FORESIGHT

SCIENCE FOR NAVIGATING CRITICAL TRANSITIONS

S20
SAUDI ARABIA 2020
SCIENCE

FORESIGHT

SCIENCE FOR NAVIGATING CRITICAL TRANSITIONS

A Report on Analysis and Recommendations from the Saudi Arabia S20 Task Force Dialogues and Consultative Activities

Riyadh, Kingdom of Saudi Arabia
November 2020

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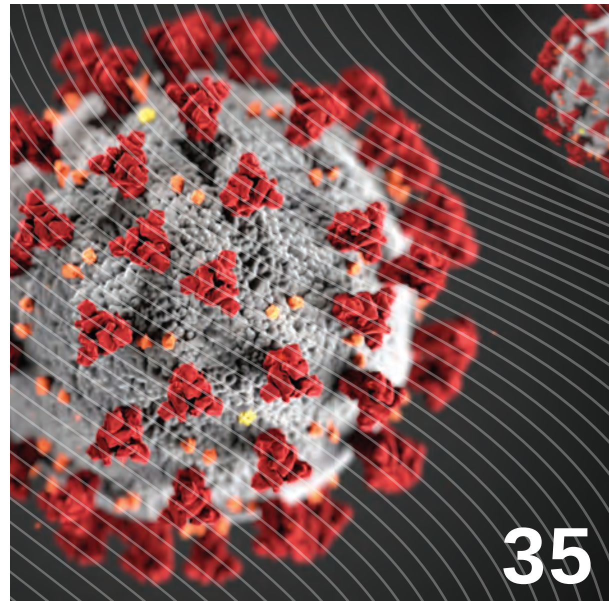

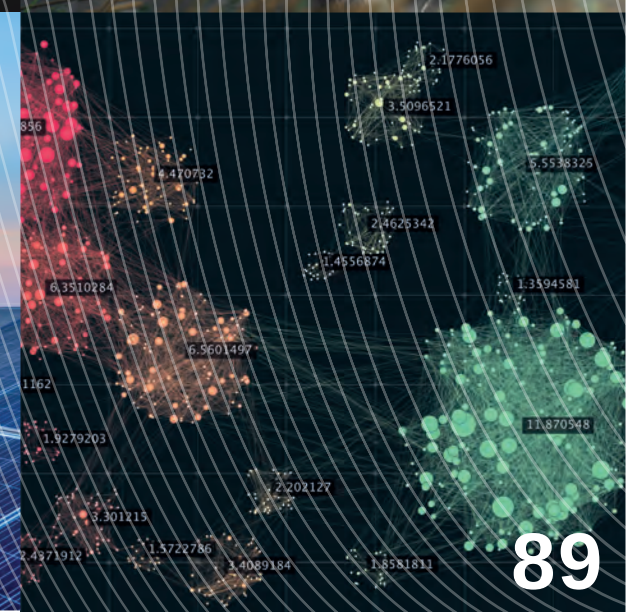

ATTRIBUTION

This report reflects the analysis developed under a Task Force process organized by the S20 Saudi Arabia. Although experts invited from the S20 Science Academies participated in the Task Force process, the opinions expressed and arguments employed herein do not necessarily represent the official views of the S20 Science Academies, nor is this report an official statement endorsed by the S20 Science Academies. Ideas in this report were influential in formulating the S20 Communiqué.

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LETTER FROM THE S20 CHAIR

Anas Alfaris, Ph.D.
Chair, S20 Saudi Arabia 2020
President, King Abdulaziz City for Science and Technology (KACST)

Our theme for the S20, Foresight: Science for Navigating Critical Transitions, has never been more relevant. With the unprecedented global disruption caused by COVID-19 unfolding day by day, this is a pivotal time in the course of our history. The lack of foresight leading into the COVID-19 pandemic left the world poorly prepared to respond on multiple levels and susceptible to public health, educational, economic, and social disruptions. Sadly, we as humans have faltered in dealing with the pandemic because we failed to comprehend second, third, and nth-order effects in our complex, interconnected global systems.

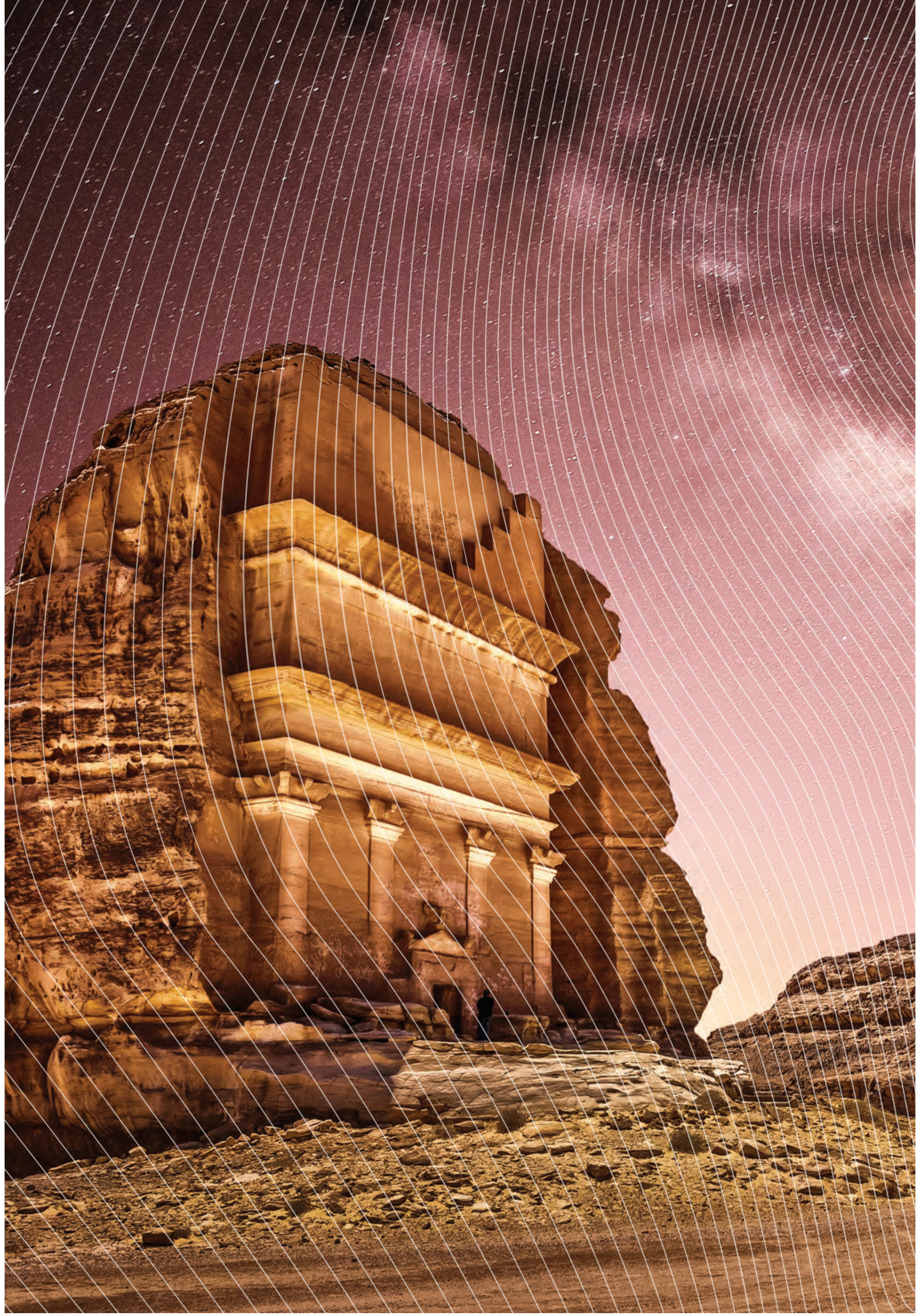
The S20's theme, Foresight: Science for Navigating Critical Transitions, is, therefore, a call to action aimed at maximizing opportunities and minimizing disruption brought about by the fast-evolving, complex, socio-technological developments in the health, environment, and digital systems. Now is the time for the science community to unite and work together to increase its efforts to engage effectively with decision-makers, clearly identify common interests, and ensure the adoption of science-based and future-ready policies to achieve a transition from Foresight to Scientific Foresight.

Using science to transform traditional Foresight approaches into Scientific Foresight is critical for supporting governments and policymakers to explore the "solution space" that may arise in the medium- and long-term versions of the future. Developing the Scientific Foresight paradigm will require participation and collaboration from many entities. A diversity of perspectives helps separates the "signal from the noise," facilitates developing a more precise understanding, enables better sharing of knowledge, and prepares us for improved dialogue with the public to elevate awareness and understanding of science and technology.

This year we set forth with a vision to expand the impact and activities of the S20. We believed that to maximize our impact, we needed to expand participation: we, therefore, proposed four S20 Task Forces. With a pandemic emerging, there was no better time for scientists from across the globe to come together in open dialogue to exchange experience and identify the critical transitions and challenges that science can uniquely help the world navigate.

This report is the culmination of their achievements. This report reflects a synthesis of expert input from four S20 Task Forces, incorporating the exceptional insight and analysis of more than 170 scientists from around the world who served as Task Force members. In addition to the analysis and insights contained in this report, the work of the Task Forces informed the ten recommendations that were advanced in the S20 Communiqué that was endorsed by all G20 Science Academies and then received by H.E. the Minister of Health on behalf of his Majesty King Salman bin Abdulaziz, who is the Chair of this year's G20.

The world needs the leadership of the G20 nations in establishing a new paradigm for Scientific Foresight. We are hopeful that this S20 report will provide the rationale and roadmap needed by the G20 to achieve that goal. The vision for Scientific Foresight developed in this report underscores that we as a science community need to increase our research collaboration as we are still navigating this Critical Transition that is the COVID-19 pandemic, and we need to advance the methodologies in use across the G20 to achieve Scientific Foresight that allows us to navigate future Critical Transitions. Scientific Foresight, properly cultivated, holds the promise of fulfilling the potential of our best minds to avoid and mitigate future suffering and achieve greater health, stability, and prosperity. The moment to act is here.



REPORT ACKNOWLEDGEMENTS

This report is a product of the S20 Engagement Group and was produced with input from over 170 international experts from the G20 countries (Appendix II). The S20 Leadership Team (Appendix I) wishes to thank the Leaders and Members of the four S20 Task Forces for their thoughtful engagement and contributions, without which this report would not have been possible.

The S20 Chair would like to thank Professor Tony Chan, President of King Abdullah University for Science and Technology for his support in hosting the S20 Summit. Furthermore, the S20 Chair would like to thank members of the S20 Steering Committee (Dr. Abdulaziz Almalik, Dr. Donal Bradley, Dr. Khalid Ibrahim Alhumaizi, Dr. Khalid M. AlKattan, Dr. Mesfer M. Al Zahrani, and Dr. Yusuf Abdulaziz Al-Turki) for their input and guidance on the development of the overall strategy and shaping priorities for the 2020 S20 cycle and for their leadership and support in hosting the S20 Webinar Series.

The S20 Chair would also like to thank Dr. Amal Fatani, the S20 Sherpa, for her extraordinary efforts to guide and support the S20 Task Forces in drafting and finalizing the S20 policy recommendations; Dr. Adnan Alsaati, Executive Advisor to the S20 Chair, for leading the development of Task Force Surveys and coordinating the development and distribution of the S20 Communiqué; Ms. Yara Al-Rajeh, Chief Advocacy Officer, for her tireless work to promote the visibility of the S20 activities with key G20 stakeholders and the global science and technology community; In addition, the S20 Chair would like to thank Dr. Teofilo ‹Jun› Abrajano for his support and leadership of the S20 Secretariat and (Dr. Stine Büchmann-Møller, Dr. Debra Turner, Ms. Andrea B. M. Hulsbosch, Ms. Madhvi Naganand, Ms. Melanie Balkner-Zielke, Mr. Abdullah Binquayeed, Ms. Mae Belle Noynay and Ms. Gumana Habis) and their knowledge partner, Accenture, for their administrative, logistical, and operational support throughout the 2020 S20 cycle.

The American Association for the Advancement of Science (AAAS), Research Competitiveness Program (RCP) provided editorial support for this report, which included content editing, formatting, editing for grammar, spelling, and punctuation, referencing, reorganization of content, and working with the S20 and Task Force leadership to enhance the clarity of the content.

The S20 Leadership Team would also like to thank the external, expert reviewers, who were engaged by the AAAS, for providing independent peer review of early drafts of individual report chapters. The reviewers were not asked to add to or endorse the report content or recommendations, and they did not see the final draft of the report before its release.

The S20 Leadership Team would also like to thank the international partners and global science institutions who shared their input and insights throughout the S20 process. We would like to especially thank the Center for the Study of Existential Risk (CSER) for their input to the S20 Foresight Task Force and the International Science Council for their advocacy support.

Finally, the S20 Leadership team would like to thank the General Directorate of Awareness and Innovation Culture at King Abdulaziz City for Science and Technology (KACST) for providing the needed support in finalizing, designing and printing this report.

EXECUTIVE SUMMARY

This Report of the G20 Science Engagement group (S20) is a call to action. The world faces impending disruptions due to the 21st century's unprecedented, highly complex, and interconnected global systems. These systems have improved the human condition in many respects, but they have also revealed transnational fragility: the economic, health, and political disruption from the COVID-19 pandemic is an active example. This Report is, therefore, founded on the modern truth that we must start analyzing our global systems in their entirety because the systems are too complex and interconnected to analyze from a single viewpoint. The pathway to better government, policy, and action is a process built on a whole-system approach that advances our capacity for Foresight, preparing us to solve or avoid future global disruptions.

Foresight is the application of structured methods to data gathering, validation, analysis, and interpretation that anticipates future circumstances and defines policy for preventing or mitigating future harm. To this point in history, Foresight exercises predicting future scenarios have been carried out mainly by policy analysts in think-tanks, universities, corporations, multinational organizations, and governments as projection and planning activities, usually with a dedicated department or unit that uses strategic foresight tools by compiling or commissioning data from experts for use in brainstorming and policy development. Science has been an ad hoc resource for many Foresight studies. However, profound global challenges, abrupt system-level changes, and resulting critical transitions impacting interconnected societal sectors require insightful leadership and vision to transform these traditional Foresight exercises.

Our capacity for Foresight must advance because the next several decades will witness a convergence of multiple critical transitions affecting our global society. These critical transitions can expose vulnerabilities, leading to harmful outcomes. In fact, critical transitions are already underway, and the world's leading economies—represented by the G20 countries—must have an expanded capacity for Foresight to alleviate system-level economic and societal disruptions that could ensue. Science and scientists must help governments identify impending risks, and they must also aggressively work together with policymakers to explore the "solution space" to address these risks. At the same time, governments can foster desirable critical transitions, providing opportunities to improve resilience in human health, environmental sustainability, and a beneficial digital revolution.

To develop recommendations for advancing Foresight, this Report assesses the global landscape of critical transitions driving the need for improved Foresight and the challenges inhibiting progress. This analysis is developed on chapters in the Future of Health, the Circular Economy, and the Digital Revolution. The Future of Health chapter considers pandemic prevention and the expansion of personalized health care. The Circular Economy chapter considers holistic solutions for our environment. And the Digital Revolution chapter addresses the transitions and path to achieving universal connectivity and smarter communities. These three global landscape assessments provide evidence and insight for a concluding chapter—Foresight: Connecting the Dots—that identifies what a revolution in Foresight looks like and how it will be enabling and have cross-cutting impacts. This final chapter on Foresight maps the path forward to achieving a new international paradigm for Foresight.

This Report, therefore, presents key insights and recommendations to the G20 to lead the advancement of Foresight in order to prevent and mitigate global disruption. Insightful developments in Foresight capacity can also drive improvements to human health and our global environment while guiding the best benefits from our ongoing digital revolution.

To develop the analysis in this Report, the Science 20 Engagement Group (S20), under Saudi Arabia's leadership of the G20, convened four Task Forces to produce a current, global perspective. The S20 selected a Saudi thought-leader to chair each Task Force in partnership with a co-chair from among the G20 science academies. Under this leadership, each Task Force comprised forty members from across G20 science academies, including diverse representation from Saudi Arabia speaking with one voice for the national perspective. The Task Force members completed a structured analysis, through a comprehensive S20 survey, to provide the primary evidence used by each Task Force in its work. Each Task Force analyzed this international evidence to determine which critical transitions with negative consequences are avoidable or unavoidable and which desirable critical transitions might be stimulated and achieved by developing and applying scientific research and policy. Each Task Force then used the global survey to assess the challenges that prevent desired progress to mitigate or achieve these critical transitions. And finally, each Task Force made recommendations regarding advances in Foresight that would allow challenges to be overcome, achieve desirable critical transitions, and realize deeply effective policy. A fourth Task Force used this breadth of global expert insight to identify the advances in Foresight required across each of the three domains and to define a holistic vision for advancing Foresight: a vision ready for adoption at the international level.

The Future of Health Task Force identified five current trends: emerging infectious and endemic diseases, demographic shifts, environmental changes, rising inequality, and rapid technological advances as potential drivers of future developments in the fields of health and biomedical research. The application of Foresight tools can help identify potential challenges and opportunities and inform the development of relevant policies and regulations to mitigate risks and facilitate positive transformations in the years ahead. Guided by an in-depth analysis of current research trends, gaps, and needs and in light of the ongoing pandemic, the Task Force outlined six recommendations to guide future investments and action priorities in health: establishing a pandemic preparedness framework; developing and using advanced therapeutics to enhance personalized care; developing high-precision and low-cost digital health technologies; deploying policies and interventions to address the demographic shift; facilitating open science and research collaborations; and developing frameworks and standards for international data sharing.

The Circular Economy Task Force recognized that the concept of a circular economy has evolved from the traditional 3R's of reduce, reuse, and recycle into a complex ecosystem that must be addressed collectively by stakeholders across the scientific, policymaking, and consumer communities. The endangerment of natural resources, damage to biodiversity, extreme weather conditions, and unequal development of rural and urban areas are key drivers precipitating unsustainable production practices and waste generation on marine and terrestrial ecosystems. Through the lens of Foresight, this chapter discusses how world leaders can begin to mitigate and counter these critical transitions that may propel us away from a global circular economy with a thriving future for our natural resources of energy, water, materials, and food.

The S20 Digital Revolution Task Force looks ahead to a future society in which digital technologies are integrated into every aspect of life and their potential is fully realized in a way that maximizes public values. To advance this vision and develop a plan for action, the S20 Digital Revolution Task Force assessed the state of science leading to universal connectivity, sustainability, security, and resilience. The Task Force identified four global trends impacting the future of the Digital Revolution: system shocks due to extreme events; rapid development and uneven penetration of digital technology; increasing environmental impacts from digital infrastructure; and demographic shifts and rapid population growth. The rapid development, distribution, and adoption of digital technologies are driving key developments in human rights, inclusiveness in society, privacy, data transparency, algorithmic fairness, ethics, and a changing societal landscape.1 Yet the research and policy frameworks across G20 nations must be strengthened to achieve universal connectivity; improve the rate of implementation of new technologies; increase the uptake of some Artificial Intelligence solutions; establish robustness, resilience, security, and privacy; and mitigate the growing environmental impact of digital technologies. The Digital Revolution Task Force developed five policy recommendations and corresponding actions aimed at leveraging Foresight and maximizing the benefits of the Digital Revolution for the benefit of the global community: bridging the emerging digital and social divide; establishing a global platform to enhance cross-sector collaboration; planning for a digitally enabled society; reducing vulnerabilities and enhancing security and resilience of digital technologies and infrastructure; and reducing environmental impact.

The Foresight Task Force connected the dots across the globally significant themes of health, the circular economy, and the digital revolution to analyze the path to creating a new paradigm for Foresight to address global critical transitions comprehensively. Traditional methods of Foresight have significant gaps: they often oversimplify complex, interconnected systems; they are not well suited to incorporating the large multidisciplinary datasets that are increasingly available; and they are not suited to working in combination with one another. Compounding these gaps in methods is the inconsistent, patchwork nature of international data sharing and uneven trust in data quality. To significantly advance Foresight internationally, the Task Force recommends embracing new methods emerging across research disciplines that can allow us to leapfrog past current shortcomings. These emerging methods span complexity science, systems dynamics, network science, gamification, game theory, decision support systems, and artificial intelligence. To bring these new methods into impactful practice, the Task Force recommends establishing a platform to implement and foster international collaboration and build trust in this refreshed and invigorated approach. What this chapter proposes, therefore, is a transition from the current practice of Foresight to a new and more capable approach: Scientific Foresight.

The analysis in this Report represents a transformational international vision. Support for increased collaboration among G20 nations and the establishment of a Scientific Foresight hub, as an independent institution serving the public good across nations and cultures, is an achievable goal through a sincere commitment to leadership. We are at a unique point of action; a tipping point where future generations could see a decision to take this path as a wise and providential step forward.

THE SCIENCE 20 ENGAGEMENT GROUP

THE SCIENCE 20 ENGAGEMENT GROUP

BACKGROUND

Science 20 (S20) is one of eight formal engagement groups of the G20 (Group of Twenty; see Table A.1 for a list of all G20 engagement groups), comprising the national science academies of the G20 members, represented by the academy presidents. While the G20 was established in 1999, and primarily as an economic forum,[2] the S20 was established relatively recently during the 2017 G20 presidency of Germany to bring a stronger scientific voice and perspective to the G20 discussions.

The S20 provides scientific expertise and advice to the G20 heads of government within the G20 arena, primarily by holding a dialogue on topics of global concern from a science-based perspective and ultimately summarizing the results of the discussion into a set of policy recommendations for the G20 leaders. S20 Policy Recommendations are provided to a G20 representative as a joint statement—the S20 Communiqué—by the G20 national science academies during a formal meeting—the S20 Summit-that officially ends the S20 cycle that year.

However, the S20 also provides scientific expertise to other G20 activities throughout the G20 cycle by participating in meetings and workshops organized by other engagement groups or G20 tracks and contributing via statements on scientific and technical topics through the course of the G20.

Each year, the S20 holds a discourse on a specific theme. This annual theme is selected by the host country and based on pressing global topics where science may lend its voice to providing policy advice to governments. In addition, the S20 aims to carry forward its previous discussions and build on the legacy of earlier S20 annual discourses, Summits, and Communiqués.

