational pharmaceutical companies have developed partnerships with research institutes and infrastructures in developing countries. The majority of these target the expansion of established capacity to develop, manufacture, and distribute health-related innovations, and relate primarily to vaccines. Both AstraZeneca and NovaVax have agreements with the Serum Institute of India, and Pfizer with South Africa-based Biovac (Biotechnology Innovation Organization, 2021[76]). The collaboration between BieGene, Singlomics, and Peking University (China) to assess the use of monoclonal antibodies is notable as one of the few public-private partnerships related to therapeutics.

Groups such as the Access Campaign have acknowledged that collaborations between industry, international non-profit organisations and LMIC-based research institutes to address COVID-19 are ‘a step in the right direction’ but also emphasise the limitations of many in not including IP waivers. While boosting global production capacity, it is common for these agreements to be bilateral and restrictive, limiting the amount of technology and know-how that is transferred and ultimately impeding progress towards independent and sustainable production in vulnerable regions. While some pharmaceutical companies committed to not enforcing IP during the pandemic to enable vaccine development in LMICs, this appears to have opened the door for patent infringement among industry rivals (Rebecca and Gross, 2022[77]).

As the pandemic response has transitioned to recovery, industry has reverted to traditional forms of competition. It has been argued that requiring pharmaceutical companies to waive IP rights could have an adverse effect on their willingness to enter into partnerships and that more pressing challenges are posed by the need for technology transfer and rapid scale-up of vaccine and drug manufacturing capacity, which is the focus of most the new pharmaceutical company partnerships in LMICs. Whilst the arguments around IP ownership and management will continue, there is much less disagreement around the need for action to support LMICs in developing the technological and human capacity required to participate in international science activities. The WHO’s mRNA vaccine technology transfer hub initiative, announced in June 2021, is a significant example of this, engaging both private and public sector actors (Box 22).

Box 22. Academia-industry partnerships and capacity building

In response to the COVID-19 pandemic, funds from a consortium of nine public and private international development partners were invested in the vaccine manufacturing capacity of South Africa-based Biovac to improve vaccine security of the region. The investment builds on a long history of activity in South Africa targeted to advancing the domestic manufacturing capacity of human vaccines. The Biovac institute, itself, is the result of a public-private partnership established in 2003 by the South African Department of Health and an industry consortium led by the Litha Healthcare Group. Since inception, over USD11 million has been invested in technological and human capacity development.

The Biovac investment complements several other regional partnerships. The Biovac Institute has been engaged by Pfizer to manufacture the BioNTech vaccine for exclusive use in Africa. In addition, a broader initiative was launched in June 2021 by the WHO and COVAX partners to establish a hub for mRNA vaccine technology transfer in South Africa. The organisations are working with a regional consortium, including Biovac, Afrigen Biologics and Vaccines, several universities, and the Africa Centres for Disease Control and Prevention. International partners will provide financial and human resources to develop human capital and know-how for manufacturing, quality control, regulation, and support the acquisition of technology licenses where needed. The initiative will form an international network in selected LMICs to advance manufacturing capacity and improve global health security. (see https://www.who.int/initiatives/the-mrna-vaccine-technology-transfer-hub).

The urgent and all-pervasive nature of the COVID crisis appeared to catalyse an unprecedented level of altruism within the private sector (and academia). For this reason, many actors have cautioned against drawing general lessons or good practices from the pandemic response and have warned of a likely return to business as usual, post-COVID. Nevertheless, looking back on the pandemic provides policy and science actors with an opportunity to understand the extenuating circumstances and conditions which allowed, in many cases, extraordinary action to be taken by public and private sector partners working in unison. The challenge now is to harness the momentum generated during the pandemic response to establish more effective and sustainable global R&D mechanisms to respond to forthcoming health emergencies and address large-scale global challenges.

Science-Industry Collaboration Policy Recommendations

Recommendation[4]	Policy Options
1. Policy-makers must develop and maintain the enabling conditions to catalyse science-industry collaborations and ensure their swift deployment during crises.	1.1. Prioritise sustained action to develop and maintain the necessary enabling conditions for academia-private sector partnerships to flourish. Credible and adequately resourced research institutions and infrastructures are important, in addition to technological and human capacity, and data sharing infrastructure, processes, and research culture. Sustained support for fundamental research is a critical element of this enabling environment. 1.2. Use a variety of policy initiatives tailored to the local context to support joint knowledge development and exchange. The policy mix might include project or cluster funding, collaborative platforms or spaces, data access, labour mobility and novel approaches to IP management. Awareness and evaluation of the existing policy mix will be important to support policy-makers in understanding potential positive or negative interactions when designing new initiatives. 1.3. Ensure that there are a variety of flexible funding mechanisms in place to support the development and maintenance of long-term, agile partnerships. Funding agencies should experiment with the development of new funding models and coordinating joint funding programmes with other national and cross-border agencies.
2. Policy-makers, funders, and other contributors must support the development and evolution of effective, and agile partnerships between academic and private-sector stakeholders to prepare for and respond to crises.	2.1. Engage industry stakeholders proactively in public research governance functions and in the development of initiatives to strengthen long-term trust and build social capital. 2.2. Use intermediaries, digital platforms, and other collaboration mechanisms to engage partners in a targeted and strategic way and support the development of communication and trust between academic and private-sector partners. 2.3. Prioritise public investment in high-risk science activities that may have limited potential for short-term economic returns, but significant potential for the generation of societal value. Policy action will be important to incentivise mission-driven science-industry partnerships at national and international levels.
3. Policy-makers, funders, and research institutions must experiment with agile and responsive funding and collaboration mechanisms to manage differing and potentially conflicting priorities, and incentives.	3.1. Ensure that science-industry partnerships are incentivised to integrate a diversity of perspectives and prioritise the needs of different population groups, including disadvantaged populations. At the international level, governments and funders have a role to play in engaging industry in developing science capacity in LMICs 3.2. Novel business models and funding approaches are required to balance conflicts between commercial, academic, and societal priorities in science-industry collaborations. Different approaches to IP and the ownership of research outcomes, including modular and flexible arrangements, should be incentivised or encouraged by policy-makers and funders. 3.3. Ensure that clear and open discussions are prioritised to establish trust and alignment when developing science-industry collaborations. This is of particular importance during crisis response when accelerated timelines may require that project activities are advanced without formal legal arrangements in place. 3.4. It is important that science programming and bureaucracy do not impede the ability of actors to develop innovative and experimental ways of working. Policy-makers should leverage context-dependent insights and guidance from a diversity of stakeholders to ensure the relevance, effectiveness, and agility of policy.

Concluding Remarks and Policy Implications

The COVID-19 pandemic has been a massively disruptive, cascading global crisis, the likes of which national and international science systems have not been challenged with for many decades. In many ways, the response has underscored that science systems must continue to evolve to address new challenges, and mitigate long-standing structural issues that limit their effectiveness. In this regard national science policy makers across the world have had to navigate a variety of important common concerns and difficulties and now face many similar challenges. At the same time, all countries are unique and important contextual differences will determine how the policy actions proposed in this report should be prioritised, designed, and implemented.

This report represents part of the learnings gathered from an analysis of how national science systems were mobilised to respond to the pandemic. It is focused on elements of science systems – access to data and information, research infrastructures, and science-industry collaborations. Findings illustrate clear points of overlap across these elements as well as science activities for policy and society – priority setting and coordination, scientific advice, and public communication and engagement (see report 2 in this series). There are also several dimensions that are common to a significant number of policy options, i.e., digital innovation, interdisciplinary engagement, and inclusion (Paunov and Planes-Satorra, 2021[2]). The functionality of different elements is connected and interdependent, as investment in one often contributes to the effectiveness of the others. Comparison of factors that enabled and challenged the mobilisation of different elements of science systems during the pandemic reveals common deficits that policy-makers must address to respond effectively to ongoing and forthcoming crises. These can be considered in terms the five meta-recommendations presented in '*Mobilising Science in Crises: Report 3 – Cultivating resilience at the interface between science, policy and society*: 1) Agile and strategic mobilisation of capacity; 2) Managing conflicting priorities; 3) Coordination and collaboration across levels of governance; 4) Transdisciplinary and reflexive science; and 5) Dynamic governance (Figure 6).