THE S20 ENGAGEMENT GROUP LEGACY

GERMANY 2017

Annual Discourse Theme: Improving Global Health Strategies and Tools to Combat Communicable and Non-Communicable Diseases.

B20	Business 20 represents the private sector
C20	Civil 20 represents civil society organizations
L20	Labor 20 includes labor unions across the G20 member countries
S20	Science 20 represents the academies of sciences in the G20 Countries
T20	Think 20 is a network of think tanks and researchers
U20	Urban 20 includes mayors from cities across the G20 city representatives
W20	Women 20 represents the interests of women
Y20	Youth 20 brings together young leaders from across the G20 member countries

Table A.1: G20 Official Engagement Groups

Under the leadership of the Leopoldina, the science academies of the G20 countries prepared the first S20 joint statement on improving global health for the G20 Summit in Hamburg. The Communiqué was handed over to the German Federal Chancellor Angela Merkel by the presidents of the national science academies at the Science 20 Dialogue Forum in Halle on March 22nd, 2017.[3] The joint statement called for action around strengthening healthcare and public health systems; for addressing social, environmental, and economic determinants of health; and for strategic instruments to combat communicable and non-communicable disease.

ARGENTINA 2018

Annual Discourse Theme: Food and Nutrition Security: Improving Soils and Increasing Productivity

In 2018, Argentina S20 delivered a Communiqué to the G20 leaders that highlighted the need to protect soils for food security, particularly in light of climate change and urbanization. The S20 Communiqué called on governments to promote soil measurement, monitoring, and modeling programs that underpin decision-making, inform policy actions and legislation, and increase international scientific cooperation programs in sustainable soil management, specifically through higher education post-doctoral programs in less developed countries.

JAPAN 2019

Annual Discourse Theme: Threats to Coastal and Marine Ecosystems, and Conservation of the Ocean Environment-with Special Attention to Climate Change and Marine Plastic Waste.

In 2019, the S20 highlighted the need for action in response to the severe environmental threats to ocean and marine ecosystems from climate change, pollution from nutrients, toxic materials and plastics, and damaging fishing practices. The S20 called on governments to use ecosystem-based approaches in assessing further development of marine resources, redouble actions that aim to reduce stressors on coastal and marine ecosystems, establish more recycling activities at multiple scales and administrative levels, and to encourage global collaboration through information sharing and establishing a global open-access data management system.

SAUDI ARABIA 2020

Annual Discourse Theme Foresight: Science for Navigating Critical Transitions.

The current S20 theme was selected to define a compelling science agenda within the broad purview of the Saudi G20 Presidency: Realizing Opportunities of the 21st Century for All and the G20 priority areas of Safeguarding the Planet, Empowering People, and Shaping New Frontiers.[4] The 2020 S20 cycle builds on the previous S20 topics by prioritizing examination of human health, the environment, and digital technology in the context of a vision for Foresight Science. The S20 advocates for Scientific Foresight as an enabling and impactful approach across these interconnected areas: the current S20 focus on Scientific Foresight maps the path forward to achieving a Scientific Foresight revolution.

THE TROIKA

The current, preceding, and proceeding S20 Presidencies are referred to as the Troika. Thus in 2020, Japan and Italy (who will host the S20 Presidency in 2021) complete the Troika with the current S20 Presidency, the Kingdom of Saudi Arabia.

S20 ORGANIZATION

The 2020 S20 was led by the S20 Chair, the Steering Committee, a Sherpa, Secretariat, and a Chief Advocacy Officer. The responsibility to make critical decisions regarding the scope of S20 activities and represent the S20 at various G20 events resided with the S20 Chair. The S20 activities were planned and implemented by the S20 Team (Figure A.1)

Reporting directly to the S20 Chair, the S20 Sherpa coordinated the S20 Task Forces' overall activities and managed the development of policy recommendations on behalf of the Chair. The Secretariat provided support to the S20 Chair on priority analysis, event planning, and other operational and logistical aspects. They also organized Task Force meetings and led media, communication, and public relations activities.

The Steering Committee, comprised of Vice-Presidents and Rectors from the major universities and research institutions in Saudi Arabia, selected the S20 Theme and provided input and guidance input on the overall strategy and structure of the S20. The Advocacy Team's primary responsibilities involved enhancing the visibility and legitimacy of the S20 with key G20 stakeholders and ensuring alignment with the other G20 Engagement Groups. The Advocacy Team was also responsible for liaising with knowledge, network, and concept partners and creating sponsorship opportunities.

The S20 Team organized and led a series of activities (Figure A.2) designed to define the theme and develop an evidence base upon which to examine thematic elements and identify and report substantive, actionable science research and policy recommendations to the G20.

SIGNIFICANT MILESTONES AND ACTIVITIES IN 2020

CONSULTATION INTERVIEWS AT THE 2019 WORLD SCIENCE FORUM

As part of the planning process, the incoming S20 team was keen on sharing the new S20 expanded approach with the science community at the WSF to better refine and align the S20 agenda and dialogues for the upcoming year. By the end of the WSF, the incoming S20 team conducted several hours of consultation interviews with scientists, representatives of academies of sciences, and global science organizations.

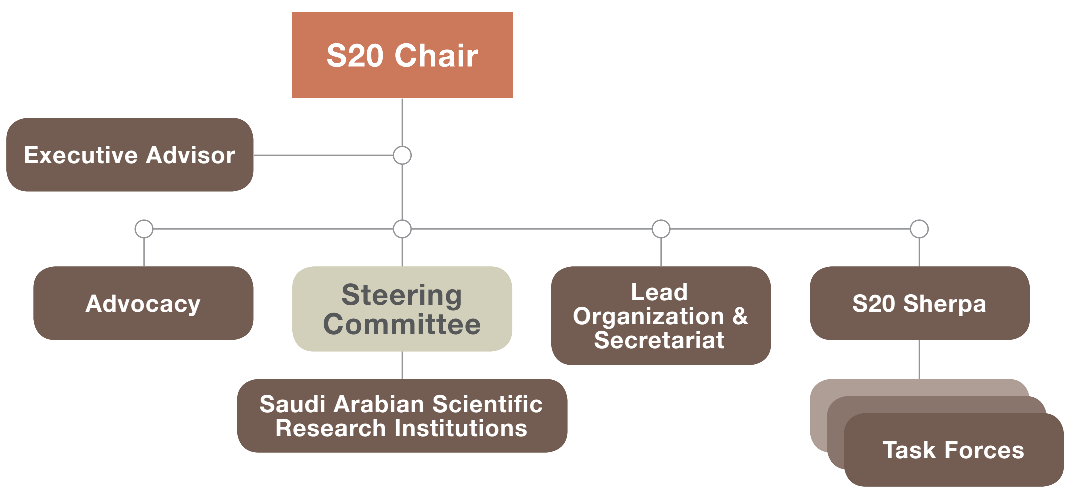


Figure A.1: Organizational Structure of the 2020 S20.

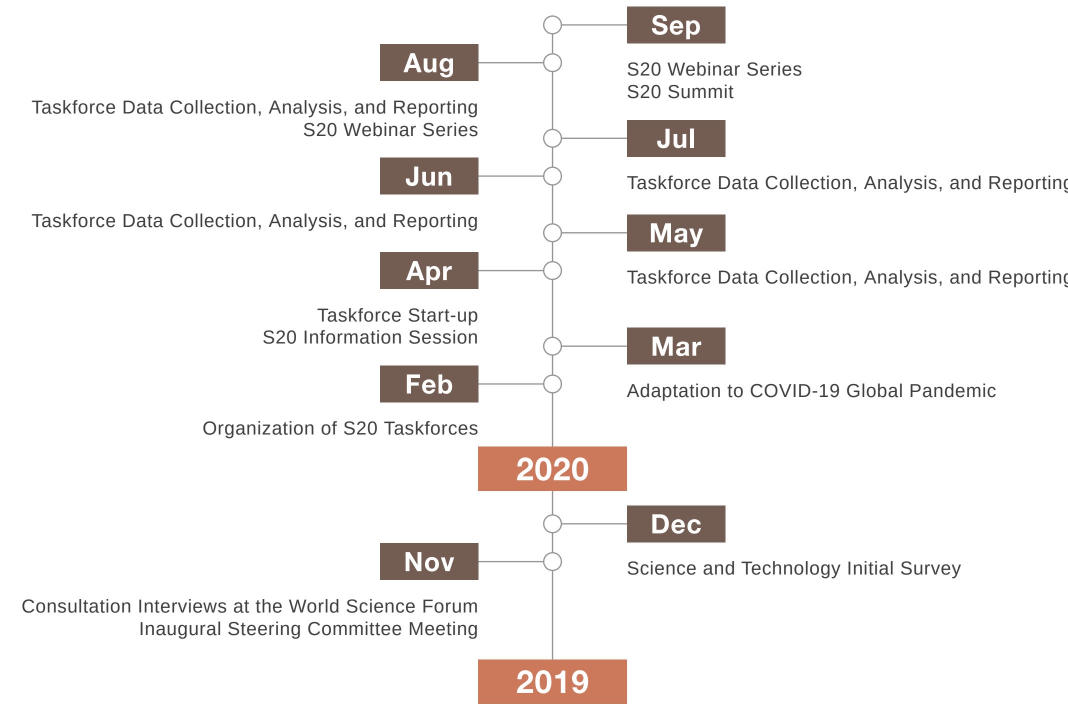


Figure A.2: S20 Saudi Arabia 2020 Key Milestones and Activities

INAUGURAL STEERING COMMITTEE MEETING

The inaugural Steering Committee meeting was held on 27 November 2019. The meeting covered a range of topics related to the governance and operational structure of the 2020 S20, key events and timeline, and the scope and themes to be addressed.

The selection of the S20 theme began with a focused discussion during the November Steering Committee meeting. Subsequently, the committee members were provided with a charge to guide their work with their university constituents, G20 members, and other global partners to generate a list of priorities and priority topic areas for S20 deliberations. Given the broad range of global challenges, a wide range of topics was offered to the committee. The committee attempted to find cross-cutting connections among the different priority areas and themes and focus on topics and current problems with known immediate implications and potential impacts that may not be readily foreseeable.

The issue of Critical Transitions emerged as a recurring theme in several discussion areas, including digital technology, the environment, and health. The potential role of foresight in anticipating outcomes across different critical transitions also became immediately clear. Foresight can play a vital role in informing the development and implementation of robust policies to enhance the resilience of societies as they go through critical transitions. The committee also recognized the science and engineering community's role in advancing foresight and its application to public policy.

SCIENCE AND TECHNOLOGY INITIAL SURVEY

To better understand the most pressing science and technology issues and developments, the Steering Committee conducted a survey within the host country (Saudi Arabia) to collect information from faculty and researchers at science and technology institutions. Findings from this survey were subsequently used to develop four international surveys underpinning the S20 dialogue. These international surveys were designed to gather input from representatives of the national science academies from the G20 countries on significant changes, or "Critical Transitions," facing societies, key challenges posed by these changes, and potential solutions to address these challenges. The survey also asked respondents to outline recommendations and corresponding policy actions that could be proposed to the G20 leaders at the end of the S20 dialogue.

ORGANIZATION OF TASK FORCES

The S20 Task Forces were structured with a Saudi Scientist as Lead and a representative of a G20 Science Academy as co-Lead. The appointment of the Task Force members was made by (i) nominations from G20 science academies, (ii) nominations by Steering Committee members, and (iii) application through the S20 website and selection based on the applicant's expertise. Significant effort was expended to identify and recruit women scientists and ensure that each Task Force was at least one-third female. Each Task Force engaged approximately 30-50 international experts in its various activities.

ADAPTATION TO COVID-19 GLOBAL PANDEMIC

As the COVID-19 outbreak rapidly escalated into a global pandemic, the S20 Team adapted its strategy and operations to maintain progress and ensure the achievement of vital S20 goals and milestones. International and national border closures and lockdowns forced the S20 Team to switch rapidly to start working virtually. This change amplified the importance of the survey instruments to focus the Task Force dialogues and required planning and execution of virtual events in place of physical meetings. The unanticipated consequences of the pandemic also required adjustments to the timeline of S20 activities and events.

TASK FORCE LAUNCH

Through March 2020, Leads and Co-Leads for each Task Force were appointed, and a platform for Task Force dialogue was established. The Task Force survey was deployed in May to gather input from members and inform future discussions. Since their establishment, the S20 Task Forces collectively conducted over a hundred meetings to identify their respective priorities, challenges, and critical transitions. The S20 Saudi Arabia was devoted to encouraging dialogue within the scientific community, especially in such a challenging time; hence, this is the first time the S20 worked in specialized task forces. The outcomes of the task force dialogues culminated in the S20 International Workshop.

INFORMATION SESSION

The original S20 agenda planned to kick-start the S20 with an official inception event in Riyadh. However, due to the COVID-19 pandemic, a virtual kick-off event, the S20 Information Session, held as a webinar on 23 April 2020.[5] The G20 Science Academies were invited to nominate their leading experts to attend the webinar and view presentations from the S20 Chair, the S20 Sherpa, and the Task Force Leads. The information session's objective was to learn more about the topics and structure of the 2020 S20 and the process for international experts to join one of the four S20 Task Forces. Participants also submitted questions and comments to be answered during the forum or later by email, through the S20 website, or during the Task Force dialogue. Approximately 160 people attended the Information Session, with roughly half the participants from within Saudi Arabia and the other half representing the national science academies or other international institutions.

S20 Task Forces

Taskforce 1: Future of Health
Preventing Pandemics and Expanding Personalized Healthcare

Taskforce 2: Circular Economy
Holistic Solutions for our Environment

Taskforce 3: Digital Revolution
Achieving Universal Connectivity and Smarter Communities

Taskforce 4: Foresight: Connecting the Dots
From Science to Action

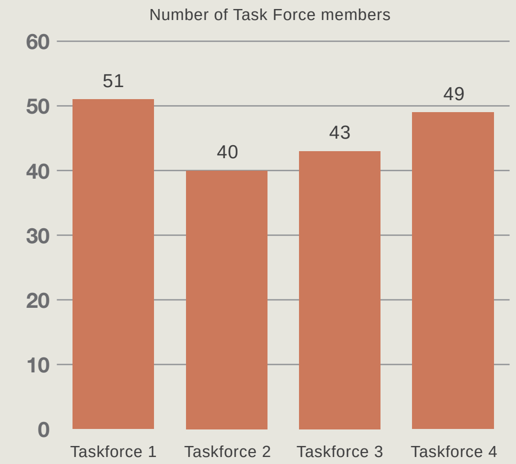


Figure A.3: S20 Task Forces

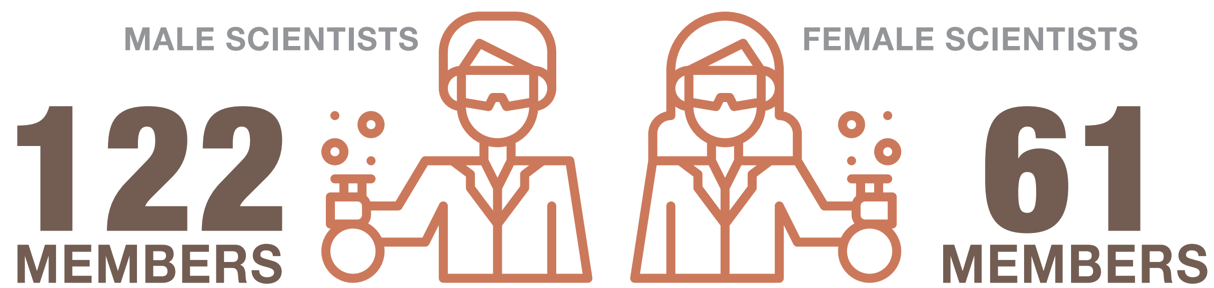


Figure A.4: S20 Task Force Distribution by Gender

TASK FORCE DATA COLLECTION, ANALYSIS, AND REPORTING

Following the Information Session, the Task Forces were assembled, the co-leads were appointed, and the Task Force work began in earnest.

Task Force member input was solicited through surveys on the key priorities and challenges outlined for each Task Force. More than one hundred twenty (120) survey responses were collected and analyzed. To supplement the surveys, Task Force leads organized additional, focused interviews with international experts (in addition to those in the Task Forces) to obtain further input regarding the survey results, particularly in the area of the science-policy interface.

The results of the surveys and expert interviews were organized and summarized into a comprehensive and prioritized set of issues, solutions, and policy recommendations that were used in the next phase of the S20 dialogue and Task Force discussions—the S20 International Workshop in August.

INTERNATIONAL WORKSHOP

This was the second major event in the S20 dialogue process. Originally, the workshop was intended to be a large, face-to-face, international meeting held over two days where the Task Forces would discuss the surveys and write up their individual Task Force policy papers. In addition, the workshop was intended to be the platform where discussions on the contents of the S20 Communiqué were to be initiated and the first steps in building consensus on this document were to take place.

Due to the continuing COVID-19 pandemic, the International Workshop was held as a virtual conference in a blend of web seminar (webinar) and web meeting modes. The policy paper write-ups were also done virtually with the Task Force leads and their co-leads working behind the scenes with their Task Force members before, during, and after the workshop to complete initial drafts of the chapters in this report.

Workshop participants numbered over one hundred fifty (150). Day one was a plenary session where the S20 Chair set the overall framework of the themes and convergence process. The S20 Sherpa also summarized the S20 process to date, the Chief Advocacy Officer highlighted the S20 contribution to other G20 activities in the G20 cycle to date, and the Task Force leads presented the findings of the surveys and initial policy recommendations and actions. Day two was a set of Task Force breakout sessions where the G20 Science Academies and other Task Force members provided feedback and comments on the previous day's policy recommendations and actions.

DEVELOPMENT OF POLICY RECOMMENDATIONS AND COMMUNIQUÉ

Following the International Workshop, a considerable amount of work was still required to shape the final policy recommendations for each Task Force and condense these into the final joint statement, or Communiqué, from the G20 Science Academies. Substantial work took place behind the scenes to gain consensus on the policy documents and the joint statement, including circulating iterations of the Communiqué and following up via virtual meetings with science academy representatives. These follow-up meetings were needed to reach a consensus on the substance and language of the Communiqué, with specific attention given to the recommendations.

DEVELOPMENT OF S20 FORESIGHT REPORT

In addition to the S20 Communiqué, the leads of each Task Force captured the Task Force deliberations in a report to be published after the S20 Summit. The report's content is based on Task Force members' input through the surveys, Task Force meetings and other communications channels, and discussions during the International Workshop. The report aims to summarize and highlight key insights provided by members of the Task Forces; however, it does not represent these members' specific or consensus views. The Task Force leads, under guidance from the S20 Team, used an iterative process to develop the report that included analysis and summarization of survey data, organization of survey findings thematically, and consultation with select members of the Task Forces to enhance the clarity of the initial content. The content was finalized and updated by the S20 Team following the completion of Task Force input.

S20 WEBINAR SERIES

In addition to the formal S20 working program, a series of five S20 Webinars were organized in August and September, one for each Task Force theme and one on the topic of Women in Science. A panel of experts was convened for each webinar to share their views on the webinar theme and respond to questions and comments from the global audience. Each Webinar was hosted by one of the S20 Steering Committee Institutions, where the institution was responsible for dedicating all needed resources to develop, distribute, and deliver the webinar.

S20 PARTICIPATION IN G20 MEETINGS

The S20 was invited to participate in broader G20 consultations, address G20 ministers and leaders, share insights with them, and advocate for key S20 recommendations founded on the S20 Task Force dialogues. The S20, represented by its leadership team, participated in the following meetings: Health Working Group 1st Meeting, G20 Digital Ministers Extraordinary Ministerial Meeting, 3rd Digital Economy Taskforce (DETF) Meeting, Side Event with the Development working Group. Importantly, and after the S20 Summit, the S20 Chair addressed the G20 Sherpas prior to their drafting meeting and presented the S20 Communiqué and recommendations during the 3rd Sherpa Meeting on 29 September 2020.

S20 STATEMENTS AND JOINT STATEMENTS

To advocate for the S20 work and amplify the science community's message, the S20 issued two statements targeting key G20 milestone events and meetings. The first statement was the Science 20 Statement to G20 Leaders on the COVID-19 Pandemic published on March 24th preceding the Extraordinary G20 Leaders' Summit. This statement called for action on three fronts: (i) policy development and decision making on scientific evidence, (ii) global scientific cooperation and sharing of accumulated knowledge and best practices, and (iii) investment in goal-oriented basic and applied research on viral transmission, prevention, and cure. The second statement the S20 published was a joint statement with the B20 on "Digitalization in Response to COVID-19" prior to the Digital Economy Task Force (DETF) third meeting. The S20 and B20 called on the G20 Leaders to act on a list of short- and medium-term priorities for a swift and globally coordinated response on many important policy issues across the entire spectrum of the digital domain.