Long-term strategy and sustained investment have been critical to enable the **agile and strategic mobilisation** of national science systems. To respond effectively, it has been important for science and policy-makers to be able to leverage and build on existing elements of science systems, including data and research infrastructures, and science-industry partnerships. These key elements contribute to the coordination and alignment of science systems at a foundational level. Research infrastructures (RIs) are particularly important in this respect as service providers and sites for the development and evolution of collaborations. For this reason, it is recommended that policy-makers act to proactively recognise and support RIs as assets for crisis preparedness and response and ensure that the appropriate technological and human capacity is in place for them to effectively perform this role. A variety of mechanisms and tools supported the mobilisation of RIs during the COVID-19 pandemic and many of them now need to be embedded in the normal operations of these facilities. For example, novel digital innovations, tools, and platforms have played a significant role in: increasing the visibility and dissemination of research results; maintaining the continuity of RI operations; and, supporting collaborations across siloes.

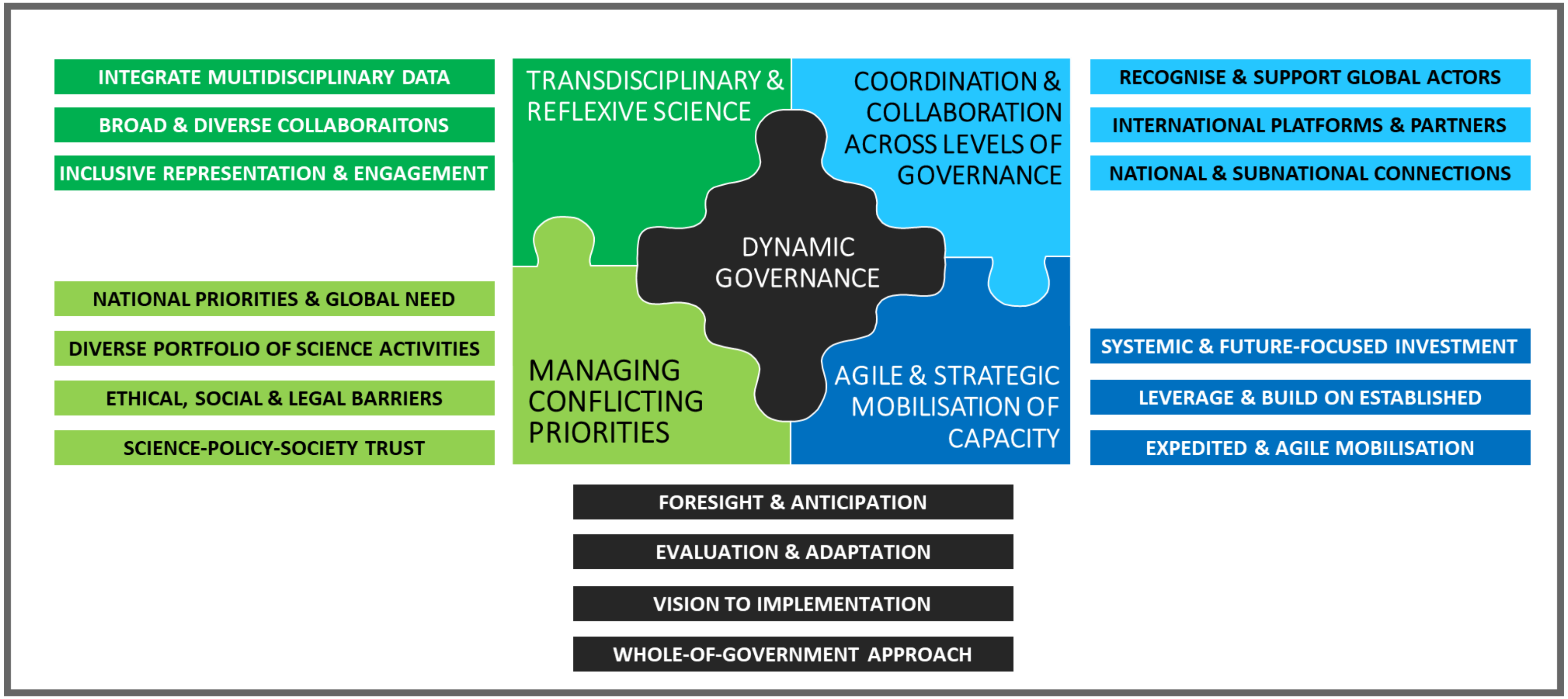
Dynamic governance processes and mechanisms have been useful in guiding strategic efforts to adapt national science systems to align with new needs. Approaches varied across jurisdictions, but good practice has included enabling and actively facilitating broad, inter- and transdisciplinary participation in science and science policy development. This requires support and incentives for inter- and trans-disciplinary research, long-term investment in promoting data and science literacy and public engagement in science. Coordinated bottom-up and top-down action has been important. At the science-industry interface, much of the activity that has occurred has been driven by individual scientists, research groups, and research institutes that are empowered by the science systems in which they operate. Conversely, top-down action at the national and international levels has been required to facilitate **coordination and collaboration across levels of governance**, leverage ongoing partnerships and research activities, and align the requirements for data, infrastructure, skills, and other resources. In this respect, the pandemic response has also highlighted areas where greater global leadership is required. The activities of biomedical or life science RIs have been limited primarily to the national and regional contexts, with the notable exception of global data networks in a few fields, such as genomics. There is an opportunity to leverage established RIs to facilitate more effective global networking and coordination during times of crises.

As the world becomes more connected and interdependent, it is likely that the ability of science systems to address forthcoming crises and grand challenges will increasingly depend on broad connectivity and collaboration. The development of **transdisciplinary and reflexive science** through the participation of a diversity of actors across disciplines, sectors, and geographies has been critical to the COVID-19 response. In many jurisdictions, the clinical and biomedical research communities were rapidly mobilised based on an initial assessment of the pandemic as largely a health crisis. As the pandemic has evolved, it has become obvious that effective action requires, not only insights from a broader diversity of scientific disciplines but also strong interactions with stakeholders from outside the science system, including industry, government, and civil society. In many contexts, a lack of recognition or prioritisation of the social sciences meant that engagement of these disciplines was belated and that, in some respects, their capacity to contribute was limited. Unique data sharing challenges, limited progress in the adoption of FAIR data principles, and a deficit in adequate data sharing infrastructures posed additional constraints for the social sciences. Notable academia-industry partnerships have been primarily limited to the life science and pharmaceutical industries with opportunities for collaboration in other areas being relatively neglected and poorly incentivised.

The COVID-19 pandemic has emphasised the importance of the social determinants of health and the need to consider disadvantaged population groups and global inclusivity in the development and mobilisation of science systems. Action is required to address structural challenges that impede the development of inclusive and representative research. Within and across borders, certain groups are more likely to be disproportionately impacted by crises or grand challenges. These same groups are also often overlooked by existing data collection methodologies and science activities, which means that resulting interventions often do not align with their circumstances or needs. In the national context, science policy-makers must take action, to promote the engagement of under-represented groups and to ensure that data collection, stewardship, and use is inclusive, representative, and ethically appropriate. To achieve truly global crisis preparedness, it will be important that stronger action is taken by national governments, funders, industry partners, and intergovernmental agencies to improve the inclusive and representative engagement of LMICs in scientific activities. It will also be important to advance the capacity of actors in these countries to collect, manage and use FAIR data for the development of science-based policies that are appropriately aligned with the local context. International RIs and science-industry partnerships are important mechanisms to support knowledge and technology transfer and the development of technological and human capacity required to enable this.

As barriers to the development of diverse collaborations are addressed, it is important to recognise, openly discuss and **manage conflicting priorities**, expectations, and constraints of different actors. COVID-19 catalysed unprecedented altruism and enabled actions previously considered to be unlikely or improbable. The advancement of international Open Science agendas has been reflected by increased and accelerated access to research data and results. The crisis has motivated action from national governments and funders to mandate access to research data and publications, and actions from publishers to make COVID- and coronavirus-specific publications openly accessible. More broadly, science-industry partnerships have leveraged trust, communication, and novel collaboration methodologies to accelerate the development of projects, often in the absence of strict contractual arrangements. At the same time, caution is required in drawing general good practice guidance from the pandemic response because of the extraordinary altruism that it inspired in many actors. Concerted international action will need to be taken to prevent a reversion to more closed 'business as usual' behaviours as this COVID-19 pandemic becomes a thing of the past.