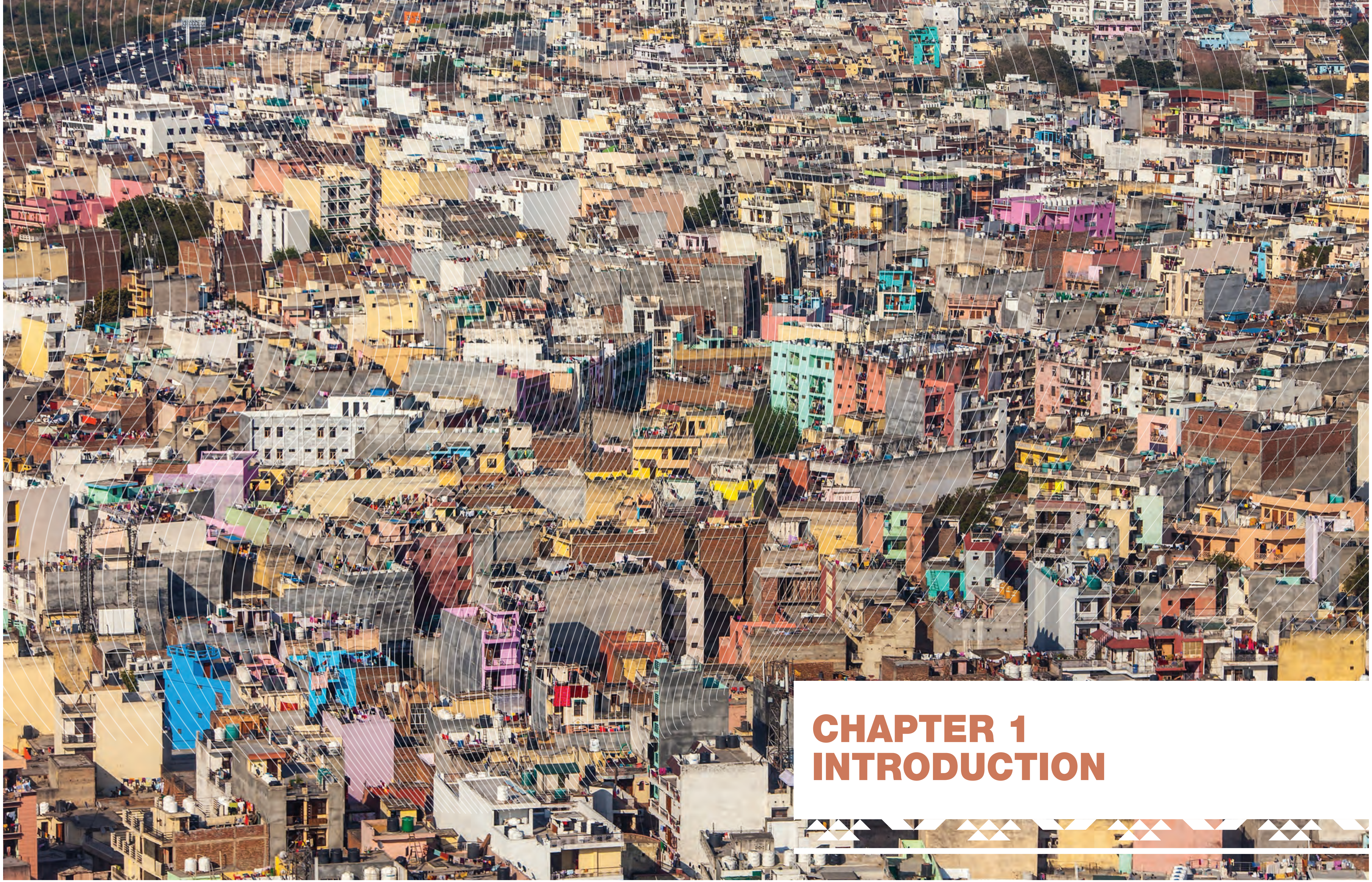
S20 SUMMIT

The S20 Summit was the concluding event for the S20 cycle. It gathered all the contributors to the S20 to certify the consensus and officially present S20's consensus-based recommendations to the G20 leaders. The Summit was held as a virtual event on 26 September 2020. The program included welcoming remarks from the S20 Chair with presentations from five Saudi Ministers highlighting the relevance of the S20 discussions and recommendations to their ministerial portfolio and the Kingdom Vision 2030. Four world experts in each of the S20 priority areas-health, environment, technology, and foresight-provided insights and inspiration on the global relevance and importance of the S20 dialogue findings. They highlighted the necessity for science to underpin and support policy and decision making and the need for collaborative activities and information sharing among technical experts and policymakers.

S20 OUTPUTS

Four types of documents were produced as outputs of the S20 process in 2020:

1. **S20 Statements and Joint Statements:** Statements and joint statements are issued to address a specific topic targeting key G20 meetings. They are intended to advocate for urgent matters that require the attention of G20 leaders. Join statements are usually issued in collaboration with other engagement groups to strengthen the call and provide multiple perspectives to the issue at hand.
2. **S20 Foresight report (the present document):** The S20 Foresight report is a detailed account of the 2020 S20 cycle that outlines the approach used by the S20 Team to plan and implement different S20 activities. The report includes a dedicated chapter for each Task Force summarizing results from the Task Force survey and discussions and presenting an expanded version of the recommendations and policy actions.
3. **S20 Policy Papers:** Each Task Force produced a policy paper presenting policy and action recommendations and the rationale for their adoption by the G20. The S20 Policy Papers provide a stand-alone summary of the outcomes of each S20 priority area.
4. **S20 Communiqué:** The S20 Communiqué is the final joint statement signed by the G20 National Science Academies. It summarizes and condenses the most important policy and recommendations from the four Task Forces into one document containing ten recommendations, each with a set of actions. The S20 Communiqué is the official document that was handed over to the G20 Presidency for consideration by the G20 leaders and heads of state.



CHAPTER 1 INTRODUCTION

CHAPTER 1
INTRODUCTION

1.A OVERVIEW

In 2008, the world experienced a global financial crisis, a critical transition that warranted the G20 discussions to be elevated to include G20 leaders. Twelve years later, we are faced with another critical transition of far-reaching impact in COVID-19.

COVID-19 is the latest in a long line of infectious disease outbreaks that have increased both in frequency and diversity over the past several decades, a period coinciding with population doubling, urbanization, globalization, and climate change.

Vulnerabilities and opportunities to improve resilience in the sectors of human health, environmental sustainability, and digitalization of economies and communities are occurring at an unprecedented pace. The world's leading economies—represented by the G20 countries-must have the capacity to foresee and alleviate system-level economic and societal disruptions that could ensue during these Critical Transitions.

In 2020, the G20 Science Engagement Group (S20) focused their collective attention on how science and scientists can help governments identify impending risks and aggressively work together with policymakers to explore the "solution space" for addressing Critical Transitions impacting highly complex and interconnected global systems. For example, the current COVID-19 pandemic is a crisis that threatens to destabilize global economies and overwhelm public health systems. Were there early warning signs that, if heeded, could have led to the development of more adaptive future-ready policies and the implementation of more effective strategies to control the spread of COVID-19? What role does science have in facilitating strategic decision making to ensure future resilience in the face of the next global pandemic?

To address these and other similar questions, the S20 identified the central theme of Foresight: Science for Navigating Critical Transitions and defined four priority areas for 2020:

- Future of Health: Preventing Pandemics and Expanding Personalized Healthcare
- Circular Economy: Holistic Solutions for our Environment
- Digital Revolution: Achieving Universal Connectivity and Smarter Communities
- Foresight: Connecting the Dots

Through a comprehensive, global landscape analysis, the S20 established the evidence base for a pathway to better government, policy, and action by transforming Foresight into a new paradigm of Scientific Foresight. This report draws from the breadth of S20 expert insight to describe the state of the science related to each priority area; the gaps that must be filled to advance science, technology, and policy; the critical transitions resulting from real or foreseen economic and societal disruptions; and the significant challenges the G20 faces to mitigate vulnerabilities, achieve benefits, and improve resilience in human health, resource and environmental sustainability, and the digital revolution.

The report's recommendations define an actionable vision for advancing Scientific Foresight: a vision ready for adoption at the international level. The impetus for the transition from Foresight to Scientific Foresight is the navigation of Critical Transitions. The nature and scope of Critical Transitions in the 21st century are surveyed in the following section.

1.B CRITICAL TRANSITIONS

Societal sectors, including health, economic, and technological, are interconnected, complex, and dynamic systems. These systems are subject to abrupt changes that can lead to positive transformation or system failure and collapse.[6,7] An abrupt system change can be caused by unpredictable external shock (e.g., natural disaster or disease pandemic) or structural vulnerability (e.g., digital connectivity disruptions). While it is difficult to accurately predict when these changes may occur, there is growing scientific evidence to suggest that these changes are usually associated with warning signs to indicate that the system is approaching a tipping point or "critical transitions or thresholds" where the system may change abruptly.[8,7]

When complex systems are exposed to frequent disturbances, their resilience tends to be reduced over time, and the recovery to their original state often takes longer[9]. This slow recovery is a good indicator and warning sign of an upcoming abrupt, and usually irreversible, change to an alternate state. The ability to detect such warning signs and identify situations where systems are approaching a critical transition point is essential for taking early action and minimizing the possibility of transitioning to a suboptimal state.

The S20 Task Forces on the Future of Health, the Circular Economy, and the Digital Revolution identified five current global disturbances or mega-trends, the impacts of which can lead to abrupt and potentially lasting changes in the health, economic, and technological sectors.

- Environmental Changes
- Demographic Shifts
- Rising Inequality
- Emerging Infectious Diseases
- Rapid Technological Advances

Some of these changes are undesirable and need to be minimized or avoided; others, however, are beneficial and could be harnessed.

1.B.1 ENVIRONMENTAL CHANGES

Environmental changes such as climate change, pollution, resource depletion, and biodiversity loss place ecological, social, economic, and political systems under pressure. As these changes intensify and become more frequent, they impact the integrity of different societal sectors, making them less resilient and more vulnerable to sudden transitions to new and sometimes less-desirable states (e.g., volatile financial markets, failed health systems, disrupted communication networks).

In the health sector, for example, environmental changes pose significant risks to human health, some of which are direct (e.g., illness, injury, and death associated with extreme climate events) and some are indirect (e.g., the emergence of novel zoonotic diseases, increases in the transmission of vector-borne diseases such as malaria, and malnutrition).[10,11] As the magnitude and frequency of these risks intensify, health systems may not have the capacity to cope with the increased burden of disease and surge in demand for health services.

Similarly, extreme environmental events may significantly impact the availability and reliability of digital systems. For example, terrestrial telecommunication infrastructures are particularly vulnerable to weather events, and it often takes a long time to rebuild this infrastructure once it is destroyed. These events often lead to a quick and sudden loss of essential information and communication technology (ICT) services, creating instability across tech-dependent sectors.

Circular economy strategies, which emphasize reducing waste and reusing and recycling materials, can mitigate the risks associated with environmental changes. Development of a Circular Economy offers new and innovative solutions that can facilitate a transition to a more sustainable economic system to meet societal needs while minimizing environmental impact.[12]

1.B.2 DEMOGRAPHIC SHIFTS

Many countries are going through significant demographic shifts due to lower birth rates, aging populations, migration, or urbanization.[13,14,10] These shifts are leading to changes in demand for and usage of services in various sectors, including health and technology.

Demographic shifts have profound implications for the future of health, potentially impacting several aspects of healthcare, including cost, demand for healthcare services, and resource allocation decisions. The changing patterns of disease burden at the national and global level due to demographic shifts will likely exert significant pressure on health systems. Unless closely monitored and adequately prepared, these systems may not cope with the additional pressure posed by unexpected events, such as disease pandemics.

By 2050, it is expected that seven billion people or two-thirds of the World population will live in urban environments.[15] Increased migration to mega-cities caused by environmental and geopolitical factors affects the already underserved rural areas and causes a heavy load on urban operations and resources. Digital solutions offer promising opportunities for effective management of population growth in urban centers (e.g., reduce road congestion, minimize energy usage, provide disaster early-warning systems, and provide infectious disease surveillance).[16]

The intensified urbanization process has also resulted in complex, long, and often fragile supply chains for urban populations. Natural disasters and health emergencies can pose significant risks to these supply chains. A circular economy can promote the resilience of supply chains and enhance their ability to withstand unanticipated external shocks by encouraging reusable products and reduced reliance on raw materials.[17]

1.B.3 RISING INEQUALITY

The growing inequality worldwide threatens to undermine human progress and destabilize many social, political, and economic systems. Economic inequality, for example, has a significant impact on population health.[18] Poor health outcomes, increased risk of exposure to diseases, and limited access to healthcare services are more likely among low-income individuals.[19] If such disparities in outcomes and access to healthcare services are left unaddressed, the additional burden on health systems and cost to society can be significant.[20] Addressing these issues requires a close examination of how health systems are structured and how they can be nudged to move toward patient-centered primary care, extend health care coverage, and improve public health programs.[21]

Digital technologies are transforming societies globally; however, their impacts (both negative and positive) are not equally distributed. One of the significant challenges worldwide is to explore ways to harness the potential of digital technologies while ensuring the costs and benefits are shared by all.[22] Variation of internet connectivity across countries, or even within the same country, is an example of a digital divide that causes disparities in access to economic, social, and political benefits.

1.B.4 EMERGING INFECTIOUS DISEASES

Emerging infectious diseases have been occurring at an increasing scale and frequency and negatively impacting many aspects of life.[23] Disease outbreaks and pandemics can overwhelm health systems and impact their ability to deliver routine healthcare. Experiences from previous disease outbreaks, such as the Ebola outbreak and from the current COVID-19 pandemic, have called into question the resilience of health systems and their capacity to absorb, adapt, and transform when exposed to unexpected shocks (such as pandemics) and to retain adequate control over its structure and functions.[24,25]

The current COVID-19 pandemic has also highlighted the important role of digital technologies in keeping people connected and enabling business continuity during a worldwide lockdown. However, with the accelerated deployment of digital solutions for pandemic-related data collection and remote data handling, many stakeholders and policymakers have realized the extent of their unpreparedness to quickly pivot to using digital tools and platforms during the pandemic, many of which are vulnerable and do not comply with data security and privacy regulations.

1.B.5 RAPID TECHNOLOGICAL ADVANCES

Advanced technologies, such as artificial intelligence, big data, the Internet of Things (IoT), and synthetic biology, impact many aspects of life and create transformational opportunities. However, the speed with which these technologies are introduced can sometimes outpace governments' and society's capacity to adapt effectively to the changes resulting from these advances.[26] Governance and regulatory safeguards are urgently needed to mitigate the potential disruptions and risks of accelerated technological changes.[27]

While the substantial progress we are witnessing in many fields, including biotechnology, nanotechnology, digital technology, robotics, and artificial intelligence (AI), has contributed to enhancing health, it also has the potential to aggravate existing problems (e.g., social inequity) and create new ones (e.g., the vulnerability of health systems to cyberattacks). For example, the high cost associated with most advanced health technologies can increase overall healthcare costs and consequently limit access to care to a select part of society. Additionally, the introduction of new and advanced technologies has serious implications for the health workforce's future. To minimize disruptive changes to the healthcare workforce, policymakers are required to develop a good understanding of where and how jobs will be created or displaced as a result of introducing new technologies. The challenges around data ownership, privacy, and sharing are another area that requires further scrutiny by policymakers and regulators to minimize the potential for significant disruptions, given that many technological advances in health depend on the open and free exchange of data.[28]

Evidence from previous studies shows that digital technologies have the potential to enable decarbonization across different sectors and to promote circular economies. However, the rapid introduction of digital technologies so far has been increasing rather than reducing greenhouse emissions.[29] Careful consideration of potential strategies to reverse these trends is needed to minimize the disruptive potential of rapid digitalization.

1.C CHALLENGES

A range of sectoral challenges impedes efforts to mitigate harmful effects from critical transitions and cultivate beneficial outcomes from critical transitions. To successfully navigate the world's critical transitions, we must overcome interrelated challenges in five domains: institutional, political, technological, financial, ethical, and in the realm of international cooperation. Institutional challenges encompass both public and private institutions. Political challenges are both domestic and global. Technological challenges concern both innovation and access. Financial challenges encompass both availability and allocation of funding. Ethical challenges are highly domain specific but often relate to awareness and avoidance of unintended consequences. Challenges in international cooperation result from and reinforce the other sectoral challenges.

Only by considering critical transitions in the context of these challenges can we develop an actionable framework for creating solutions. These sectoral challenges are summarized below in preparation for detailed analysis in the specific contexts of the upcoming chapters on the Future of Health, the Circular Economy, the Digital Revolution, and Foresight.

I.C.1 INSTITUTIONAL

Institutional challenges fall into three categories: human capacity, infrastructure, and policy/practice. Common human capacity challenges include the lack of an adequately prepared scientific/technical workforce needed for institutions to fulfill their responsibilities. This challenge is exacerbated by limited or non-existent mentoring or in-service professional training opportunities and can lead to very limited research in areas where an institution may have significant national responsibility. A lack of acquisition and maintenance of infrastructure is also a challenge limiting responsiveness to critical transitions. Largely independent of these factors are the challenges posed by policies and procedures: institutions do not collaborate well with each other, they lack a commitment to long-term planning and preparedness, and they are subject to broader governmental policies on funding that further drive short-term and often crisis-mode thinking. In some cases, the challenges posed by poor policy and practice are compounded by the lack of standardization of policy among institutions that have (or should have) a complementary or collaborative relationship.

I.C.2 POLITICAL

Political challenges include both internal and international barriers. Internal political roadblocks may include a lack of political will for needed investments or research allocations or disagreements between political parties on funding priorities. Frequent changes in government leadership can further complicate funding priorities. Additionally, arcane and strict regulatory laws and policies can also serve as significant deterrents to innovation and deployment. Lastly, uncertainty and reluctance among policymakers to develop policies to regulate development and use fairly can slow the rate of innovation. International complications such as geopolitical conflicts can also present a significant problem for adoption, as they can result in destabilization of nations and regions and alter both the availability of resources for development and the political priorities of a government.

I.C.3 TECHNOLOGICAL

Technological challenges generally involve limitations that hinder the current state-of-the-art. Sometimes, the available technology available is insufficient to solve a given problem. Additionally, access to technology can present itself as an issue of equity within and between countries. Unfortunately, this is a consequence of expenses related to patent protection of technologies. Other significant challenges include infrastructural constraints and lack of adequate standards and systems needed for information sharing. Digital technologies in particular can be accompanied by increased vulnerability, for example, to cyberattacks from malicious actors. Lastly, there is a perceived lack of transparency behind some automated and algorithmic systems, and they are sometimes at risk of perpetuating bias.

I.C.4 FINANCIAL

Financial challenges consist of fiscal roadblocks to technology development, innovation, implementation, and adoption. The high cost of development and deployment, combined with limited financial support for R&D, is a recurring theme that stands in the way of application. Limited involvement from academia or the private sector and lack of public-private investment is often a direct hindrance. Moreover, the financial disparity in low-income communities and countries often results in a slowed process of diffusion for new technologies. Lastly, the long period of gestation required for certain advanced technologies to find their way to a practical application can often be associated with high costs.

I.C.5 ETHICAL

Ethical challenges include the societal implications of technological developments. Privacy, vulnerability, and data ownership is a major ethical concern within the realm of digital technology. A lack of ethical frameworks for new technologies is needed to avoid perpetuating socioeconomic inequities. Limited awareness among the public and policymakers as to the societal impacts can be another roadblock. Additionally, misinformation and distrust in surveillance systems have increased substantially in recent times. Lastly, the environmental impacts of technology-in energy usage, for example-present yet another ethical challenge.

I.C.6 INTERNATIONAL COOPERATION

There is often a disconnect in standards and policies for technology between countries, making collaboration difficult. Moreover, there is a lack of effective models and agreements for international collaborations. Restrictions on data sharing present another barrier for countries looking to cooperate on technological projects. These restrictions can be compounded by a lack of uniformity in privacy protections and data quality. Unfortunately, global trade disputes and perceptions of competitiveness between nations further the divide between potential collaborators.

1.D FORESIGHT: NAVIGATING CRITICAL TRANSITIONS

1.D.1 INTRODUCTION

Foresight is "an approach and a process which requires broad thinking and results in the generation of multiple scenarios and ideas."[30] The foundations of foresight as a tool to anticipate and manage critical transitions date back several decades to the US National Research Council's report on transitioning towards a sustainable future.[31] The European Commission defines Foresight as "the systematic outlook to detect early signs of potentially important developments. These can be weak (or early) signals, trends, wild cards or other developments, persistent problems, risks, and threats, including matters at the margins of current thinking that challenge past assumptions."[32]

A variety of methods can be used in foresight studies to widen the perspective on potentially unexpected outcomes, giving critical insight to policymakers in facing global uncertainties on critical transitions and the role of disruptive technologies. For example, "Horizon Scanning" is one of the most established and used foresight methods as a valuable tool for assessing and anticipating future developments. International corporations use it as part of their risk management strategy for emerging issues analysis and identification of wild cards (events with low probability and potentially high-impact risks). By envisioning new opportunities, foresight studies promote inclusiveness, openness, and public engagement in the process of policymaking, and therefore, allow for a more comprehensive and broader understanding of the scientific and technological capabilities as well as social and economic realities in G20 societies.[33]

Foresight offers tools to allow for the systematic integration of knowledge to identify emerging issues and trends and explore possible future scenarios to inform policy decision making.[34] Foresight-informed policies are better positioned to mitigate vulnerabilities across sectors and strengthen these sectors' capacity to anticipate and adapt to current and future changes. While affirming the need for broader application of foresight, the S20 Engagement Group also highlighted challenges to implementing foresight, including existing limitations of resources and infrastructure to conduct foresight studies and restrictions on collaboration within and among countries to share relevant knowledge and data.

This report presents Foresight recommendations that would overcome challenges, achieve desirable Critical Transitions, and realize deeply effective policy. In addition, the analysis identifies the advances in Scientific Foresight required across each of the three domains and defines an actionable vision for advancing Foresight: a vision ready for adoption at the international level.

1.D.2 A FRAMEWORK FOR FORESIGHT ANALYSIS

To advance insight and action, this report adopts an analytical framework for Foresight (Figure 1.1) that guides the analysis and recommendations. The Foresight Framework begins with recognizing the five Critical Transitions discussed above that affect all Priority Areas discussed here. A chapter is dedicated to each of the four S20 priority areas, and in each of these chapters, a common set of Critical Transitions and challenges is analyzed from the viewpoint of the priority area. From this structured analysis, a picture of the complexity of interconnected systems emerges together with a snapshot across the G20 of ongoing Foresight activities. This analysis reveals gaps in methods, institutions, and international coordination that must be addressed. The output of this report's use of the Foresight Framework is a vision for Scientific Foresight that will allow the G20 to create a more resilient world. The report concludes with a comprehensive set of actionable recommendations that will allow that vision for Scientific Foresight to be realized.

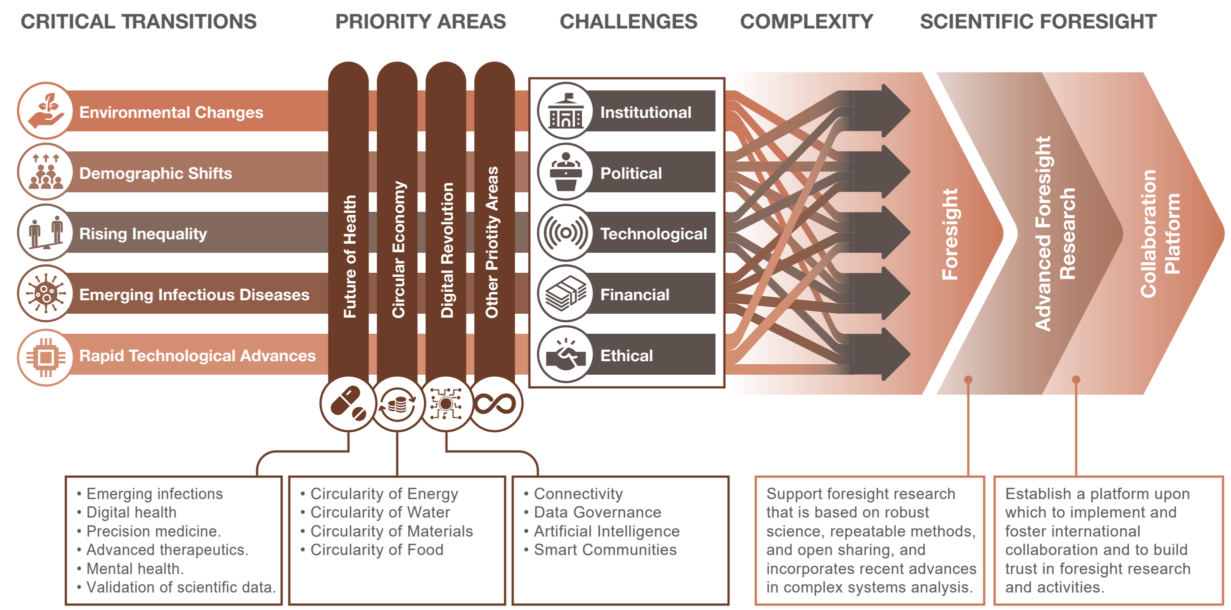
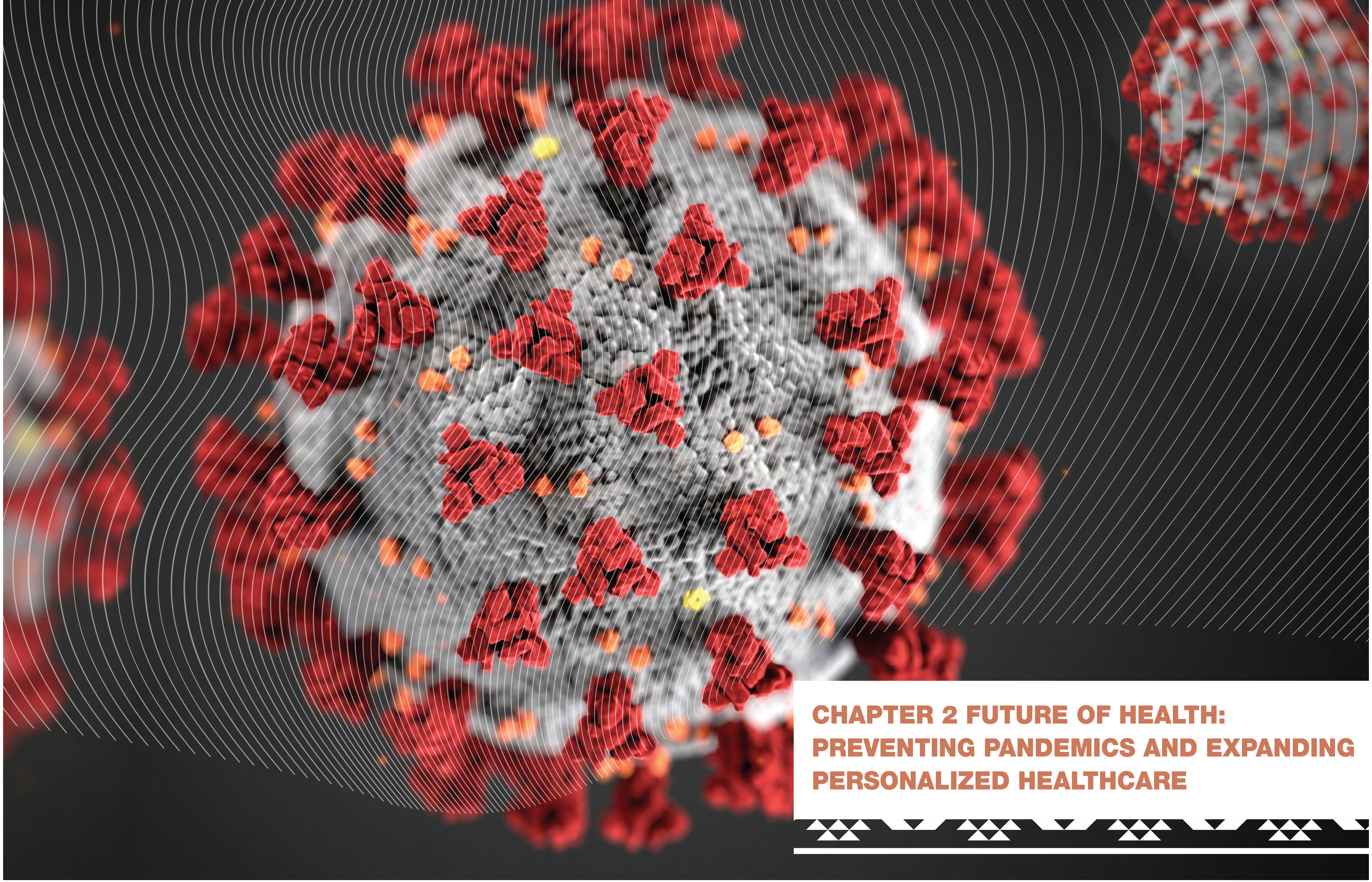


Figure 1.1: The S20 Foresight Framework for systemic analysis of critical transitions, S20 priority areas, challenges, and complexity leading to a vision for Scientific Foresight and actionable recommendations to achieve that vision.



CHAPTER 2 FUTURE OF HEALTH: PREVENTING PANDEMICS AND EXPANDING PERSONALIZED HEALTHCARE

CHAPTER 2 FUTURE OF HEALTH: PREVENTING PANDEMICS AND EXPANDING PERSONALIZED HEALTHCARE

2.A THE FUTURE OF HEALTH

2.A.1 OVERVIEW

The G20 is an essential platform for raising awareness of the critical challenges facing health globally and garnering the commitment needed to find practical solutions to these challenges. The Future of Health Task Force was established under the Science 20 (S20) group to "address the science of current and emerging global health threats, evaluate the potential contribution of science and innovation in offering solutions, provide relevant policy recommendations for governments, and identify barriers and bottlenecks that can prevent policies from being implemented on the ground."[35] The Task Force convened experts representing the national academies from G20 countries to discuss critical trends impacting the future of health and healthcare. The Task Force highlighted key challenges and opportunities concerning these trends and formulated a set of recommendations leading to clear policy directions for G20 leaders.

Considering current health events worldwide, the Task Force decided to focus its deliberations on two primary areas: (i) preventing pandemics and (ii) expanding personalized healthcare. The two areas were identified as priorities due to their immediate relevance to national, regional, and global health and their potential to improve health. The Task Force deliberations were guided by the premise that while the current COVID-19 pandemic dominates policymakers› attention across all countries, it should not detract from other priorities and challenges facing the future of health globally.

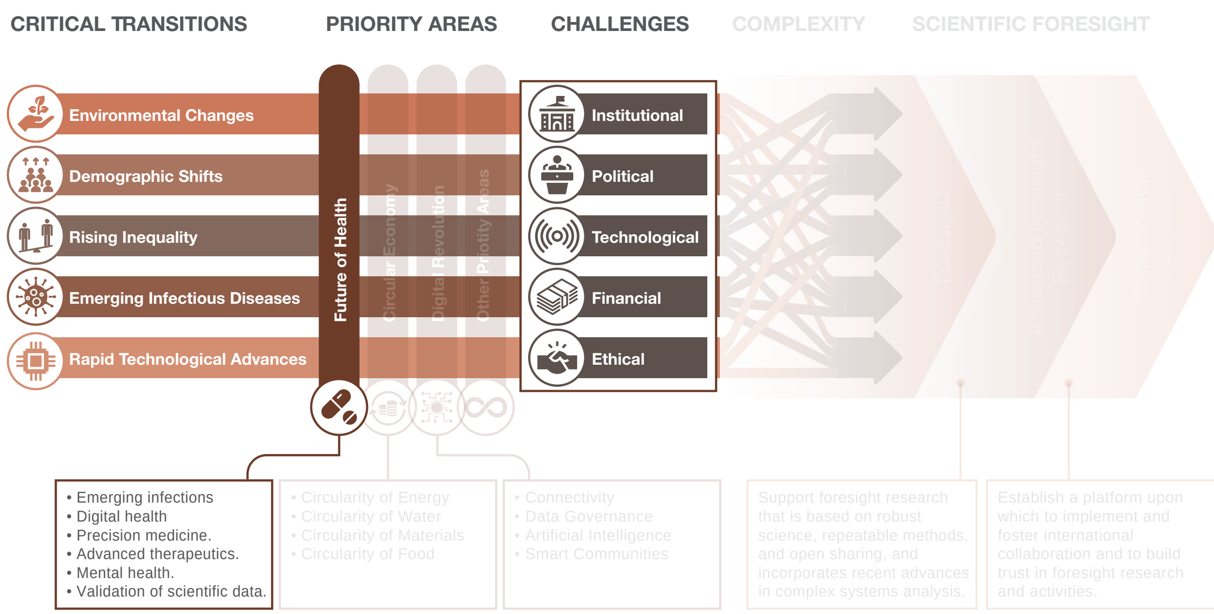


Figure 2.1: The S20 Foresight Framework for analysis, highlighting the Future of Health priority area and its sub-themes.

A scoping exercise was led by the S20 Future of Health Task Force Co-Leads to identify sub-themes for in-depth analysis and discussion. The scoping exercise relied on outcomes from previous S20 communiqués, expert opinion of Task Force members, and a survey of current health issues that are of global concern. Accordingly, the following areas/sub-themes were identified:

- Response to Pandemics; response to emerging infections and pandemics with a focus on prevention and vaccine development.
- Digital Heath: digital health as a tool for promoting universal health coverage.
- Precision Medicine: focusing on gene-environment interaction, pharmacogenomics, and the development of biomarkers.
- Advanced Therapeutics: application of advanced/novel therapeutics in disease management and control.
- Mental and Emotional Health: focusing on the mental health consequences of the current pandemic and primary mental healthcare for vulnerable groups.
- Validation of Scientific Data: focusing on epidemiological modeling and modeling of healthcare costs and resources.

The Task Force identified five current trends as potential drivers of future developments in health and biomedical research: emerging infectious diseases due to environmentally/genetically modified organisms, demographic shifts, environmental changes, inequality, and rapid technological advances. Governments are confronted with several challenges as they try to mitigate the impacts of these trends; some of these challenges are explored in this chapter. The Task Force process provided a platform to share knowledge and ideas among representatives from the G20 countries and find common ground and establish agreement on a set of recommendations and corresponding science and policy actions to enhance the resilience and preparedness of health systems.

2.A.2 SUB-THEMES IN THE FUTURE OF HEALTH

RESPONSE TO PANDEMICS

The recent COVID-19 pandemic is a stark reminder of the impact of infectious diseases on human health and the global economy. From its first appearance in the Wuhan district of the Hubei Province of China in early December of 2019, the disease has rapidly spread through to 213 countries/territories, with over 26 million cases and nearly 900,000 fatalities as of September 3, 2020.[36] It has put health systems in every country at risk and forced nations to impose severe restrictions on population movements leading to unparalleled economic distress. The global research and development (R&D) enterprise has the potential to address critical challenges facing many countries in the areas of pandemic preparedness and response through increased investment and attention in three areas:

Vaccine Development: a valuable lesson from the current pandemic is that vaccine development should be prioritized on the global research agenda. Vaccine development can be accelerated by investing in fundamental research to understand the epidemiology, immunopathogenesis, clinical presentation, and outcomes of infectious diseases; and in data sharing among scientists worldwide.

Disease Detection and Diagnosis: Early detection and diagnosis is key to preventing the spread of infectious diseases and informing necessary medical interventions.[37] Research that leads to rapid, accurate, and low-cost tests to diagnose current and future diseases is a clear priority area.

Leveraging Social Science in Pandemics: As countries worldwide continue to grapple with the evolving social implications of the COVID-19 pandemic, social science approaches can be leveraged to strengthen the capabilities and effectiveness of societies to respond to future pandemics. Research areas that could benefit from increased attention and support include (i) risk communication research that facilitates evidence-based decision making and behavioral change; and (ii) health policy research to inform the development and implementation of evidence-based approaches for public health policies in areas of pandemic preparedness, testing, prevention, treatment, and resources allocation.

DIGITAL HEALTH

Digital health, defined as the "use of information and communications technologies to improve human health, healthcare services and wellness for individuals and across populations,"[38] has become a cornerstone of modern healthcare systems. It includes a broad spectrum of health-related solutions that have contributed to improved healthcare access, a better quality of care, and lower healthcare costs.[39] Digital health technologies have also contributed to enhanced collaboration among scientific and professional disciplines, leading to rapid advances in research and better health outcomes. In the near future, artificial intelligence (AI) and machine learning (ML), combined with big data analytics, will likely become the standard practice in delivering healthcare, integrating evidence and data from different sources to inform decision making. The Task Force highlighted several promising research areas with the potential to expand the use of, and access to, digital health technologies:

- Development of low-cost, high-precision, contactless sensor systems for widespread patient monitoring;
- Personalization of artificial-intelligence assistants to help vulnerable populations;
- Leveraging of digital tools to understand how communicable diseases are transmitted and monitor their spread in communities;
- Identification of new psychological and mental health interventions adapted for digital delivery;
- Development of health-oriented smart cities that apply Internet of Things (IoT) during the planning phase; and
- Investment in research to inform future policies and frameworks that regulate health-related data access and use, including the ethics, privacy, confidentiality, and security of sensitive individual data.

PRECISION MEDICINE

Precision medicine is "an emerging approach for disease treatment and prevention that takes into account individual variability in genes, environment, and lifestyle for each person."[40] It involves the use of multi-dimensional data to improve healthcare decision making. By integrating systems biology data with historic and population-level data, the field of precision medicine holds the promise of enhancing the prevention, diagnosis, and treatment of diseases in a more cost-effective way.[41] Further advances in precision medicine can be achieved by supporting research and evidence-based policy in four areas:

Development of New Tools for Analyzing and Sharing Large Datasets: A continuing challenge in precision medicine is scientists› ability to share and analyze large datasets.[42–44] New tools are needed to enable researchers to work with and share large volumes of data. To fully extract value from genomic data, researchers and the private pharmaceutical industry will need to develop data and analytic capabilities to store, process, analyze, and interpret the large amount of new data. Big-data analytics and artificial intelligence tools may be employed to identify new potential targets or analytes of interest in the context of specific disease states. These analytes (for example, an elevated amount of protein X associated with a specific genetic marker) could then be used to study the longitudinal impact of drugs on a patient and inform the development of biomarkers, drugs, and improvement in patient stratification. The use of AI to expedite genome sequencing and accelerate precision medicine discoveries (e.g., clustering and segregating populations from large data sets into groups to facilitate the development of customized treatments) is a promising area in this field.[45]

Technical Advances in Genome Sequencing and editing: Collaborative research is needed to develop faster, more accurate, and more cost-effective whole-genome sequencing tools. The use of AI to expedite genome sequencing and accelerate precision medicine discoveries (e.g., clustering and segregating populations from large data sets into groups to facilitate the development of customized treatments) is a promising area in this field. Biomarker discovery through Next Generation Sequencing (NGS) platforms can be used in varying population groups to define genomic and epigenetic differences to promote biomarker discovery. This is especially important in rare and polygenic diseases, neurodegenerative diseases such as Alzheimer's, Parkinson's, Amyotrophic Lateral Sclerosis, and diseases associated with metabolic syndromes such as type II diabetes and cardiovascular diseases.

Economic Evaluation of Precision Medicine Technologies: The high cost of precision medicine technologies (e.g., whole-genome sequencing, exome sequencing, and evaluation of 'genetic risk scores') is currently a limiting factor for their large-scale application.[43] Technical advances in genome sequencing will likely reduce costs. However, research is needed to measure and demonstrate the returns on government investment in genome sequencing technologies to encourage government funding of precision medicine technologies and accelerate cost reduction.

Genomics and Precision Public Health Research: Precision medicine aims to customize treatments based on an individual's genome structure, lifestyle, and environmental conditions. Population genetics is a highly focused research area that will require approaches to leverage and apply knowledge across different disciplines to inform the interpretation of genetic data. Considering the varied effects on different ethnic and population groups from recent pandemics, the application of precision medicine approaches to pandemic response and preparedness is an area that requires further examination.

ADVANCED THERAPEUTICS

Current traditional therapeutic approaches have been facing several challenges, mainly related to their lack of specificity. Approaches in cellular therapy, immunotherapy, gene therapy, and nanoparticle drug delivery have been investigated to address this limitation, and some of these modalities have successfully been incorporated into the standard of care for several diseases.

The introduction of simple gene-editing tools, namely CRISPR-Cas9, and the evolution of viral transfection methodologies, have facilitated the shift towards these advanced modalities. The acceptance of viral vector, for example, has promoted Chimeric Antigen Receptor (CAR) T cell development that was lately granted FDA approval and implemented as the standard of care for some diseases.[46,47] Clinical trial for in vitro gene editing using CRISPR-CAS9 has also been approved for multiple diseases in addition to the recent approval of the first in-human trial for blindness.48 With sustained funding, the near future could witness a vital leap toward these advanced, often personalized therapies. The introduction of innovative and cost-effective therapies will improve treatment outcomes and quality of life and further enhance competitiveness in the pharmaceutical industry. As advanced therapies continue to be introduced and incorporated into routine healthcare, additional research is needed to inform policy discussions in several key areas, including:

- Ethical considerations of introducing gene/cell therapy into clinical practice, particularly around communication, education, and informed consent of the patient and regulatory frameworks for gene therapy;
- New valuation approaches to assess the cost-effectiveness of advanced therapies, given the high cost and unique characteristics of advanced therapies[49]; and
- Inequality in access to advanced therapies within and among countries that could potentially widen health disparities due to the high cost and need for specialized infrastructure required for therapy development and delivery to patients.[50]

MENTAL AND EMOTIONAL HEALTH

With the growing global burden of mental health illness, collaborative efforts and resources are needed to conduct innovative research to better understand disease burden, pathogenesis, and clinical management. This research should go beyond mental healthcare to explore the pathways and social determinants that lead to mental illnesses among individuals and populations and assess the effectiveness of various treatment options. The current pandemic has further highlighted the need to address mental and emotional health issues driven by stress and anxiety. Some of the priority areas for collaborative research among the G20 countries are summarized here. However, these priorities are not intended to be exhaustive and are only presented as examples:

- Measuring the psychological impacts of pandemics, particularly among vulnerable population groups (e.g., the elderly and individuals with co-morbidities). Anxiety associated with social isolation, fear of contracting the disease, the ability to access testing and treatment, and financial implications of job loss or business closure due to the pandemic is a multi-faceted concern. Other psychological impacts that need to be explored include loneliness, risk of physical and emotional abuse due to the lockdown, and grief by those who have lost loved ones.
- Assessing the potential psychological impact of constant exposure to pandemic-related news through traditional and social media channels.
- Assessing the effectiveness of telemedicine and other digital health approaches in the diagnosis and management of mental health disorders.
- Assessing the effectiveness of different approaches for promoting mental health and wellbeing during pandemics.
- Using integrative epidemiological and neuroscience methodologies to identify biomarkers of individuals at risk for mental health disorders.
- Conducting research to test innovative interventions to avert/delay neuro-progression of mental health disorders.

VALIDATION OF SCIENTIFIC DATA

The COVID-19 pandemic has presented scientists and policymakers with unprecedented opportunities and challenges, considering the speed with which research data is being generated and disseminated to address the myriad of evolving issues. As policymakers rely on this data to inform their decision-making, it is more crucial than ever to reinforce research integrity principles and validate the scientific data collected from different sources. There are also challenges in data storage, security, selective access, sorting, visualization, and sharing that need to be addressed. A variety of approaches are available to improve the validation of pandemic data, including international collaborations to conduct comparative analyses of epidemic data collected in different countries, the use of appropriate samples in population surveys, the application of robust data collection protocols and quality assurance techniques, and the implementation of novel approaches to collect health information. Furthermore, scientific validation of pandemic data needs to account for vulnerable populations and growing inequities among populations (e.g., the elderly, populations with lower socioeconomic statuses, and indigenous populations). Several research areas could benefit from additional attention and support to enhance pandemic preparedness and response, including developing and validating statistical models to provide credible and reliable estimates of disease transmission, use of health care services, and costs during pandemics.

GAPS IN FUTURE OF HEALTH RESEARCH AND POLICY

The Task Force identified several gaps in the health and biomedical sciences that need to be addressed to enhance governments' capabilities to meet current and future challenges.

Gaps in affordability and equitable access to new and advanced therapies need to be addressed within and among countries. As we anticipate the release of a COVID-19 vaccine, equal access to the vaccine is expected to be an issue. Higher-income countries usually have easier access to vaccines compared to low-income countries.[51] Governments, industry, and the non-profit sector need to invest in vaccine development and distribution infrastructure that ensures the ability of countries to respond effectively and equitably to current and future pandemics. Another area where gaps in equitable access and affordability continue to grow is precision medicine. The high cost associated with precision medicine constitutes a significant barrier to facilitating access to this technology in low- and middle-income countries (LMICs), which can contribute to worsening global health disparities in cancer prevention and treatment.[52]

In the midst of the current COVID-19 pandemic, it is essential to raise awareness of the burden caused by endemic infectious diseases such as malaria, dengue, and chikungunya. For example, the World Health Organization (WHO) reported 4.2 million dengue cases in 2019.[53] Climate change is likely to increase the spread of these diseases, many of which have significant health as well as social and economic impacts (e.g., reduced life expectancy, physical disability, malnutrition, growth failure, and cognitive impairment).[54] The Task Force emphasizes the importance of not forgetting the global burden of these diseases and to allocate sufficient resources to prevent and manage these diseases.