Figure 6. Meta-themes and corresponding interventions to improve resilience in relation to complex crises and societal challenges



Note: This is a conceptual representation of the cross-cutting meta-themes discussed in detail in report 3. Meta-themes are depicted as the five central puzzle-pieces and interventions are shown as the corresponding color-coded rectangles. Dynamic Governance sits at the heart of the puzzle to represent the importance of structural change in this area as a key enabler of the interdependent transformations required in other areas. Similarly, Managing Conflicting Priorities and Agile and Strategic Mobilisation of Capacity comprise the bottom layer of the puzzle to illustrate the foundation required to enable Transdisciplinary and Reflexive Science and Coordination & Collaboration Across Levels of Governance.
Source: Authors' design.

Endnotes

[1] A curated selection of significant quotations was taken primarily from the ‘Enhancing access to research data during crises’ workshop held in April 2021. A complete list of workshop participants is available in Annex 4. Note that as the workshop was unscripted, some quotations have been edited as necessary to ensure understandability. The selection was made to limit overlap or repetition among the quotations featured. The number of times a key issue is featured in the quotations is not indicative of its significance.

[2] The CARE Principles build on several foundational pieces of work. Notable amongst these is the 2007 United Nations Declaration on the Rights of Indigenous Peoples, which recognises the importance of types of knowledge that fall beyond mainstream conceptions of knowledge, and confirms the importance of Indigenous rights to self-determination, Indigenous culture and IPR, and Indigenous research ethics. The declaration also codifies the idea of Indigenous Data Sovereignty, a concept that has been expanded on in several countries, including Canada, New Zealand, Australia, and the United States.

[3] For insights on the uptake and use of data and knowledge by science system stakeholders, please refer to other reports in this series: report 2– cahapter on Science Advice; and, report 3– chapter onTransdisciplinary and Reflexive Science.

[4] Policy recommendations can be viewed as critical actions with universal relevance to the ability of science systems to prepare for and respond to crises. On the other hand, policy options represent potential measures which might be taken to achieve or progress towards the related recommendation. Stakeholder roles and responsibilities and how selected options are implemented will be dependent on the national context in which they are applied.

[5] Many of the policy reports produced by GSF over the last two decades have included discussion of the challenges posed to science policy-makers by the heterogeneity and increasing complexity of RI ecosystems. RIs are often dependent on diverse and evolving financial, political, and historical national contexts. They are difficult to define, characterise or group, and can have very different governance and financial models. This heterogeneity appears to pose a significant challenge to science policy-makers in their ability to develop and leverage RIs to their fullest potential.

[6] In the context of the ‘Mobilising Science’ project, the analysis of academia-industry interface is made specifically from the perspective of policy for public science. The role of private sector research and related policy has been limited to issues at the interface with public sector research.

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Annex 1: Recommendations and Options for Preparedness and Response

Note: See following page for policy recommendations and options targeted to the response phase and a brief explanation to aid interpretation.

RESPONSE

DATA ACCESS

ENABLE REPRODUCIBILITY AND EXPEDITE USE OF RESEARCH DURING CRISES

- Mandate registration of publicly funded studies to improve efficiency and trial design
- Incentivise researchers to make data and publications resulting from publicly funded research openly accessible
- Accelerate access to important research with appropriate safeguards in place

PRIORITISE ETHICAL COLLECTION AND USE OF DATA AND EXPEDITE HIGH-PRIORITY ACCESS

- Extraordinary data collection measures must maintain full transparency and accountability
- Support data repositories in testing and adopting novel technologies, including federated computing environments
- Proactively engage with industry to leverage data and analytical capacity during crises
- Promote universal adoption of procedures and agreements that enable ethical data use

SUPPORT FAIR, OPEN ACCESS, AND USE OF DATA

- Tailor support to the needs of disciplines to enable the adoption of Open Science
- Leverage and build on established efforts to advance Open Science and data sharing policies. Expand global participation
- Connect research owners and users using tools and communication platforms
- Raise the visibility of open data and knowledge resources and support reuse
- Drive the adoption of enabling technologies to facilitate use of existing knowledge

ENSURE INCLUSIVE AND ETHICAL DATA COLLECTION AND USE

- Incentivise and support the engagement of civilian groups in data science activities
- Encourage the engagement of neglected groups in data collection and use

ADDRESS STRUCTURAL CHALLENGES TO INCLUSIVE SCIENCE

- Strengthen the technological and human capacity of LMICs to enable use of FAIR data
- Support initiatives led by or inclusive of LMICs to develop and host data assets
- Ensure LMICs are represented in international efforts to advance Open Science