Implementation research can facilitate the effective application of evidence-based and cost-effective interventions in healthcare practice and inform the development of robust and relevant policies

Gaps in Biomedical and Health Research and Policy:

- Affordability and Equitable Access
- Endemic Infectious Diseases
- Implementation and Health Systems Research
- One Health Approach
- Mental Health
- Biomedical Research Ethics

> **Implementation research or health systems research means getting ministers of health to articulate the questions that are very relevant for them programmatically, and then link with academics in order to answer those questions. This is the key point of implementation research, is that policy makers are part of the research. We are asking the policy makers are part of the research. We are asking the policy makers are part of the research. We are asking the policy makers to articulate their issues, which could then be converted into research questions to be answered. Research results are then fed back to the policy makers to inform their decision making.**
>
> **Dr. Soumya Swaminathan**
> **Chief Scientist, World Health Organization**

to address critical gaps, especially in the context of LMICs.[55] Despite the many calls to increase investment in this research area, implementation and health systems research continue to be under-resourced.[56–58]

The current pandemic highlights the importance of the One Health concept. The current pandemic highlights the importance of the One Health concept. Because more than 75% of emerging infectious diseases are zoonotic in origin, adopting the One Health approach can help prevent and control these diseases.[59] Given its transdisciplinary, multi-sectoral nature, the approach has the potential to facilitate science and policy collaborations at the local, national, and global level to optimize the health of people, animals, and the environment.[60] Investments in the development of human resources and creation of organizational structures and networks to facilitate collaboration among various relevant disciplines and sectors is critical to enable an effective One Health response to current and future infectious diseases.[61]

The global burden of mental and substance use disorders is high, surpassing that of cancer and cardiovascular diseases.[62] The COVID-19 pandemic has exacerbated mental health issues due to social distancing practices, the economic consequences of lockdown measures, and challenges in accessing mental healthcare services.[63] There is a need to assess pandemic's impact on mental health, search for new ways to organize mental health services, and investigate novel psychosocial and medical interventions to alleviate the mental health disability associated with the pandemic.

While an international ethics framework exists,[64] a wide range of current and emerging bioethical issues in biomedical research needs to be examined, considering the perspectives of all relevant stakeholders. Potential issues that need to be examined include the use of digital technologies, artificial intelligence, and machine learning in biomedical research and clinical care, health equity and health disparities in research, and genomics research.[65]

2.B CRITICAL TRANSITIONS AND THEIR IMPACTS

The current health landscape is going through rapid structural changes. The Task Force explored the patterns and dynamics of these changes to understand better the underlying processes leading to them. Such understanding can be applied to develop contingency plans and policies to leverage these changes› transformative power and mitigate potential risks.[66] The Task Force highlighted several current trends with the potential for causing disruptions or transformations in the health sector and identified areas where foresight could be effectively applied to manage these transitions.

*The US Centers for Disease Control and Prevention defines the One Health approach as "a collaborative, multisectoral, and transdisciplinary approach—working at the local, regional, national, and global levels—with the goal of achieving optimal health outcomes recognizing the interconnection between people, animals, plants, and their shared environment."

2.B.1 EMERGING INFECTIONS DISEASES

While the threat of emerging and endemic infectious diseases is not necessarily new[67] (Figure 2.2), infectious diseases continue to pose a significant risk to the economy and society in most countries.[68] Governments worldwide have faced significant challenges and disruptions controlling the spread of the COVID-19 pandemic and preventing and mitigating against its broader socioeconomic impacts. The current pandemic has highlighted a renewed sense of urgency to develop and apply more reliable tools to understand better the potential impact of infectious diseases on major societal sectors, including health.

All around the world, the COVID-19 pandemic has exposed the existing weaknesses in the delivery of healthcare services, including the lack of necessary infrastructure and resources to enable an effective response to pandemics.[69] Many organizations in the healthcare industry have had to shift production lines to cope with pandemic-related needs. To cope with these weaknesses, many health systems tried to mitigate some of the immediate challenges (e.g., shortages in personal protective equipment, oxygen therapy, vaccines, medications, diagnostic tests, and limited workforce capacity and burnout). One of the consequences of these mitigation efforts has been the diversion of attention and resources away from regular healthcare and research efforts, leading to difficulties in meeting patients' healthcare needs with diseases other than COVID-19, such as cancer, diabetes, and cardiovascular diseases. Health

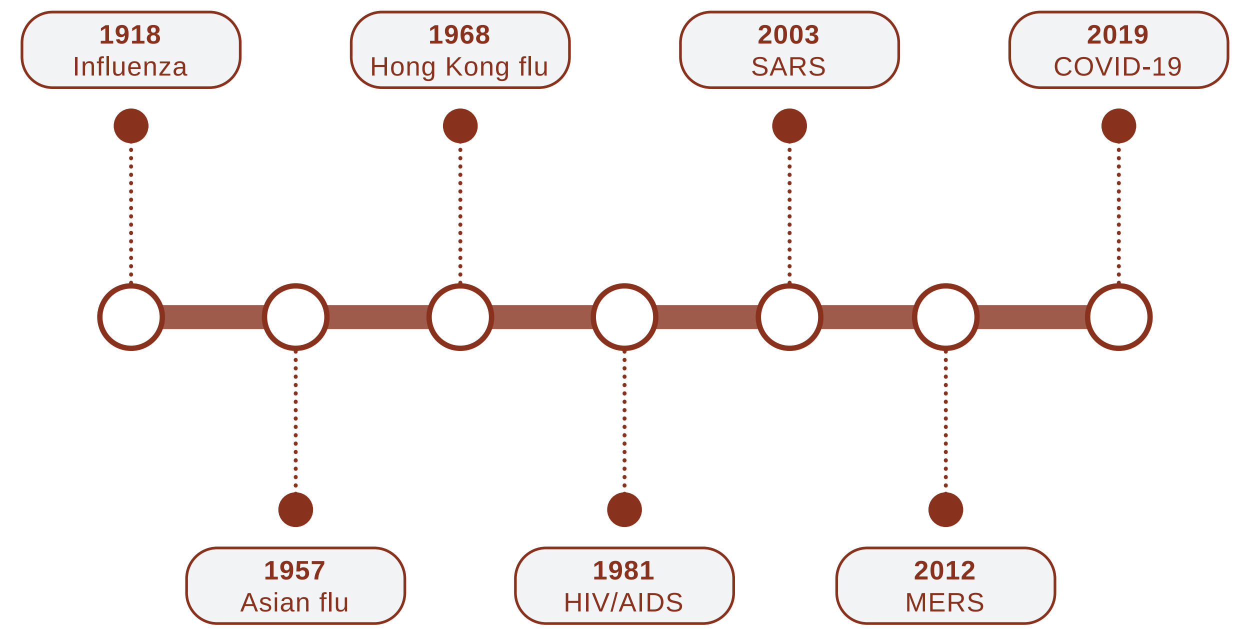


Figure 2.2: Major Epidemics and Pandemics in the Last and Current Centuries

systems are trying to tackle other consequences resulting from immediate mitigation efforts, including exacerbated inequities between socioeconomic groups, the risk of losing gains made in fighting other diseases, and the myriad of mental health issues associated with the pandemic.

From a public health and health policy perspective, the pandemic has highlighted traditional public health surveillance systems› limitations.[70] Furthermore, the use of unvalidated data to inform the development of disease control measures has contributed, in some instances, to inconsistent and continuously changing public health and policy decisions, a result that may have negatively affected public trust in open science and scientific institutions and experts.

While the negative impacts of the current pandemic threaten to disrupt the healthcare delivery landscape, they have also created several transformative opportunities. For example, the global efforts to address the pandemic have facilitated the creation and sharing of new scientific knowledge and technologies, including prediction models and systems for reporting infectious diseases that can be leveraged to prevent and respond to future pandemics.[71] The pandemic has also encouraged efforts to conduct comparative studies, validate pandemic data provided by different countries, and influence public recognition of the importance of collective healthcare systems.[72]

In the digital health domain, the successful use of technologies for tracking COVID-19 symptoms, contact tracing, and training of the health workforce and public during the pandemic will likely lead to further support and investment in developing new and innovative digital solutions.[73] The pandemic has increased the demand, use, and normalization of telemedicine and telehealth, leading to broader acceptance by the public and more innovative ways to leverage digital health solutions to provide cost-effective healthcare.[74]

2.B.2 ENVIRONMENTAL CHANGES

Environmental shifts caused by climate change and other factors such as globalization, urbanization, and population growth pose significant risks to health. Direct risks include illness, injury, and death associated with extreme climate events. Other health risks are indirect and mediated by changes in biophysical and ecological systems. Examples include the emergence of novel zoonotic diseases, increases in the transmission of vector-borne diseases such as malaria and chikungunya, and the potential emergence of antibiotic resistance, malnutrition, and mental health problems.[10,11] While some of these risks can be remediable; others are potentially irreversible.[75] The accelerated emergence of infectious diseases is an example of the disruptive impact of environmental changes.[76]

Given the broad range of risks posed by environmental changes, the likely implications for the health sector can be significant and far-reaching. For example, climate change can alter the transmission patterns and prevalence of infectious diseases such as yellow fever and dengue in different parts of the world. This, as a result, can affect investment decisions in new vaccines and therapeutics for the novel re-emergence of these illnesses.[77]

Public health agencies and health systems in many countries have embraced the concept of preparedness and adopted several measures and practices to reduce the health burden associated with environmental changes. For example, in response to previous climate-related emergencies, many health systems have begun to introduce changes to how their facilities are designed and operated to ensure their ability to remain open and serve patients during and after times of crisis.[78]

Additional focus needs to be placed on the intersections of humans, other animals, and the environment. The accelerated rate of the emergence of new infectious diseases (and re-emergence and persistence of old ones) is attributed to rapid changes in human ecology.[79, 80] The Task Force discussed the potential role of the One Health approach as an effective multidisciplinary and multisectoral paradigm to address the negative impacts of environmental challenges on human health.[81] Examining and addressing issues related to access to and quality of food, air, and water may help identify and mitigate health risks resulting from environmental changes.

2.B.3 DEMOGRAPHIC SHIFTS

Many countries are going through significant demographic shifts due to reduced birth rates, aging populations, migration, or urbanization.[14,82,83] These shifts have significant implications for health policy and planning, including rising healthcare expenditures, increased demands for geriatric healthcare services, and a need to focus more attention and resources on preventative care and personalized medicine.

Population aging represents a significant demographic shift that is affecting most countries. It is usually associated with an increased burden of disease, chronic non-communicable and communicable diseases, and healthcare costs.[84] Depending on their place of residence and socioeconomic status, elderly populations are offered different types of healthcare services giving rise to potential unmet needs and health disparities. To address this challenge, health systems are continuously searching for cost-effective healthcare models that guarantee access and improve the quality of healthcare services offered to the elderly.

Increasing urbanization coupled with aging and lifestyle changes is likely to increase the burden of communicable and non-communicable diseases, especially in Low-income and Middle-income Countries (LMICs).[85] Already under strain from the burden of communicable diseases, health systems in LMICs are exploring different approaches to adapt to the additional disease burden posed by the global shift in demographics to minimize costs and enhance quality and sustainability of healthcare services.[86]

2.B.4 RISING INEQUALITY

Rising inequalities around the world have significant implications for health systems. At the individual level, those with low income are more likely to have an increased risk of exposure to diseases and limited access to healthcare services.[19,87] This has direct and indirect impacts on health and can lead to long-term consequences manifested in increased level and complexity of health conditions, and, in turn, increased burden on health systems.

Globally, there is a gap between LMICs and advanced economies in terms of patients' ability to benefit from new research advances, primarily due to issues around availability, affordability, and limited infrastructure and resources. The Task Force raised concerns over global inequality in relation to most of the sub-themes discussed, including equal access to vaccines in response to pandemics, to precision medicine advances, and the benefits of digital health technologies.

Adapting to the inequality trend requires health systems to examine their structure and consider the need to re-orient themselves to focus on prevention, health promotion, and patient-centered primary care. Long-term, this can reduce the burden of chronic diseases and relieve the pressure on health systems and leave them more able to respond to health emergencies such as pandemics.

2.B.5 RAPID TECHNOLOGICAL ADVANCES

The rapid evolution of health technologies has created new opportunities and significantly impacted the health sector. For example, artificial intelligence and machine learning, combined with data science analytics, are expected to revolutionize the practice and delivery of healthcare in the near future. These advances are turning healthcare into a form of information science, using big data to assist in decision-making at different levels. However, inequitable access to advanced health technologies and the potential for disruption, as too many innovations are being introduced without proper vetting for quality and safety, are significant challenges posed by rapid technological advances in the health sector. These challenges have led to wide recognition of the need for policy frameworks to regulate newly introduced health technologies.

Rapid technology development in the health sector has also created several transformational opportunities. The real-time availability of data to health professionals enhances their ability to diagnose and treat diseases effectively and is an example of positive change with implications for improving patient safety and healthcare costs. Advanced health technologies, such as genome mapping, enable more accurate predictions of disease complications, enhancing patients' treatment and quality of life. Furthermore, novel nanoparticles for the targeted delivery of drugs potentially allow for better treatment outcomes and decreased side effects. The pandemic underscored the need to develop innovative therapies to combat the spread of the virus and more effectively target the pathogenic mechanisms underlying disease development. It also facilitated the launch of Phase I clinical studies of advanced therapies against SARS-CoV2, including immunological therapeutic approaches.[88]

2.C CHALLENGES

Informed by the discussion of the current trends driving change in the health sector, the Task Force identified a set of critical challenges in six main categories for which recommendations and corresponding policy actions need to be developed: institutional, political, technological, financial, ethical, and international collaboration challenges.

2.C.1 INSTITUTIONAL

Shortages of an adequately trained scientific workforce were identified as the primary institutional challenge that needs to be addressed. More specifically, the Task Force emphasized the need to address the lack of researchers with specialized training and advanced skills to conduct work in advanced therapeutics, precision medicine, and digital health. This challenge is further compounded by the limited opportunities for international scientific exchange and mentoring. Encouraging governments to invest in training and continuing education opportunities for early career researchers and healthcare professionals is one way to address this challenge. Topics of interest would range from omics and precision medicine to environmental and foresight sciences. Promoting knowledge sharing and exchanges through global collaborations between experts and institutions are additional ways to promote scientific workforce capacity development globally.

Examples include scholarships and outreach programs for specialists and young scientists or higher-level training focused on specialized areas in emerging technologies or data science.

The limited investment in infrastructure to implement digital health technologies continues to be a significant challenge in many countries, especially in LMICs. The relative lack of operational capabilities is a key factor limiting the introduction of advanced therapy and precision medicine into day-to-day healthcare practice. A compelling case for the return on government investment in expanding the infrastructure to support the implementation and use of digital health technologies needs to be made to address this challenge.

The lack of institutional commitment to long-term planning and preparedness was another challenge highlighted by the Task Force. Limited and uncoordinated funding and research support to meet institutional foresight needs and limited training opportunities in foresight science and methods were highlighted as key factors contributing to this challenge. Education and training opportunities are needed to build institutional capacity in foresight methods and best practices. Additionally, there is a need for heightened awareness of the necessity of aligning institutional long-term strategic plans with foresight insights.

2.C.2 POLITICAL

Difficulties in resource allocation and prioritization decisions were the primary political challenge identified. Scarcity of resources, competing priorities, and frequent changes in governments and mandates further complicate this challenge by restraining the ability of policymakers and planners to integrate foresight into long-term strategic plans.

Unclear policies and uncertainties in the regulatory environment around new technologies in general, and specifically concerning advanced therapy and precision medicine research and practice, are an additional significant challenge. The uncertainty among policymakers concerning whether to support these technologies and their reluctance to develop policies to regulate their development and use can hinder the speed of scientific progress in these areas. Open and frequent communication between researchers and politicians about the implications of advanced health technologies is needed to educate policymakers about the potential risks and benefits involved. This will allow the policymaker to expedite the decision-making process when developing policies that govern the advanced therapeutics field.

Limited opportunity to share data and resources was identified as another challenge that could significantly hinder scientific advances, especially during health emergencies such as the current COVID-19 pandemic. While the challenge can be attributed to technical difficulties around data standards and interoperability, the consideration of health data during pandemics as a national security secret is a key contributing factor.

2.C.3 TECHNOLOGICAL

Inequitable access to advanced health technologies within and across countries is a major challenge, primarily due to the expenses required to patent-protect these technologies, subsequently limiting their application in some countries. Infrastructure constraints, such as low broadband internet connectivity, barriers against the adoption of interoperability and content standards, and inadequate systems to support information sharing and decision making for advanced therapies, pose additional significant challenges.

Encouraging the development of low-cost technologies that are accessible to vulnerable populations and less-developed countries has the potential to address the inequity challenge. Implementing social policies to promote digital inclusion in underprivileged areas and public places (e.g., public transportation and schools) can also address this issue.

2.C.4 FINANCIAL

Given fiscal constraints and competing priorities for public and private budgets, there is limited financial support allocated for basic and translational health-related research or implementing digital health technologies and electronic structures needed for newly emerging therapeutic approaches. This is attributed mainly to the high cost of advanced research and development activities and the establishment of the infrastructure needed for many digital health technologies.

The Task Force explored several options to address financial challenges:

- Establishing a pool of international funds to support research and development activities in the health sector and foresight research to assess and manage the financial risks associated with funding research in different areas.

- Establishing multilateral programs to support the development of infrastructure needed to implement digital health technologies.
- Re-setting funding priorities for health-related research to emphasize social and behavioral science and reaching out to private donors to illustrate the economic returns on investment from minimizing the societal burdens from behavioral and mental health disorders.
- Granting easier access to international funding bodies and private stakeholders that invest in the reproducible development of advanced health technology products.
- Signing international agreements to allow for cost reduction and access to patents under certain circumstances (e.g., the COVID-19 pandemic).
- Allocating funds for innovation in high priority patient-oriented research.
- Conducting cost-effective evaluations of existing and future therapies to demonstrate affordability to the public.

2.C.5 ETHICAL

Concerns over the privacy and confidentiality of data collected through digital health technologies are a major ethical challenge. As the amount of data sent and received by healthcare providers, patients, and other actors in the sector continues to grow in the coming years, data vulnerabilities and risks are expected to grow exponentially. Policy frameworks must be developed to regulate the management and sharing of health data. There is also a need for technologies that will guard against unauthorized access to and misuse of personal health information.

Other challenges include the lack of ethical frameworks and guidelines to regulate the use of data and technologies such as artificial intelligence and the potential to exacerbate health inequities spurred from the use of digital health technologies. Previous studies have identified several factors that contribute to how the digitization of health may "(re)produce social inequalities in health," including unequal access, digital skills development, and cultural attitudes and infrastructure around digital health technologies.[89] Strategic stewardship is needed to ensure that the benefits of digital health are shared across all societal groups within and across countries. Additionally, the adoption of new technical and financial approaches and measures to incentivize new technologies with lower costs may help address access barriers. In many countries, the population lacks a thorough understanding of the potential risks and benefits of advanced therapies. As the ethical code for advanced therapies is still under development, governments should consider creating an international consortium to define common protocols in long-term studies. This would provide a platform for researchers and policymakers to discuss ethical and legal issues, build consensus, and develop and formalize global guidelines and policies on research ethics. Policies would also include sureties for the confidentiality of patients involved in advanced therapy.

Governments should also inspire an open international forum to discuss all issues related to advanced therapies, to define international guidelines for the ethical use of advanced therapies and inform the development of a universal statement on potential benefits, risks, and associated ethical issues and facilitate an easier transition toward a wider application of advanced therapies.

2.C.6 INTERNATIONAL COOPERATION

Among the international cooperation challenges are the limited availability of international cooperation agreements for research and development and the lack of effective models for promoting international coordination and collaboration on a wide range of topics. This is partly due to some countries' individualistic regulatory approaches that can complicate cooperation in various priority health research areas.

The lack of policies to regulate the international exchange for digital health technologies, lack of international standards for data protection, particularly in developing countries, and the stringent restrictions on rapid data sharing and the absence of a legal framework to regulate data exchange across countries are other significant challenges.

Governments can play a significant role in establishing and increasing partnerships across academia, industry, and government offices on national and international levels by strengthening their actions in three areas:

- Supporting the adoption of Open Science principles.[90]
- Supporting the establishment of a global clearinghouse for the exchange of reports, data, best practices, and foresight initiatives conducted around the world to serve as a hub for sharing knowledge and building consensus around highly relevant and timely research topics.
- Supporting the development and implementation of country-level e-health strategies.

> **We should, in my view, make support for a shared international approach to health information and assessment central to our request on behalf of the scientific academies.**
>
> **Professor Robert Williamson**
> **Council Member, Australian Academy of Science**

2.D RECOMMENDATIONS

Ensuring the involvement of policymakers in defining the priorities for the health research agenda is pivotal to addressing short- and long-term gaps between science and its regulatory policy development. The ability of countries to address critical challenges and respond to transformative opportunities when presented hinges on the alignment of future policies with the complexities of a constantly changing environmental and sociopolitical context.[91] The Task Force endorsed the concept of implementation or health systems research as a downstream approach to address the daily realities of health policy and systems and to incorporate their needs in future health research agendas.[92]

Deliberations resulted in the following set of recommendations and corresponding policy actions to address some of the challenges identified in this chapter.

2.D.1 ESTABLISH A PANDEMIC PREPAREDNESS FRAMEWORK

RECOMMENDATION

Advance existing pandemic preparedness toward an internationally collaborative framework to monitor and respond rapidly to emerging diseases and handle future pandemics.

RATIONALE

The COVID-19 pandemic has presented scientists and policy makers with unprecedented opportunities and challenges in terms of the speed with which research data is being generated and widely disseminated. As policy makers rely on this data to inform their decision making, the need for a framework that integrates data from a variety of sources while ensuring the integrity and validity of this data has never been more important. The new framework should incorporate insights from diverse research disciplines, including infectious disease, epidemiology, and genomics, and must have the ability to respond independently to emerging critical diseases and to handle future threats of pandemics.

POLICY ACTIONS

1. Embrace the One Health principles and approach to establish a research agenda across countries to study the health impacts of pandemics and changing lifestyle, with emphasis on social and behavioral science and mental health research.
2. Use mixed foresight methods and frameworks to capture, manage, and incorporate scientific knowledge within supportive ethical and legal systems.

3. Create platforms (e.g., international conferences) to enable the sharing of insights and knowledge gained during the response to pandemics.

2.D.2 DEVELOP AND USE ADVANCED THERAPEUTICS TO ENHANCE PERSONALIZED CARE

RECOMMENDATION

Promote advanced therapy and precision medicine research to enhance personalized care, with a view to concurrently improve technology, cost, and accessibility.

RATIONALE

Traditional therapeutic approaches have been facing several challenges, mainly due to their lack of specificity. Multiple advanced therapy options are currently available and continue to be developed to overcome these limitations, including omics technology, tailored cellular therapy, specific immunotherapy, and gene therapy and nanomedicine.

POLICY ACTIONS

1. Expand the health research platform by empowering active participation of patients in research design and development.
2. Promote a multidisciplinary integration of basic, patient-oriented, and population-based research.
3. Formulate policy frameworks and guidelines to reduce uncertainties in the regulatory environment around advanced health technologies.
4. Invest in developing scientific workforce capacity, particularly in the areas of advanced therapeutics and digital health.

2.D.3 DEVELOP HIGH-PRECISION AND LOW-COST DIGITAL HEALTH TECHNOLOGIES

RECOMMENDATION

Promote the development of high precision and low-cost digital health solutions.

RATIONALE

Digital health technologies have contributed to enhanced collaboration and coordination of care and facilitated the achievement of more rapid advances in research and better health outcomes. While the current pandemic has accelerated and expanded the use of digital health technologies, such as telemedicine, critical gaps continue to exist in the access and use of these technologies.

POLICY ACTIONS

1. Invest in infrastructure development to accommodate the implementation of digital health solutions.
2. Leverage predictive models to develop a more comprehensive understanding of pathogenic mechanisms, identify new drug targets, and develop more personalized diagnostic and therapeutic modalities.
3. Promote the use of implementation or health systems research to explore available options to minimize the existing gap in access and use of digital health technologies within and across countries.
4. Establish multidisciplinary approaches to integrate and manage data collected from various devices and health mobile apps.

2.D.4 DEPLOY POLICIES AND INTERVENTIONS TO ADDRESS CRITICAL EMERGING ISSUES

RECOMMENDATION

Deploy policies and interventions to address critical emerging issues in the health sector, including the challenges arising from demographic shifts.

RATIONALE

The current pandemic has exposed several weaknesses in existing systems and policies that have contributed to their inability to respond effectively to unanticipated challenges. The use of research insights to inform future policies can empower policy makers and governments to develop more robust plans and strategies and enhance the resilience of systems and population in the face different future scenarios.

POLICY ACTIONS

1. Account for critical changes and uncertainties resulting from environmental and demographic shifts in future health policies to mitigate against unanticipated risks and address concerns about growing inequities.
2. Emphasizing the importance of knowledge synthesis approaches for decision support. These include conducting global systematic reviews and meta-analysis.
3. Promote international collaboration to conduct comparative analyses of pandemic data collected from different countries and encourage the use of appropriate samples in population surveys.
4. Encourage the application of robust data collection protocols and quality assurance techniques and the implementation of novel approaches to collect health information and to apply adequate measures to protect individuals´ health information.
5. Address the mental health impacts of health emergencies such as pandemics (e.g., stress and anxiety resulting from social isolation, risk of contracting the disease, digital gap, and accessibility to testing and treatment).

2.D.5 FACILITATE RESEARCH COLLABORATIONS AND ACCESS TO RESEARCH DATA AND RESOURCES

RECOMMENDATION

Facilitate international multidisciplinary research collaborations through rapid and easy access to research data and resources as well as improved mobility of scientists.

RATIONALE

Limited opportunities for collaboration and communication within the global scientific community can delay innovation and hinder scientific progress by restricting researchers' ability to exchange critical knowledge and information in a timely fashion.

POLICY ACTIONS

1. Establish funding programs through public-private partnership and encourage a broad range of collaborative international R&D activities in basic, clinical, and population health research through different mechanisms such as the establishment of advanced research hubs.
2. Support easier mobility of scientists between nations to facilitate sharing of best practices.

2.D.6 DEVELOP FRAMEWORKS AND STANDARDS FOR INTERNATIONAL DATA SHARING

RECOMMENDATION

Develop frameworks and standards for international data sharing, especially for genomic data, as well as multi-national biorepositories.

RATIONALE

As the importance of international research collaborations in modern science continues to grow, the need for robust frameworks and guidelines to regulate access, use, and exchange of data becomes critical to facilitate scientific progress.

POLICY ACTIONS

1. Establish platforms to facilitate the safe and secure exchange of health information among institutions using data standards.
2. Create health database platforms that are accessible globally and that link registry-based and personal health data using the latest database technologies such as blockchain.
3. Invest in building biorepositories that represents all ethnic backgrounds, which is crucial for personalized medicine.
4. Update existing policies and ethical frameworks to regulate the use of health-related data focusing on privacy, confidentiality and security associated with access to and use of sensitive individual health data.
5. Promote the application of robust standardized data collection and quality assurance techniques.

CHAPTER 3 CIRCULAR ECONOMY: HOLISTIC SOLUTIONS FOR OUR ENVIRONMENT

CHAPTER 3 CIRCULAR ECONOMY: HOLISTIC SOLUTIONS FOR OUR ENVIRONMENT

3.A THE CIRCULAR ECONOMY

3.A.1 OVERVIEW

For all practical purposes, Earth is a closed system apart from energy input from the sun. The thin atmospheric layer near the Earth's surface where life predominates relies on the adequate circulation of the planet's available resources. Because human activity has a measurable effect on (and in many cases dominates) global biogeochemical cycles, we must analyze and perfect our Circular Economy to sustain humanity and the natural ecosystems on which we rely.

The European Commission defines the Circular Economy as one in which "the value of products, materials, and resources is maintained in the economy for as long as possible and the generation of waste minimised." [93]

The Ellen MacArthur Foundation expands on this, explaining that "a circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems." [94]

Moreover, after analyzing definitions from 147 sources, Kircherr et al.[95] proposed that Circular Economy is

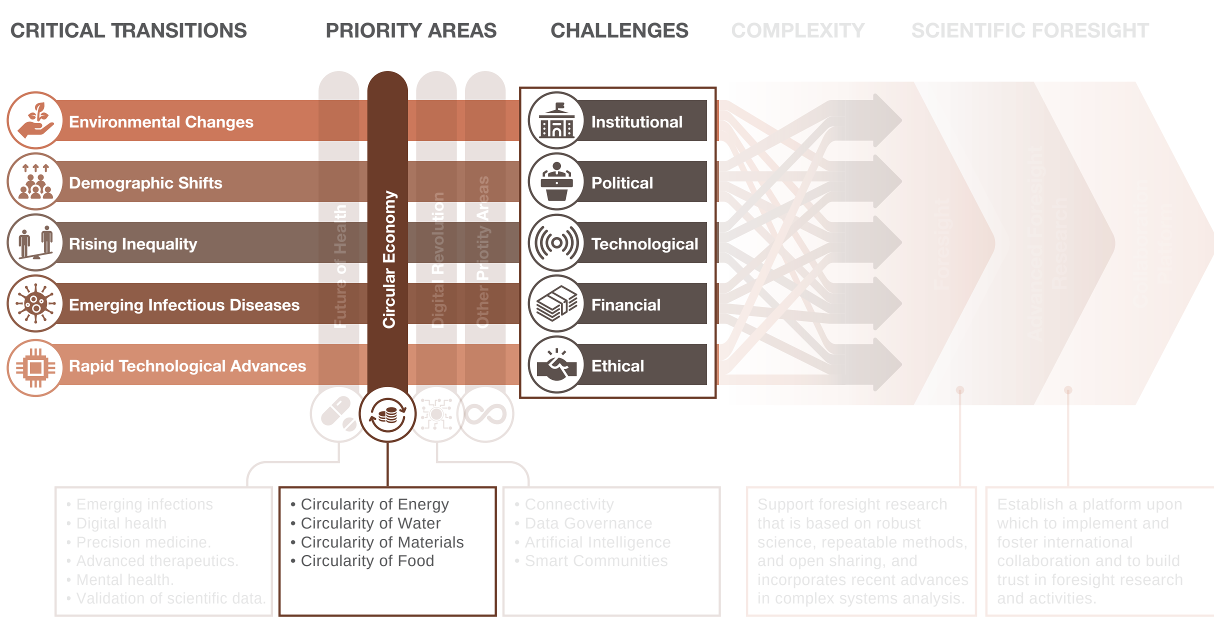


Figure 3.1: The S20 Foresight Framework for analysis, highlighting the Circular Economy priority area and its sub-themes.

...an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair re-use, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.

Developing a circular economy, therefore, supports sustainable development, protects the environment from harmful waste, advances economic prosperity, expands social equity, and improves the lives of future generations.[95] These benefits and definitions of the Circular Economy can be understood and studied in comparison to the currently prevailing linear economic model of take, make, and dispose. By contrast, the Circular Economy is often expressed as Reduce, Reuse, and Recycle (the 3Rs) or via a more detailed framework of 9Rs: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover.

The concept of the Circular Economy has been generally accepted in the scientific and policy communities as a means to address current societal and environmental issues and mitigate harmful outcomes of future critical transitions. However, as this report will explore, the complexities and challenges of achieving a circular economy need to be understood and addressed by multiple stakeholders, including scientists, policymakers, and consumers.

The G20 and S20 summits of Japan (2019) and Argentina (2018) analyzed aspects of the Circular Economy, highlighting the harmful consequences of unsustainable production practices and waste generation on marine and terrestrial ecosystems. This report builds on that previous work and broadens the scope to consider the Circular Economy in its entirety and from a global perspective, integrating discussion of challenges arising from complex, interconnected Critical Transitions and the potential responses to those challenges.

To advance the analysis in 2020, the S20 formed a Task Force on the Circular Economy with representation from the academies of science of the G20 countries and scientists and engineers from academic institutions in the S20 host country, Saudi Arabia. The Task Force held scoping discussions and conducted a survey in order to identify four sub-themes for analysis:

- Energy: waste linked to energy production and use
- Water: circularity in water resources and consumption
- Materials: metals, plastics, wood, and other organic and inorganic materials produced and consumed on a global basis that fall outside of the other three sub-themes
- Food: circularity in food consumption and production through farming, livestock, and fishing/aquaculture.

This sub-theme analysis allowed the Task Force to identify a broad set of gaps in research and knowledge that must be addressed to make progress on the development of the Circular Economy. This analysis informs a set of recommendations aimed at closing the loop in the material cycles affected by human actions. These recommendations span a range of actions in policy, research, and transnational collaboration. With G20 leadership, we see these recommendations as actionable, timely, and achievable.

> **In order to get to 1.5 degrees [warming] we will need the circular economy...and we will need it faster than we have ever gone through an energy transition.**
>
> **Dr. Cherry Murray**
> **U.S. National Academies of Science, Engineering, and Medicine**

3.A.2 SUB-THEMES IN THE CIRCULAR ECONOMY

Because all elements of the Circular Economy are interdependent, the S20 Circular Economy Task Force sought to make the discussion in this report tractable by focusing on four domains: energy, water, materials, and food. These domains encompass critical areas for human action to advance the development of the Circular Economy.

ENERGY

The analysis of energy in the context of the Circular Economy is focused on avoiding the environmental impact of emissions and waste linked to energy use and reaching and sustaining a level of greenhouse gases in the atmosphere sufficiently low to maintain a 1.5°C global warming target. In addition, circularity in the energy sector aims to reduce, reuse, and recycle materials used for energy generation while minimizing waste and reducing wasteful energy consumption.

Today, most of our energy is produced from fossil fuels,[96] and despite the rapid growth of renewable energy sources, the US Energy Information Administration predicts that renewables will still be insufficient to completely replace fossil fuels even by 2050.[96]

The massive amounts of fossil fuels that are burned every day to power all facets of modern life produce emissions that pose major risks, both in the short-term, near power plants, and the long-term due to effects on the global climate. There is strong scientific evidence that emissions from burning fossil fuels are responsible for environmental problems like air pollution, global warming, acid rain, and acidification of the oceans. These emissions also contribute to extreme heat and cold, the increased intensity of storms, sea-level rise, and more severe flooding and drought. Therefore, it is essential to clarify that circularity in the context of energy means the ability to avoid or close the circle of pollutants resulting from burning fossil fuels like carbon dioxide, nitrous and sulfur oxides, unburned hydrocarbons, and soot. In the case of renewable energy sources like solar, wind, and geothermal, the objective is to

- Increase the speed of their deployment by providing large-scale and long-term storage solutions to mitigate their intermittency,
- Reduce their dependence on finite mineral resources,
- Increase their efficiency,
- Reduce their land use,
- Prolong the lifespan of power plants, and
- Find eco-friendly ways to recycle power plant equipment and materials.

The combined impact of predicted global population growth and energy consumption linked to the improvement of human development, each expected to increase by one third from 2017 to 2050, necessitates the challenge of reducing the CO_2 emissions by around half, from 32 Gt to 18.4 Gt.[97]

Many technological solutions will be required to meet this challenge: accelerating energy efficiency in all sectors, accelerating the deployment of renewable energy (as well as other sources such as nuclear energy, which has no greenhouse gas emissions but requires removal or recycle of radioactive waste), as well as reducing the use of fossil fuels and closing the circle of harmful emissions from their use.

Finding technical solutions that allow the most efficient use of energy produced (e.g., maximum utilization of wasted heat and the ability to capture harmful emissions, remove their toxicity, and reintroduce them in making useful products) would help humanity avert major problems. However, achieving these goals requires complex systems that are difficult to build and run. Furthermore, the recycling of harmful emissions requires large amounts of energy. As a system, an enormous amount of solar energy is available, and that energy is the primary driver of cycles within the Earth's atmosphere. Research, development, and demonstrations at scale are needed in order to reduce the cost and enable economic utilization of solar and other renewable energies—either directly as a substitute to energy from fossil fuels or indirectly as a source of energy to drive endothermic reactions required to recycle harmful emissions from burning fossil fuels. Further, to prevent continued global warming beyond 1.5°C, greenhouse gas emissions must also be directly removed from the atmosphere.[98]

WATER

Fresh water is a finite resource. Although 70% of the Earth's surface is covered with water, most of it is salty water in oceans, with only 2.5% of the total available as fresh water.[99] With the increase of Earth's population, increased economic activity, and rising living standards, water availability for agricultural, industrial, or domestic use is becoming more challenging. One study concluded that the world could face a 40% global deficit by 2030 under the current business-as-usual scenario.[100] While some regions have ample water resources, climate change is disrupting water resources globally. The United Nations World Water Development Report 2020[100] highlighted this issue, citing a report[101] stating that "About four billion people live under conditions of severe physical water scarcity for at least one month per year." Around 1.6 billion people, or almost a quarter of the world's population, face economic water shortage, which means they lack the necessary infrastructure to access water.[102]

These stresses require human intervention to close the circle of water from unusable to usable and back, either through artificial or engineered nature-based interventions.[103] It is estimated that, globally, 80% of wastewater is released to the environment untreated,[104] suggesting that with the right technology, most of this untreated wastewater can be circulated back for useful consumption while alleviating shortages and protecting the environment. The process is expensive due to the large amount of energy, specialized equipment, materials, and human capital required to design and run these systems. Overall, there are increasing technical challenges that need to be solved to provide the water needed for all human activities. However, the ability to recycle water provides opportunities to recover valuable organic and inorganic materials that can be used in agriculture as fertilizer and in industrial applications. In the case of large desalination plants, there is the possibility of mining rare metals dissolved in the sea and brackish streams. The effects of critical transitions on water circularity, the challenges of achieving circularity, and suggested solutions are discussed in the following sections.

MATERIALS

The term "materials" in this report refers to materials from (i) mineral non-organic origins like metals, (ii) from organic fossil hydrocarbon origins like most plastics, and (iii) from organic living origins (excluding food) like wood. Each of these types of materials is nearly finite on Earth. With population increase, expanding economic activity, and rising living standards, there are increasing demands for materials for industrial applications ranging from construction, which depends on relatively abundant materials, to advanced electronics, motors, and batteries, which are highly dependent on finite resources, especially rare earth metals. Materials that are organic and mostly derived from fossil hydrocarbon feedstocks, like plastics, are increasingly used in disposable packaging and utensils.

Despite their immense value to humanity, materials of various types are becoming an increasing source of pollution throughout a product's lifecycle. The Global Circularity Report 2020[105] suggests that at present, the world only reuses or recycles 8.6% of materials (biomass, fossil fuels, ores, minerals). As these materials find their way into junkyards, landfills, streams, and the oceans, they become a significant pollution source, damaging ecosystems. The increased demands for some materials can be a source for geopolitical competition and tensions that affect the lives of many populations.

Designing products for re-use and ease of recycling materials, swapping out toxic materials, or treating materials to remove toxicity and prepare them for re-use can increase sustainability and minimize environmental damage. Recycling different materials requires different levels of technical complexity, but in most cases, there is a need for large amounts of energy, possibly water, and the associated economic costs and human capital to design and run these systems.

FOOD

The production of food from agriculture, animal husbandry, and fishing is dependent on energy, water, and materials. Humanity has learned over centuries to increase food supplies by applying human ingenuity to increase the available amount of food-producing assets and to increase the productivity of these assets. Humans have practiced circularity in the food production cycle since antiquity. Turning the outputs from food metabolism in living organisms into nutrients reused by creatures lower in the food chain is ingrained in nature. Humans have long understood to optimize this process towards improved productivity. When food is wasted, although the wasted food will be recycled through natural processes of decay, that process is harmful to humans and the environment when it happens in trash bins and landfills rather than in composting facilities producing high-quality fertilizers.

Key Research Areas with Significant Knowledge Gaps:

- Renewable energy
- Energy storage (including hydrogen production and storage)
- Carbon capture, utilization, and storage (including natural capture)
- Integrated solid waste management and industry 4.0 technology
- Space technology and geoinformation systems for resource management
- Micro-recycling and Micro-factories for recovering and producing high-performance products and components
- Smart farming and plant biotechnology to develop drought and salinity resistant crops

Better ways to minimize waste throughout the production and consumption value chains are needed.[106–109] Furthermore, better ways to recycle water and nutrients, including nutrients from biomass and food waste during the farming cycle using advanced technologies, may allow increased food production from areas that are traditionally less able to produce food, such as arid lands and urban areas.

GAPS IN CIRCULAR ECONOMY RESEARCH AND POLICY

Despite the relatively new interest in the field of Circular Economy, close to fifty organizations, ranging from governmental agencies to academic institutions and research labs, to think-tanks and non-governmental organizations, were identified across the G20 nations that have focused attention and resources on aspects of the Circular Economy.

Over the last decade, research has focused on developing renewable energy, energy storage, CCUS (Carbon Capture, Use, and Storage), and energy efficiency in buildings, transportation, and industrial processes. Satellite imaging has focused on advancing the management of water, waste, land, and agriculture. Smart farming, agroforestry, and plant biotechnology have focused on improving efficient water use, reuse, and recovery while the development of temperature and salinity-tolerant plants has sought to maximize crop yields. There has also been research on green chemistry to minimize waste and use waste streams to co-generate energy. Micro-recycling has been developed for on-site recovery of valuable components to enable micro-factories to produce high-performance products and components.

Critical scientific and technological gaps remain in these areas, particularly in developing and adopting solar energy, hydrogen production and storage, natural carbon capture and efficient CCUS technology, desert farming, and efficient water management.

The major barriers in the global R&D ecosystem to enable the transition to a circular economy are lack of tax and regulatory incentives in many countries, large capital needs to rebuild the economy in a circular fashion with very different supply chains, and the general lack of standards and agreement on measurements of the Circular Economy worldwide. There is resistance from entrenched interests, limited acknowledgment of the externalities (e.g., market failures of the linear economy), and a lack of collaboration and coordination between all stakeholders. Government focus on developing technological innovations only goes so far in what will necessarily be a complete culture change in society to one where materials are considered valuable and Reduce, Recycle, Recover, Reuse is the norm, as are new business models of renting services instead of owning material goods and products. Government funding of technologies typically stops at very low technology readiness levels, where the private sector is expected to take over. However, many of these technologies are capital intensive and need massive scale-up and deployment before they become economically viable. Thus, they are too risky for venture capital and companies to take on. Research on circularizing agriculture specific to particular regions has been limited. Moreover, though there is a growing end-customer demand in some regions, such as Europe, for companies to change to a more circular model, there has been limited consumer education about the benefits of recycling and job creation that the Circular Economy can bring.

> **We have to increase the awareness of public stakeholders and decision-makers about circular economy…**
>
> **Dr. Jose Tundisi**
> **Brazilian Academy of Sciences**

Addressing these significant barriers will require partnerships between nations and between stakeholders within nations (i.e., federal and local governments, the private sector, NGOs, academia, and the general public), to agree on definitions and standards for circularity and the necessity of adopting it. Studies are needed for effective incentive schemes for industry and agriculture and strategies to increase public acceptance of circularity. For example, research is needed on how best to overcome the perception of health risks related to drinking recycled water. Increasing the funding for multi-disciplinary and multi-sector, system-focused research will be needed to design technical and sociological solutions for circularity. Demonstrations and pilots of aspects of circularity are needed to reduce costs and generate economic gain and public acceptance. Training of researchers and the workforce who may lose jobs in the linear economy for new jobs created by the Circular Economy will be essential. It is also important to ensure that indigenous, disadvantaged, and marginalized groups are involved in the solutions.

Vital Needs to Advance Science:

- Development and deployment of new technologies and processes advancing circularity
- Multi-disciplinary and systematic research to promote circularity
- Understanding of drivers and barriers to adoption of circularity, health risks, and public perception of reusing and recycling wastewater
- International collaboration, public-private collaboration, actions to improve consumers' responsibility to adopt circularity
- Economic viability of recovery and reuse and mitigation of associated market failure
- Ensuring involvement of indigenous and marginalized groups
- Desert farming, efficient water management, adoption of circular carbon economy including efficient CCUS tech, the technology roadmap
- R&D on cost-effective circular economy technologies such as new materials, renewables, and nature-based solutions
- Training of researchers and investment in specialized research centers

3.B CRITICAL TRANSITIONS AND THEIR IMPACTS

The S20 Circular Economy Task Force examined a range of global-scale inflection points and ongoing critical transitions to evaluate their known or anticipated positive and negative impacts on aspects of the Circular Economy. Below are five examples of critical transitions in the areas of environmental change, demographic shifts, rising inequality, emerging infectious disease, and rapid technological advances that require immediate and rapid advancement of global research, development, and policymaking.

The examples illustrate that linear economy paradigms cause shocks in life support systems such as health, environmental, and financial systems—shocks that disrupt global supply chains and cause severe hardship to human communities. Strengthening the Circular Economy improves sustainability and the environment and therefore provides mitigation strategies. However, the broad application of a circular economy has its own set of challenges discussed in detail in the next section, followed by policy recommendations to overcome these challenges.