RESEARCH INFRASTRUCTURES

SUPPORT RIS AS CRISIS PREPAREDNESS AND RESPONSE ASSETS

- Engage RIs and users in developing policy to address crises and grand challenges
- Designate and support qualified RIs as national or regional crisis response centers
- Prepare and empower RIs to respond to crises through activities beyond set mandates

INVEST IN CAPACITY REQUIRED FOR RESILIENCE

- Advance partnerships with public and private sector research provides to facilitate training, mobility, and connectivity

PRIORITISE SYNERGIES BETWEEN RIS

- Empower RIs as collaboration switchboards for interdisciplinary research activities
- Encourage and incentivize RIs to engage industrial users and build trusted relationships

PRIORITISE COLLABORATION BETWEEN NATIONAL AND INTERNATIONAL RIS

- Establish mechanisms for collaboration and improve visibility of ongoing research
- Broaden the mandates of national RIs and support participation in international networks
- Invest in infrastructure critical to the response of LMICs to crises and grand challenges

SCIENCE-INDUSTRY COLLAB

DEVELOP EFFECTIVE SCIENCE SYSTEMS

- Align the policy mix to support knowledge 'co-creation' and transfer with the local context
- Establish diverse, flexible funding initiatives to support science-industry collaborations

SUPPORT STRONG, EFFECTIVE, AND AGILE PARTNERSHIPS

- Use intermediaries and other tools to engage partners in a strategic way and build trust

EXPERIMENT TO MANAGE CONFLICTING PRIORITIES

- Support science activities with the potential to generate societal value
- Ensure that public-private partnerships integrate diverse perspectives and needs
- Incentivise and support different approaches to IP and the ownership of research results
- Prevent bureaucracy from inhibiting innovative business models or processes
- Use open communication to establish trust and alignment between partners

Legend

- Policy Recommendation
- Policy Option requiring action in identified stage of crisis response
- Policy Option requiring action in preparedness & response

Overlap between functional areas

- Data access
- Research infrastructures
- Public communication & engagement
- Priority setting & funding
- Scientific advice
- Public communication & engagement

Note:. The two tables show recommendations and policy options and in terms of relevance to the preparedness and response stages of the crisis management cycle. Policy options pertaining to both stages are shown in both tables. Overlaps and potential points of synergy between areas of policy for science (this report) and science for policy and society (report 2) are indicated with icons.

Annex 2: Expert Group Membership

Country	Name	Position	Organisation
AUS	Julian Thomas	Director, Professor of Media and Communications	Swinburen Institute for Social Research
BEL	Marie Delnord	Public Health Researcher, Epidemiologist	Sciensano, Belgian Public Health Institute
CAN	David Castle	Researcher in Residence	Office of the Chief Science Advisor, Government of Canada
CZE	Petr Bartůněk	Group Leader	Institute of Molecular Genetics,Czech Academy of Sciences
CZE	Tereza Stöckelová	Researcher, Associate Professor of General Anthropology	Institute of Sociology of the Czech Academy of Sciences
FRA	Yazdan Yazdanpanah	Director	ANRS Maladies Infectieuses Emergentes
JPN	ARIMOTO Tateo	Principal Fellow	Center for Research and Development Strategy (CRDS), Japan Science and Technology Agency (JST)
JPN	Mr. OYAMADA Kazuhito	Fellow	JST
JPN	Mr. KANO Hiroyuki	Fellow	JST
KOR	Dr. Inkyoung SUN	Head, Office of Development Cooperation Research	Science and Technology Policy Institute (STEPI)
KOR	Myong Hwa Lee, Ph.D	Head, Office of National R&D Research	Science and Technology Policy Institute (STEPI)
NLD	Prof. dr. F.W.A. (Frans) Brom	Professor, Normativity of Scientific Policy Advice	Ethics Institute, Utrecht University
NOR	Trygve Ottersen	Executive Director	Norwegian Institute of Public Health
PRT	Vanda Oliveira	S&T Programme manager	FCT
PRT	Isabel Carvalho-Oliveira	Delegate and NCP for Health in the Horizon Europe Programme	Agency for Clinical Research and Biomedical Innovation
ZAF	Dr Ntsane Moleleki	Senior Specialist – Policy Investigation	National Advisory Council on Innovation (NACI)
ZAF	Dr Tozama Qwebani-Ogunleye	Project Manager	Institute of Traditional Knowledge, Vaal University of Technology (VUT)
UK	Randolph Kent	Director	Humanitarian Futures
UK	Mike Bright	Deputy Director, International	UK Research and Innovation