3.B.1 ENVIRONMENTAL CHANGES

Unsustainable levels of deforestation, fishing, and hunting have driven and, enabled by the linear economy paradigm, are hindering Earth's natural ability to regenerate biosystems to the point of irreversibility if not remedied by human intervention.

Compounding the irreversible loss of biosystems are the signs that climate science has been giving us for many years that climate patterns we have been used to for the past several centuries are changing. Although these changes have been gradual, scientists predict that we are approaching a tipping point where we will see extreme events like severe temperature changes and severe precipitation or drought. These changes are exacerbated by manmade activity, especially the massive burning of fossil fuels and greenhouse gas emissions. The evidence is strong for anthropogenic warming, so adopting a circular economy and especially a circular carbon economy is an essential approach to mitigating the situation.

3.B.2 DEMOGRAPHIC SHIFTS

Population growth has led to an unprecedented number of people on the planet, a number that has doubled in only the last 50 years. Coupled with rising living standards based on unwise consumption and an environmentally damaging linear economic paradigm, the current population can lead to a dangerous scarcity of resources such as fossil fuels, fresh water, materials, and food. If not remedied, such a situation may lead to social unrest, geopolitical tensions, and possibly irreversible damage to water and food supplies.

3.B.3 RISING INEQUALITY

Rising inequality globally is a critical transition that places particular pressure on the development of the Circular Economy. While thriving economies may advance their Circular Economy goals to reduce consumption of materials, this reduction may create a positive feedback loop with rising inequality: countries that supply materials no longer in demand may fall farther behind economically, and these countries are frequently the destination for materials to be recycled further compounding inequality.

In addition, as the United Nations Industrial Development Organization (UNIDO) concluded, "the Circular Economy could cut poorer countries out of the global supply chains they have worked so hard to enter." [110] Emerging economies that have begun to develop manufacturing capacity to compete globally may find their products cannot be sold without further investments to comply with new standards for the carbon footprint of manufacturing, the ability of materials in the product to be recycled and reused, and the reduction in certain types of allowable materials. Complicating this challenge is that emerging economies often do not have the engineering and research capacity to develop these adaptations. The critical transition of rising inequality, therefore, not only must be considered in developing Circular Economy solutions, it must be considered as a potential consequence of those solutions.

3.B.4 EMERGING INFECTIOUS DISEASES

The unequal development of rural areas compared to urban areas leads to massive human migration to urban centers. On one side, rural areas see extreme expansion and specialization in agricultural land use enabled by energy-intensive mechanization and encroachment on wildlife habitats that enables more zoonotic diseases. On the other side, hypergrowth and over-concentration in urban areas lead to intense transmission of new diseases leading to pandemics, as is seen with the ongoing COVID-19 case. In addition to that, over-urbanization leads to long, fragile supply chains to provide life necessities as the over-urbanized areas exceed the land carrying capacity, making them very vulnerable to disruption of supplies, with the pandemic exacerbating the situation even further.

3.B.5 RAPID TECHNOLOGICAL ADVANCES

Rapid advances in technology lead to unsustainable global increases in the demand for finite resources, greenhouse gas emissions, and an increasing waste stream. To choose one example over the last sixty years, the global proliferation of air conditioners and refrigerators, while certainly a boon to households and industry, led to an increase in demand for copper and aluminum, a significant increase in the emissions of CFCs, and a new waste stream of old, dysfunctional products. The CFC emissions had the doubled effect of catalyzing stratospheric ozone destruction and being a greenhouse gas more effective than CO_2 in trapping heat in the troposphere. The ozone depletion from CFCs drove a critical transition of such global concern that countries joined in signing the Montreal Protocol to phase them out.

More recently, the global explosion in demand for smartphones has had driven a similar critical transition. It is surprising to reflect that the iPhone was launched barely more than a decade ago, in July 2008. However, since its launch, the demand (and need) for smartphones and tablet computers has permeated the planet, and with it, the demand for the rare earth elements (REE) critical to manufacturing the devices. While this critical transition and its global impact have also led to a response by some companies, such as Apple,[111] to introduce recycled materials to products, remove arsenic and beryllium from products, and commit to being carbon neutral by 2030, not every manufacturer is similarly responsive, and new advances in technology will continue to drive critical transitions affecting the Circular Economy.

3.C CHALLENGES

Key challenges to advancing the Circular Economy are described below in terms of institutional, political, financial, and technological systems, as well as in the context of ethical issues and the potential for international collaboration.

3.C.1 INSTITUTIONAL

Institutional challenges considered by the Circular Economy Task Force include a focus on infrastructure encompassing circularity and lack of collaboration and coordination among relevant stakeholders and authorities at national and international levels.

A variety of institutional barriers impair the advancement of the Circular Economy, such as the lack of scientific research, understanding, and adaptation of circularity in strategic plans and projects.

Another institutional barrier is the limited access to data, intellectual property, and know-how. The lack of data sharing and exchange will slow the implementation of the circular economy, specifically in less developed countries. Data banks at both national and international levels are needed to accelerate the adaptation of circularity among these countries.

Within the water sector, challenges tend to be related to the prevalence of the linear production and consumption model and the existing legislation, infrastructure, and resource pricing models built based on it. To market and use much of the material that can be recovered from wastewater streams, they need to be relabeled from "waste" to "resource." To ensure the safe and efficient use of these materials, health and industrial standards to regulate their use and marketing need to be developed and enforced.

3.C.2 POLITICAL

Lack of standardization and clear policy for resource recovery and recycling is a major political challenge. Similarly, the complexity of regulations, the lack of conducive legal systems, and inadequate institutional frameworks impair the circularity of resources. In some cases, regulations are too strict, making it impossible to use recycled resources.

Another concern is the geopolitical conflicts and destabilization of some regions, which impact the adoption of the Circular Economy. The Circular Economy should be considered as an opportunity to ensure socioeconomic sustainability, environmental protection, and protection from future disasters.

Different levels of expectations and the lack of awareness of circular economy benefits is another political challenge that needs to be addressed.

3.C.3 TECHNOLOGICAL

Numerous technical challenges must be overcome to advance the Circular Economy. To close loops, it is necessary to collect the used resources at the highest value point, improve their properties for the next use, and introduce the improved resource back into the loop as a useful product. In many cases, the available technology does not yet work or is not economically viable. There is a need for more research, innovation, development, and demonstration.

At the level of a single household, office, factory, or farm, technology needs to be more affordable and allow easy retrofitting for rooftop solar or wind collectors, wastewater treatment, and small-sized waste food composting. Beyond the single household, large systems require interdisciplinary research along with governmental intervention to realize such solutions. These large systems of systems[112] also require holistic life cycle assessment of technologies in addition to social, economic, and environmental research to determine feasibility.

Case studies in the energy and materials sub-themes illuminate additional technological challenges faced in advancing the Circular Economy. In the energy sub-theme, the technical challenges are manifest in Carbon Capture, Sequestration, and Utilization (CCSU). Many of the currently available technologies merely delay the emissions of CO_2 rather than eliminate them permanently, while technologies that do sequester CO_2 more permanently require more research and development to scale them and make them cost effective.[113,114]

In the materials sub-theme, the recycling of plastics illustrates technological challenges (discussed in more detail in the New Plastics Economy Global Commitment).[115] The quality and manufacturing requirements for plastic products favor inexpensive virgin feedstocks, limiting recycling's technical and economic viability. These limitations are complicated by the lack of infrastructure for recovery of plastics in durable goods, the lack of reliable markets for recycled materials, and low tipping fees for waste materials.[116] Improving recyclability requires a systemic approach across the value chain (coordinating material and application design with collection, sorting, and reprocessing) and increased coordination across material innovation, product design, end-of-life recovery, and recycling.[117] Technological development of next-generation plastic resins that permit easy depolymerization, re-manufacture, and re-use together with developments in the chemical recycling of plastic mixtures, may ultimately offer improved recovery of materials or energy from plastics.[117]

3.C.4 FINANCIAL

The financial challenges related to developing and adopting a Circular Economy are institutional, governmental, and individual. Research institutions require funding to carry out the basic and applied research required to develop new technologies: this could be in the form of dedicated grant programs or government and industry contracts. These grants and contracts also need to be more targeted at Circular Economy goals. Advances that are currently the outputs of unrelated research projects could be more frequently achieved if the funding were targeted at Circular Economy needs.

To bring new technologies into use, industry needs financial resources and incentives as well. Often a new technology, while proven effective and beneficial in academic studies or via a pilot implementation, requires significant funding to scale to full adoption. This may mean, for example, shutting down production for retooling or may require the construction of entirely new facilities. Inevitably, bringing new technology to market requires staff training and marketing initiatives as well. In industries that may already be operating on the edge of profitability, these costs can be impossible to bear.

The government plays a critical role, therefore, in resolving the financial challenges for these private institutions. However, governments face financial challenges as well, especially in emerging economies where investment in primarily long-term goals such as advancing the Circular Economy must be weighed against very tangible near-term needs in health, education, food security, housing, and water resources, for example.

At the end of the Circular Economy ecosystem is the individual. The costs of new technologies or government policies that advance the Circular Economy are often passed along to the individual. Relic technologies (e.g., incandescent lightbulbs) are often much less expensive in the near-term than their replacements (e.g., LED lighting). The price difference is partly due to product development costs, but the costs of externalities such as environmental degradation are also typically not factored into the cost of relic, non-circular products even though society as a whole still bears these external costs via expenditures on health care and ecosystems rehabilitation, for example. There are also hidden costs to the individual beyond the purchase price: the time, effort, and personal education needed to use and adapt to new technologies can be significant.

In total, the above financial challenges inhibit economies of scale from supporting the development of the Circular Economy—the non-circular (or linear) economy model has benefitted from these economies of scale and therefore appears artificially more attractive.[118]

3.C.5 ETHICAL

The ethical challenges in the Circular Economy fall into three categories: job loss and export, not-in-my-backyard issues, and exclusion of some populations from the benefits. As the Circular Economy develops, Job loss and export of those jobs to other countries is inevitable. In many countries, the entire national economy relies heavily on extractive industry, and a significant goal of the Circular Economy is to lower the outputs from these industries that draw on the planet's finite, irreplaceable resources. Advancing the achievement of the Circular Economy cannot be done without considering and providing solutions to the job losses and national economic impacts that could shift hundreds of millions of people into poverty.

Another challenge in the ethics of the Circular Economy is the shift of waste streams from advanced economies to emerging economies. Re-use and recycling require disassembly and reprocessing of disposed material. To lower costs, the disposed material is often transported by ship to countries where environmental protections and worker safety laws are weak (or weakly enforced). Materials intended for re-use and recycling are often those that contain metals such as cadmium, chromium, and lead, which can be toxic as workers are exposed to them in high concentrations or as they move into the environment.

Finally, although a goal of the Circular Economy is to obtain an overall improvement in sustainability and ecosystem health globally, the benefit will not be homogeneous and, more importantly, some countries and regions may be excluded. The Circular Economy requires investment both financially and of political will, and while many benefits of the Circular Economy are transboundary, others are primarily within a country's borders. As the technologies and policies evolve to advance the Circular Economy, attention must be given to countries and regions that may be unable to take advantage of these advances. In addition, attention must be paid to highly competitive business environments that may further inhibit the sharing and collaboration needed for mutuality of benefit.[119]

3.C.6 INTERNATIONAL COOPERATION

The lack of collaboration between key stakeholders holds back the advancement of the Circular Economy. For example, there is no coordination on science and engineering research priorities between the S20 and the Global Research Council (GRC), a gathering of national research funding organizations. There is also a need for an umbrella concept on circularity in different resources for bringing all countries and stakeholders together irrespective of political and socioeconomic differences.

Another challenge is the heterogeneity in the use of circular economy technologies among nations, which creates instability in the market and can affect technological operations. The potential solutions to this challenge include having multi- and bi-lateral agreements, developing initiatives in the World Trade Organization (WTO) to promote cross-border diffusion of technology and trade, and developing easy-to-implement solutions considering local context.

An important area of international cooperation is to regulate the extraction and use of energy, water, mineral, and wildlife resources that span the land and sea borders of multiple countries. Examples include oil fields, rivers, and fisheries, where activities on one side of the border may negatively impact the other side of the border.

Another concern for international cooperation is the organization of markets and global trade for recycled products. Policy on trade currently does not adequately distinguish between waste materials and those intended for recycling. The potential solution is to encourage the G20 leaders to create the right market conditions by removing unnecessary regulations on aesthetic and quality standards not applicable to the recycled components or materials.

3.D RECOMMENDATIONS

This section identifies and summarizes the key recommendations emerging from the S20 Circular Economy Task Force’s global landscape analysis.

3.D.1 DEVELOP CLOSED-LOOP MATERIAL CYCLES

RECOMMENDATION

Develop an integrated and efficient closed-loop systems approach to natural resource extraction, processing, distribution, consumption, disposal, and recycling.

RATIONALE

Unlike the traditional linear economic model based on a ‹take-make-consume-throw away› pattern, a circular economy is based on sharing, leasing, reusing, repairing, refurbishing, and recycling, in an (almost) closed loop, where products and the materials they contain are highly valued. In practice, it implies reducing waste to a minimum. Moving towards a more circular economy could deliver opportunities including reduced pressures on the environment, enhanced security of supply of raw materials, increased competitiveness, innovation, growth and jobs.

POLICY ACTIONS

1. Encourage research, development and use of innovative technologies to reduce pollution as well as generate value from waste.
2. Leverage advanced digital technologies such as Internet of Things (IoT), Artificial Intelligence (AI), big data, and blockchain technology to improve efficiency and resiliency of natural resource utilization as well as enhance synergies of circularity in energy, water, materials, and food.
3. Establish legal and economic incentives to promote large-scale acceptance and application of recovered resources and products by end-users in different sectors.
4. Invest in technologies to allow for closed loop systems, especially for key sectors such mining, manufacturing, agriculture, commerce, services and urban dwellings by conducting and leveraging a holistic assessment of each nation’s needs, resource availability, waste generation and technological capacity.
5. Promote closed-loop systems toward zero waste of business operations and extending the boundary of sustainability.
6. Adopt smart approaches for curbing consumerism and overconsumption and pursue demand management scenarios. Enhance the shift from efficiency to sufficiency, maintaining responsible consumption without sacrificing social welfare.
7. Encourage research, development and use of innovative technologies (of product, process and organization, i.e. hard and soft technologies) to enhance workforce use, in line with a shift from efficiency to sufficiency (in terms of quantity and quality).
8. Develop integrated assessment models and perform scenario analyses to determine the socioeconomic, environmental, and human health co-benefits of waste reduction and valorization, as well as identifying strategies to reduce unintended effects throughout the processes.

3.D.2 PROMOTE CARBON REDUCTION AND REMOVAL

RECOMMENDATION

Promote atmospheric carbon reduction through advancing the 3Rs (Reduce, Reuse, Recycle) and increasing effectiveness and use of Removal, the fourth R.

RATIONALE

Rising greenhouse gas emissions are driving rising atmospheric carbon levels. Carbon circularity will support global commitments and responsible development while reducing pressures due to hyper growth in urbanization. Advancing the principles of reduce, reuse, recycle and recovery will help with the adoption of carbon circularity.

POLICY ACTIONS

1. Conduct techno-economic feasibility studies and lifecycle assessment to determine how to optimally combine renewable and fossil energy sources coupled with 4Rs-related technologies in an integrated power generation system that leads to carbon neutrality goals.
2. Promote investment in carbon capture, utilization and storage R&D and standardization of technologies such as CCUS, BECCS, CO2-to-X, based on their merits.
3. Encourage deployment of emerging technologies that support carbon circularity at testbed sites.
4. Encourage research, development and use of innovative technologies, such as Carbon Capture Utilization & Storage (CCUS, BECCS, CO_2-to-X), to reduce as well as generate value from greenhouse gas emissions in the energy sector.
5. Promote forest and marine plants restoration as a method for carbon capture and reuse while simultaneously restoring biodiversity.
6. Promote renewable energy and affordable storage in general as a means of reducing dependence on carbon.
7. Leverage innovative technologies and systems approaches to strengthen carbon circularity in the food-energy-water nexus and achieve resource resilience and sustainability at multiple scales.
8. Put a price on carbon emissions as a signal that emissions are harmful and should be reduced; carbon prices could be introduced through a carbon tax or a system of tradable emission allowances (“cap-and-trade”) and governments should use revenues from carbon taxes or auctioned permits to support environmental innovations to build a low-carbon economy.
9. Support the effort to reduce carbon emissions by increasing the efficiency along the whole chain of fossil-based energy system and increasing the share of renewable energy in the energy mix.

3.D.3 MEASURE AND TRACK ADVANCES IN THE CIRCULAR ECONOMY

RECOMMENDATION

Develop indicators and values, and track progress to facilitate the transition towards a circular economy.

RATIONALE

Tracking circular economy topics in a consistent manner globally is needed to support the transition towards a circular economy. Standards for measurement need to be adopted and indicators identified to best track progress. Indicators will be needed to track all critical transitions.

POLICY ACTIONS

1. Develop science-based circular economy metrics, and performance indicators capturing micro and macro scales and describing the net resources used to help tracing and capturing key progress in the transition from linear-based to circular-based economies.
2. Build on work done by international organizations such as the UN, WEF, and EU in developing internationally accepted metrics, indicators, standards and guidelines circular economy principles, systems, and technologies.
3. Develop circular economy indicators for organizations considering sustainability and business models on materials and for monitoring and promoting circularity.
4. Promote science-based circular economic targets and policies for public and private institutions, including local authorities and municipalities to reduce inefficient resource utilization while promoting environmental conservation, management, and restoration.
5. Develop global, regional, and national circular economy models and foresight scenarios to perform prospective, integrated assessment to better understand the impacts and challenges of the Circular Economy.
6. Develop circular economy indicators for organizations considering the use of workforce as well as the use of resources.

3.D.4 ADVOCATE FOR ADOPTION OF TECHNOLOGY AND PRINCIPLES

RECOMMENDATION

Advocate for and improve visibility of mature, adoptable technologies that advance the Circular Economy and promulgate principles more thoroughly within environmental, social, and economic communities.

RATIONALE

Awareness of circular economy technologies and principles are limited among policymakers, producers, and the public. Increasing awareness will support in the adoption and widespread deployment of circular economy principles.

POLICY ACTIONS

1. Develop programs to raise public awareness and literacy on the need for circularity to achieve sustainability and environmental protection to accelerate voluntary adoption of the Circular Economy.
2. Develop programs to raise awareness among decision makers in different stakeholders at all levels on how to achieve the Circular Economy and reap its benefits.
3. Develop educational materials and programs on circular economy to be included at all educational levels to raise awareness and open career paths to innovation, startups, and jobs in all aspects of circular economy.
4. Introduce labelling schemes showing environmental footprints to make consumers aware of the environmental impacts of products they consume.

3.D.5 EXPAND TRANSDISCIPLINARY CIRCULAR ECONOMY RESEARCH

RECOMMENDATION

Encourage cross-sectoral, bi-lateral, and multi-lateral collaboration and data sharing to advance circular economy systems and policies.

RATIONALE

The Circular Economy will require collaboration across multiple stakeholders within and across countries, as global systems are highly interconnected. Collaboration and sharing will be needed on data, research, standards, and technologies to enable the success of circular economies.

POLICY ACTIONS

1. Adopt UN Sustainable Development Goals 1-17 and encourage international collaboration through establishing a global platform for exchanging ideas and good practices on circularity.
2. Establish cross-industry partnerships, in collaboration with the scientific community to advance R&D of circular economy systems.
3. Collaborate and assist technically and economically to promote circular economy technologies.
4. Support early and mid-career Circularity researcher and entrepreneurs through visitations, events, and platforms for businesses (both large and MSM enterprises).
5. Encourage developing methods for generating, collecting, and sharing data on circular economy in a standardized and open access manner, preferably using digital technologies to facilitate collaboration among all circular economy stakeholders.

3.D.6 FUND CIRCULAR ECONOMY TECHNOLOGIES

RECOMMENDATION

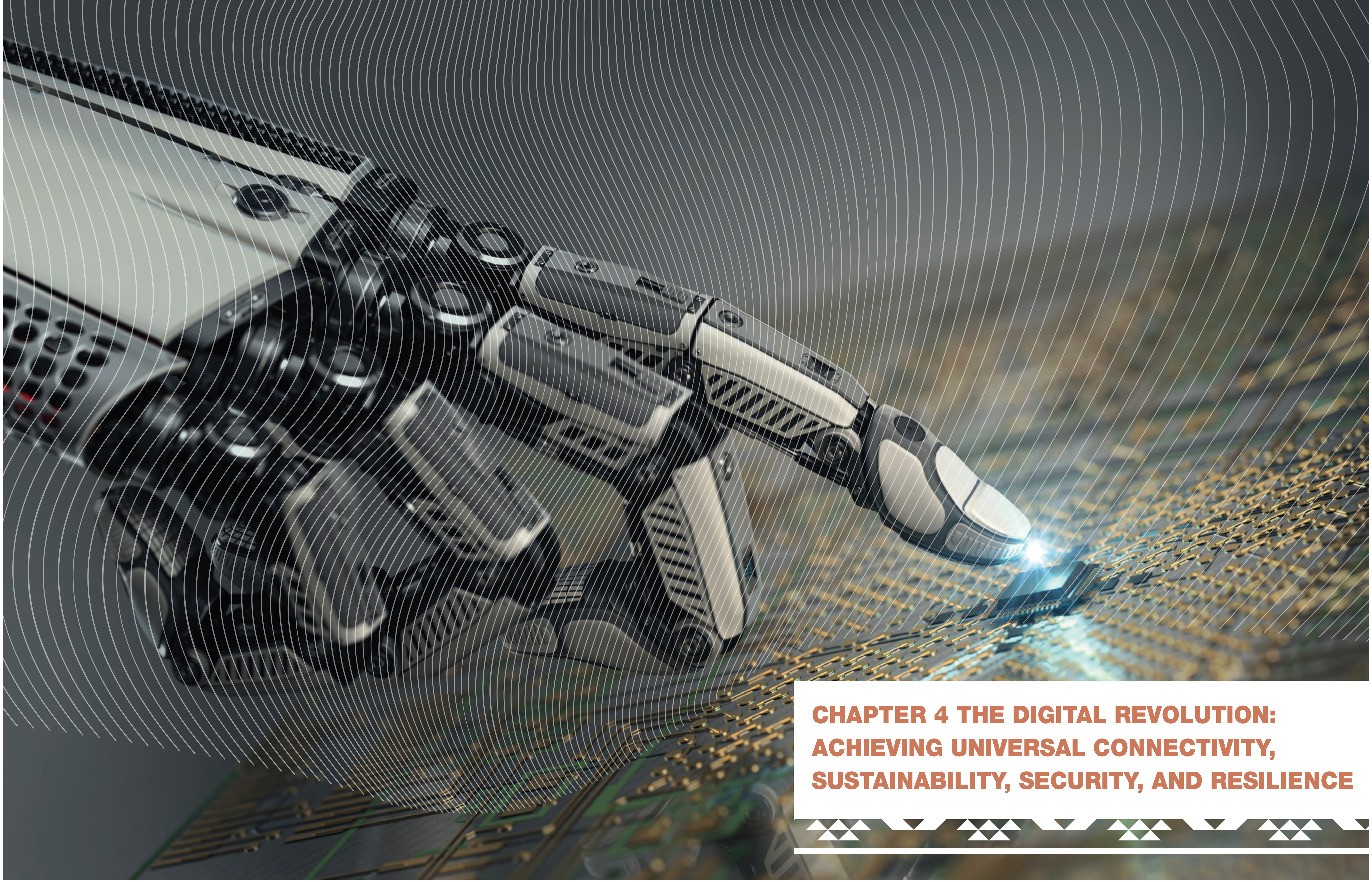
Create funding and support for circular economy technologies.