Annex 3: International Workshop Series Overview

	Workshop	Description
R1: POLICY FOR SCIENCE	**I. 23 April 2021:** Enhancing access to research data during crises	**Organised in partnership with the RDA and co-located with RDA's 17th Plenary meeting.** Sessions focused on high-level policy frameworks and domain-specific issues. Biomedical and clinical data, omics and epidemiology, and social sciences and interdisciplinary research were addressed in individual sessions. https://one.oecd.org/document/DSTI/STP/GSF(2021)13/FINAL/en/pdf
R1: POLICY FOR SCIENCE	**II. 11 May 2021:** Mobilizing research infrastructures in response to COVID-19	**Organised in partnership with Science Europe and held as a satellite event of the 2021 International Conference on Research Infrastructures (ICRI).** Sessions explored key challenges and good practices for the emergency management and operation of research infrastructures across different research domains. https://one.oecd.org/document/DSTI/STP/GSF(2021)12/FINAL/en/pdf
R1: POLICY FOR SCIENCE	**III. 16 September 2021:** Improving academia-private sector interactions	**Organised in partnership with the OECD working party on Technology and Innovation Policy (TIP).** Actors directly involved in participating in or funding research involvling public and private sector partners presented specific case studies. Policymakers then provided short interventions reflecting workshop learnings in relation to national contexts. https://one.oecd.org/document/DSTI/STP/GSF/TIP(2022)1/FINAL/en/pdf
R2: SCIENCE FOR POLICY & SOCIETY	**IV. 4-5 October 2021:** Priority setting and coordination of research agendas	Case study presentations and moderated discussions covered setting, steering, and coordinating research priorities during crises. Specific focus was placed on data collection, evidence for public health and social measures, and maintaining agility and flexibility. In a final panel discussion, participants reflected on the importance of international cooperation and global and national preparedness for future crises. https://one.oecd.org/document/DSTI/STP/GSF(2022)1/REV1/en/pdf
R2: SCIENCE FOR POLICY & SOCIETY	**V. 3-4 March 2022:** Scientific advice in crises	A diversity of scientific disciplines was represented by key experts in scientific advisory processes and policy development. Critical issues included interplays between science, policy, and politics; transdisciplinary knowledge; public communication and trust; coordination across governance levels; and implications for future crisis response. https://one.oecd.org/document/DSTI/STP/GSF(2022)1/REV1/en/pdf
R2: SCIENCE FOR POLICY & SOCIETY	**VI. 22 April 2022:** Public communication and engagement in science	This final event expanded on insights developed in earlier workshops regarding the role of civil society in a science-based response to crisis. Sessions were designed around the mitigation of mis- and disinformation; managing and communicating uncertainty; public engagement; and long-term trust. In a final panel discussion, participants reflected on the importance of advancing novel participatory approaches, while ensuring feasibility and buy-in from citizens, as well as policy and science actors. https://one.oecd.org/document/DSTI/STP/GSF(2022)9/FINAL/en/pdf

Annex 4: Policy for Science Workshop Participants

Workshop Session	Name and Title	Organisation	Country
Enhancing access to research data during crises			
Basic medical and clinical research	Nevine Zariffa, Scientific Project Lead	International COVID-19 Data Alliance (ICODA)	UK
	Michael Brudno, Chief Data Scientist	University Health Network	CAN
	Marie Paule Kieny, Director of Research	Inserm	FRA
Omics research and epidemiology	Niklas Blomberg, Director	ELIXIR	EU
	Priyanka Pillai, Academic Specialist in Bioinformatics	University of Melbourne	AUS
	Dr. Xihong Lin, Professor of Biostatistics; Coordinating Director of the Quantitative Genomics Program	Harvard and MIT	USA
Social sciences and interdisciplinary research	Stefania Milan, Associate Professor of New Media and Digital Culture	University of Amsterdam	NLD
	Dr. Katja Mayer, Senior Postdoctoral Fellow of Science and Technology Studies	University of Vienna	AUT
	Dr. Yukio Ohsawa, Professor	University of Tokyo	JPN
National and international policy perspectives	Camilla Stoltenberg, Director General	Norwegian Institute of Public Health (NIPH)	NOR
	Kazuhiro Hayashi, Director of Research Unit for Data Application	National Institute of Science and Technology Policy (NISTEP)	JPN
	Yazdan Yazdanpanah, Director	ANRS Maladies Infectieuses Emergentes	FRA
	Dr. Claudia Bauzer Medeiros, Professor of Databases	University of Campinas and FAPESP	BRA
	Michael Kahn, Policy Analyst and Evaluator of STI	Stellenbosch University	ZAF
	Dr. Kiwon Jang, Senior Researcher	Korea Research Institute of Bioscience and Biotechnology	KOR
	Steven Kern, Deputy Director of Quantitative Sciences	Bill & Melinda Gates Foundation	USA
	Konstantinos Repanas, Policy Officer, Open Science Unit	European Commission	EU
Mobilising research infrastructures in response to COVID-19			
Adapting RI processes in emergency situations	Christos Arvaniditis, CEO	Lifewatch-ERIC	EU
	Philip Gribbon, Head of Discovery Research	Fraunhofer and EU-Openscreen	EU
	Dr. Makoto Tsubokura, Professor of Computational Fluid Dynamics	RIKEN Center for Computational Science and Kobe University	JPN
Preparedness and response of life science and health RIs	Dr. Michaela Mayrhofer, Head of ELSI Services and Research	ELSI-BBMRI	AUT
	Volker Gerdts, CEO	VIDO-INTERVAC	CAN
	Bryan Charleston, Director	Pirbright Institute	UK
Policy lessons learned and the potential role of research	Martin Taylor, Executive Director	Canadian Research Data Center Network	CAN
	Yazdan Yazdanpanah, Director	ANRS Maladies Infectieuses Emergentes	FRA
	Antonio Zoccoli, President	Istituto Nazionale Fisica Nucleare (INFN)	ITA
	Lukas Levak, Director	Ministry of Education	CZE
Improving academia-private sector interactions			
Challenges and good practices in co-creation during the crisis	Frank von Delft, Professor of structural chemical biology	University of Oxford	UK
	Kathryn Funk, Program Manager of PubMed Central	National Institutes of Health (NIH)	USA

	Jerry Sheehan, Deputy Director	National Library of Medicine – National Institutes of Health	USA
	Kirsimarja Blomqvist, Professor of knowledge management	LUT University	FIN
	Catalina Lopez-Correa, CSO	Genome Canada	CAN
	Hande Alpaslan, Head	TUBITAK, STI Policies Department	TUR
	Duygu Saracoglu, Senior Policy Expert	TUBITAK, STI Policies Department	TUR
Policy tools and instruments	Mark Ferguson, Director General	Science Foundation Ireland (SFI)	IRL
	Myong Hwa Lee, Head of the Office of National R&D Research	Science and Technology Policy Institute (STEPI)	KOR
	Tateo Arimoto, Visiting Professor of STI Policy	National Graduate Institute of Policy Studies (GRIPS)	JPN
	Kazuhito Oyamada, Fellow	Center for Research and Development Strategy (CRDS)	JPN
	Marnix Surgeon, Deputy Head	European Commission, Common Mission and Partnerships Service	EU
	Catarina Resende Oliveira, President	Agência De Investigação Clínica E Inovação Biomédica (AICB)	PRT
Key Takeaways	Catherine Ewart, Associate Director, International	UK Research and Innovation (UKRI), Science and Technology Facilities Council	UK
	Goran Marklund, Deputy Director General *Chair, TIP Working Party*	Vinnova	SWE
	Tiago Santos Pereira, Principal Researcher *Vice Chair, TIP Working Party*	Conselho Económico e Social (CES)	PRT
	Jerry Sheehan *Vice Chair, TIP Working Party*	Office of Science and Technology Policy (OSTP)	USA
	Kimikazu Iwase, Principal Fellow	Center for Research and Development Strategy (CRDS)	JPN
	Kai Husso *Vice Chair, TIP Working Party*	Ministry of Economic Affairs and Employment	FIN