RATIONALE

Circular economy technologies are new and require financial support to advance from concepts to commercially viable systems. Given the immaturity of technologies, support will be needed to incentivize companies and countries to transition towards a circular economy.

POLICY ACTIONS

1. Support funding for multidisciplinary research into circular economy technologies and their assessment.
2. Identify technical, socioeconomic, and administrative problems that need to be solved to achieve a circular economy and realize its benefits by conducting holistic assessments of each nation's needs, resource availability and technological capacity.
3. Promote public investments in shortlisted technologies and sub-themes, particularly those that allow for closed loop systems by conducting and leveraging a holistic assessment of each nation's needs, resource availability and technological capacity.
4. Provide incentives to private sector firms, such as tax cuts, for undertaking required R&D and investment initiatives to change to a circular economy.
5. Establish legal and economic incentives to foster acceptance and application of recovered resources and products by end-users in different sectors such recycled combustion emissions, recycled wastewater, recycled materials, and recycled foods.
6. Introduce appropriate regulations, such as: setting standards for waste collection and recycling; imposing firms, hopefully with the help of artificial intelligence applications, to trace the nature and path of the used materials so as to make their recovering and recycling easier.
7. Introduce policies that will add the cost of unsustainability and environmental damage resulting from toxic and unused waste to the prices of products and services to create fiscal benefit for producers and consumers to adopt a circular economy approach.
8. Support measures for the secondary (i.e. recycled) materials market.
9. Encourage public-private partnerships to invest, collaborate and benefit economically from circular economy R&D.
10. Design specific R&D funding for not-for-profit organizations (for example, grassroot innovators, social innovators, and worker cooperatives) in order develop new circular economy technologies under public-community financial schemes.
11. Allow a bottom-up approach by giving sub-national entities authority to enact initiatives promoting the Circular Economy.



CHAPTER 4 THE DIGITAL REVOLUTION: ACHIEVING UNIVERSAL CONNECTIVITY, SUSTAINABILITY, SECURITY, AND RESILIENCE

CHAPTER 4 THE DIGITAL REVOLUTION: ACHIEVING UNIVERSAL CONNECTIVITY, SUSTAINABILITY, SECURITY, AND RESILIENCE

4.A THE DIGITAL REVOLUTION

4.A.1 OVERVIEW

Digital technologies are driving one of the most profound changes in human society and the global economy since the Industrial Revolution. This move into the so-called Digital Future, or Digital Revolution,[120] impacts all facets of life, including business, manufacturing, agriculture, transport, education, healthcare, entertainment, the arts, the home, and social interactions. In short, technology and society are becoming more and more interwoven.

The Digital Revolution offers many opportunities for society. In addition to the more apparent benefits of e-commerce, e-health, online education, and automated agriculture, citizen science and citizen-generated data help this enterprise. Interconnected sensors and actuators making up the Internet of Things (IoT) in urban settings are enabling Smart Communities to manage the urban environment better.

The Digital Revolution Task Force believes that the Digital Revolution's over-riding objective should be to maximize benefits to society aligned with and addressing public values, including fairness, equal access, transparency, and privacy.[121,122] Throughout this report, the Task Force focuses on considerations and policies that can be implemented to maximize benefits to society.

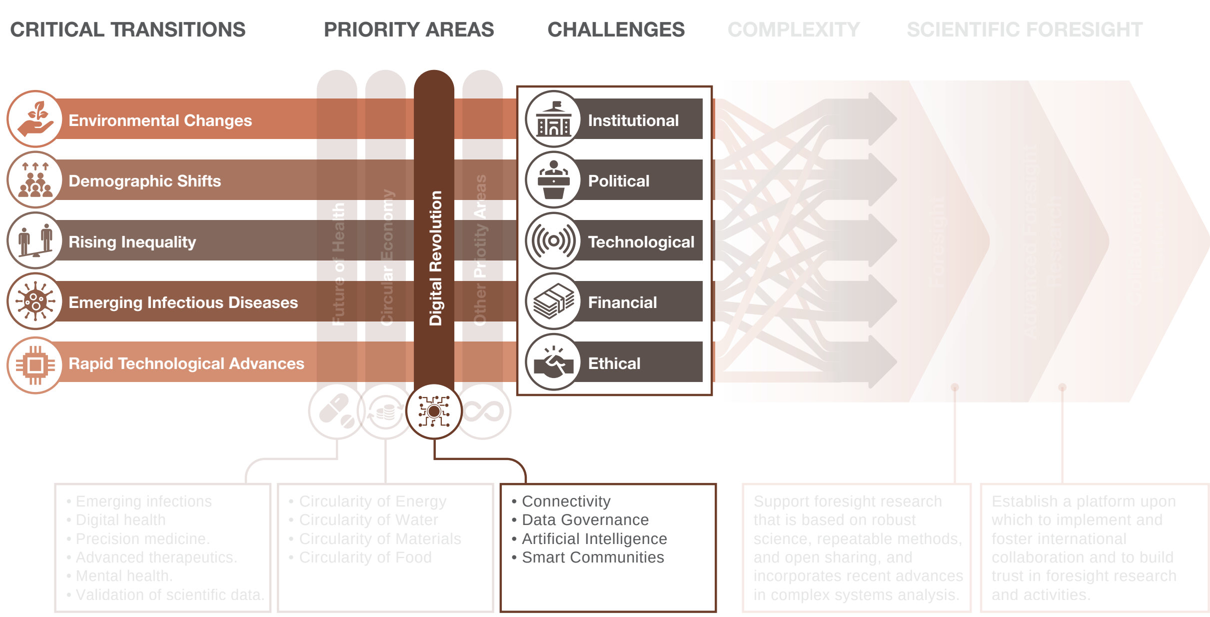


Figure 4.1: The S20 Foresight Framework for analysis, highlighting the Digital Revolution priority area and its sub-themes.

Modern technologies like Artificial Intelligence (AI), Machine Learning, Blockchain, Self-Sovereign Identities (SSIs), Robotic Process Automation (RPA), IoT, Social Media, Robotics, and Data Analytics are redefining the way businesses operate and are affecting individuals and homes. Advances in telehealth and personalized medicine are changing the health sector, aided by AI and deep learning advances. Fiberoptic and mobile technologies bring faster networks, universal connectivity, and more stable connections to the world. Enhanced digital content and applications, along with better digital privacy, security, inclusiveness, fairness, and transparency, coupled with more accessible hardware, are making digital connections available to large segments of society.

The Digital Revolution has only just begun. Existing technologies are continually advancing, and new technologies will emerge that have an even greater capacity to feed the Digital Revolution. However, while the Digital Revolution is changing the world in very profound ways, its role in society is not fully understood. Governments and societies may not be adequately positioned to benefit from its opportunities or address its resulting challenges fully.[121,122]

The S20 Digital Revolution Task Force has a vision of a future society in which digital technologies have been integrated into every aspect of life, and their potential has been fully realized in a way that maximizes public values. Considerations of the Digital Revolution's future and its impact should be focused on benefits to humanity, including key developments in human rights, privacy, data transparency, ethics, and digital inclusiveness and literacy.

To help advance this vision and develop a plan for action, the S20 Digital Revolution Task Force assessed the state of science leading to universal connectivity, sustainability, security, and resilience, and analyzed the critical global issues relating to the Digital Revolution's future. This report examines how scientists and policymakers across the G20 nations might advance digital technology research and policies and establish and use Scientific Foresight to mitigate or achieve anticipated or future disruptions.

Issues considered include:

- Managing the course of technology development so that societies are in control of the outcome;
- Assuring that everyone benefits from the digital economy; and
- Defining policies to mitigate risks surrounding data privacy, security, fairness, and transparency.

This S20 Digital Revolution Task Force analysis presents a current global perspective on four sub-themes in the Digital Revolution:

- Connectivity: enhancing our understanding of

- the science and technology behind achieving universal connectivity of people, organizations, machines, businesses, devices, data, and processes;
- Data Governance: analysis of the benefits of using large data sets by governments, institutions, and businesses, while at the same time providing privacy and security;
- Artificial Intelligence: an examination of the future opportunities provided by AI and overcome the challenges that impede its widespread implementation, such as racial bias; and
- Smart Communities: understanding how Smart Communities can enhance the livability of urban environments: one challenge facing the world today and likely in the foreseeable future will be digital innovations required to adapt to a post-COVID-19 world.

Through this analysis of the four globally significant sub-themes, we Identify technology opportunities and challenges that are ripe for global collaboration and highlight promising policies that must guide the evolution of digital economies and smart urbanization. This analysis informs a set of recommendations aimed at (a) enhancing the development of technologies that drive the Digital Revolution and (b) facilitating the implementation of policies that help to advance the Digital Revolution and guide the evolution of digital technologies for the benefit of all.

4.A.2 SUB-THEMES IN THE DIGITAL REVOLUTION

CONNECTIVITY

Increased connectivity has been a defining feature of the Digital Revolution over the past three decades. In this context, communication systems and networks are becoming the dominant mode of information access and exchange. Wireless technologies are allowing developing economies to leap into the information age without necessarily investing in the costly infrastructure of wiring to every home and office. Similarly, advanced technologies are offering people in more developed economies more freedom and flexibility. The Internet of Things (IoT) connects everyday objects (e.g., household appliances, cars, thermostats, etc.) to the internet through integrated devices, enabling seamless communications between people, processes, and devices without requiring human-to-human or human-to-computer interactions.[123–126]

The primary desired characteristics of such emerging and future communication systems and networks are:

- Universal connectivity, enabling access to all people, regardless of their location or socioeconomic status;[127]
- Power efficiency (reduce environmental impact);[123,128]
- Spectral efficiency (increased capacity);[123–126,129]
- Resilience, robustness, and dependability;
- Security and privacy;
- Inclusiveness by ensuring affordability in order to offer global internet access for all;[127,130]
- Global coverage in order to offer connectivity to remote/rural/inaccessible areas, as well as in sea/air environments; and[127,131]
- Absence of adverse effects on human health.

DATA GOVERNANCE

Data are core to enabling the Digital Revolution as they feed applications that facilitate daily activities. Therefore, it is essential to adopt and develop policies and regulations to strengthen the governance of data. It is equally important to develop protocols and methods that assist in various aspects of data governance, including data fairness, unbiasedness, non-discrimination, interpretability, and privacy-preserving. While the use of small and large data sets is proliferating across all aspects of society, there is a glaring lack of global policies and data governance standards. Meanwhile, there is an increasing spread of misinformation, fake news, adversarial data, and manipulation and misuse of data through cybercrime.[132–134] What are missing are well-articulated international laws and regulations that govern the collection, sharing, and processing of data.

Scientific methods of data privacy and protection need to be advanced, for example, to:

- Address gaps related to differential privacy, in which some information about a dataset is shared, but information about individuals in the dataset is not;
- Develop and govern Blockchain and SSIs to securely identify, authenticate, and access information;
- Establish trusted hardware;
- Develop encryption-based methods for protecting data security and privacy; and
- Originate computational algorithms from the domain of AI.

ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) is poised to lead the way to the next phase of the Digital Revolution, with the potential to disrupt every industry, making each more innovative and productive. While intelligence was once deemed a uniquely human trait, the availability of rich data sets and increased processing power has enabled AI to behave intelligently and to enable a new era of robotics. AI is a multidisciplinary field of science with contributions from mathematics, statistics, cognitive science, psychology, neuroscience, and linguistics. The theoretical underpinning of AI has been established since the work in the 1950s by computer scientists such as Alan Turing and John McCarthy.[135–137] AI has been a critical priority for the G20 countries due to its enormous economic and social impact.[123–130,138–145]

The exponential growth in computing power and the rapid decline in data storage cost have been key technological enablers of AI. The development of cross-domain open-source and open-standard platforms can facilitate the use of AI technologies and enable deployment by integration with existing digital infrastructure. However, the benefits of AI cannot be fully realized by improving the capability of AI techniques: the concerns it raises must also be addressed. To this end, ongoing efforts are focused on establishing frameworks for building trustworthy AI, characterized by multiple areas of focus such as accountability, transparency, explainability (i.e., the ability to be able to explain to a user why the AI process came to a particular conclusion or recommendation), and fairness.[146147] This work is critical to increasing human trust in technology and ensuring its ethical and moral compliance.[146,148–154]

SMART COMMUNITIES

Smart Communities and Smart Cities are urban and rural regions that use sensors and actuators connected to the IoT to manage resources and services. The objective of Smart Communities and Smart Cities is often seen as improving the efficiency, effectiveness, and sustainability of services provided by city or community officials. Examples of services that can be enhanced in this way include public services such as transport, waste management, public security and safety, traffic management, and utilities. Smart Communities can also facilitate community-driven, bottom-up initiatives for the common good. Examples include NGOs and other intermediaries tackling societal challenges. There is a need for policies to be set to facilitate community-driven initiatives that take advantage of Smart Community infrastructure.

The Digital Revolution has expedited the development of Smart Communities and Smart Cities through advancements in a wide range of digital technologies and innovation. In fact, many of the

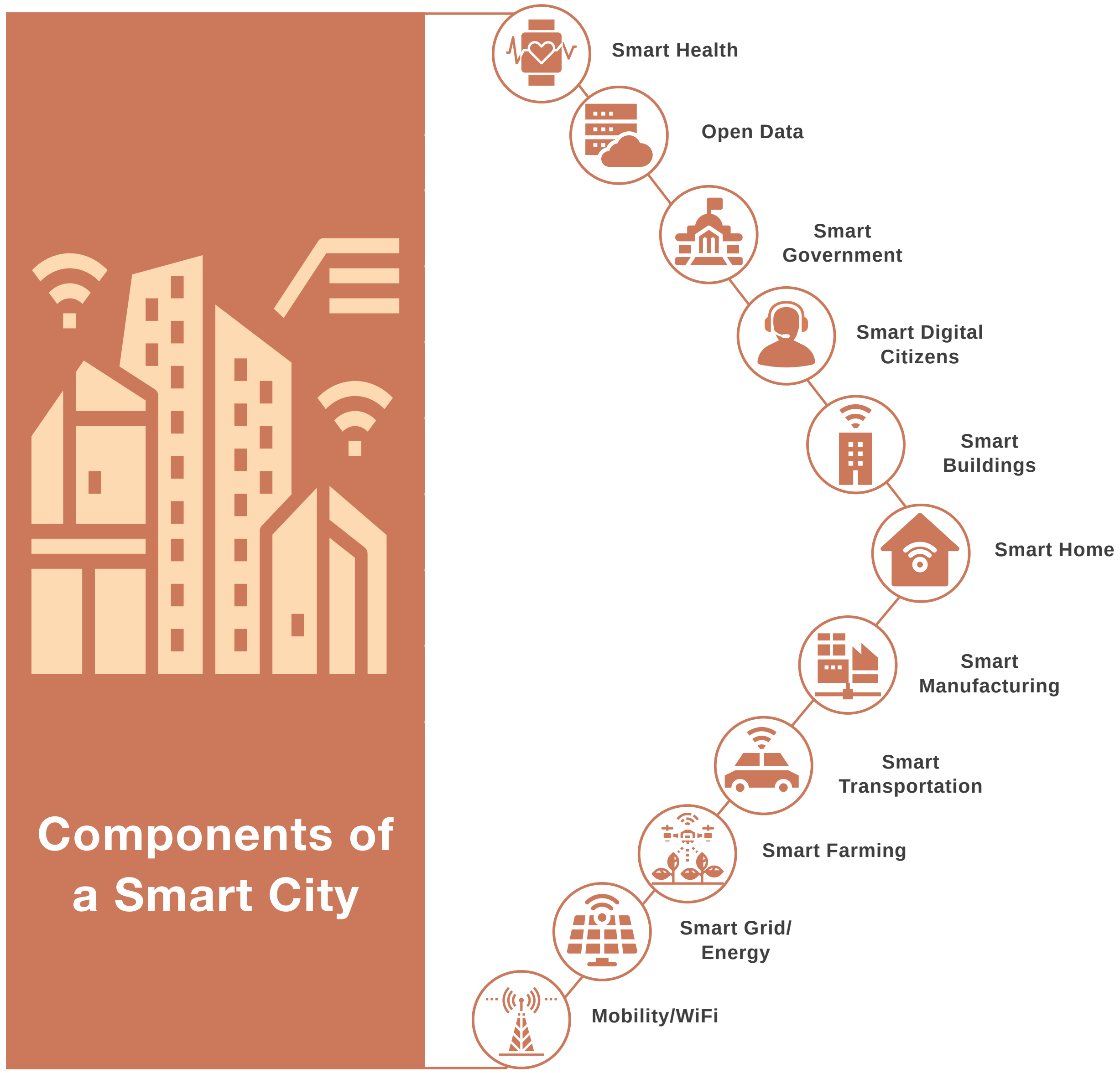


Figure 4.2: Components of a Smart City

technologies and applications critical to Connectivity, Data and Algorithm Governance, and Artificial Intelligence will feed into the development of future Smart Communities.

The growth of national economies and global competitiveness will depend largely on integrating urban and rural communities into the global digital infrastructure and decreasing disparities in the availability of and access to digital technology and digital literacy and training. Enhanced quality of life becomes possible by introducing smart applications and e-services such as e-health care, e-learning, and any service possible using smart devices and IoT technology. The transformation of traditional urban infrastructure and services into intelligent systems will affect many fields such as energy, mobility, home, office, environment, social services, and workforce development.

> **[There is a] need to make digital literacy as important as other forms of literacy: mathematical literacy, reading and writing... Digital literacy should be something that we strive for in all humans.**
>
> **Dr. Richard F. Rashid**
> **Emeritus Researcher, Microsoft, USA**

GAPS IN DIGITAL TECHNOLOGY RESEARCH AND POLICY

A wide range of research topics related to connectivity, data and algorithm governance, AI, and smart communities are currently being pursued across the G20 nations. Some of these activities are part of international and national research programs; others are pursued by academic researchers in small groups.

Despite the wide range of research activities currently underway in G20 countries, there are many gaps in the research and policy framework across G20 nations that need to be addressed. These gaps fall into five main areas: the Digital Divide; the uneven rate of implementation of new technologies; slow uptake of some Artificial Intelligence solutions; robustness, resilience, security, and privacy; and the growing environmental impact of digital technologies.

Digital Divide

A Digital Divide is emerging between those who can take advantage of the Digital Revolution and those unable to. Some segments of society in G20 countries do not have access to adequate broadband services. In some instances, this is caused by a lack of connectivity in particular regions due to geography or challenges related to adopting rapidly advancing technologies. In other cases, this Digital Divide is due to socioeconomic or socio-political barriers that create differential access to digital resources by particular groups, such as people who are disabled, elderly, or have other educational, economic, or social disadvantages, such as women or minority groups. Such social divides also impede the development of digital literacy and thus expand the Digital Divide.

Improved education across all communities will equip citizens better to benefit from the Digital Revolution, reduce the Digital Divide, and create a more inclusive society. In addition, to improve education in the use of digital technologies, there is a need for increased Digital Revolution-related capacities of teachers, professors, and trainers. In short, there is a need to «train the trainer.» Further advances in the Digital Revolution will require a skilled workforce to provide new advanced technologies and develop these technologies for real-world applications. To assist more young people in considering careers in digital technology, improved (general) science education and technical literacy in schools and training and professional development support are needed to help students enter technical careers in developing and servicing networks, equipment, and software. At the advanced technology level, increased emphasis on digital-related science and engineering courses in universities is needed, as well as enhanced technologies for self- or unsupervised learning. Massive open online courses (MOOCS) may help expand access to education and training resources.

Uneven Rate of Implementation of New Technologies

An impediment to some digital technologies' widespread deployment is a lack of interoperability across different digital infrastructure platforms.

> **Society is ever more dependent on digital technology structure and data. Everything depends on it, and without it, we are in real trouble. Any impact or damage to the structure is more significant now than it ever was before.**
>
> **Dr. Rod Tucker**
> **Australian Academy of Science**

Examples of this problem exist in areas of e-health and some proprietary technology implementations for smart communities. Another impediment is a lack of awareness among some potential users of the capabilities and opportunities provided by digital technologies. An example of this is in municipal governments where officials may be unaware of technologies that would help in the implementation of smarter infrastructure. Part of this gap is related to the need for more education (see above), but it also reflects on a shortage of use-case examples to help promote the implementation of Smart Communities. Another gap is a lack of interaction between technologists working on digital technologies and social scientists with expertise in technology-human interactions and cultural changes resulting from the Digital Revolution.

Slow Uptake of Some Artificial Intelligence Solutions

The widespread uptake of AI technologies is hindered by a lack of reliability, robustness, security, and trustworthiness in some systems.[155] Many of these issues are technical and are likely to be resolved with further research. The issue of trustworthiness has more to do with society's acceptance of a computer algorithm making certain decisions. In recent years, there have been several incidents of discrimination stemming from race and gender bias in AI,[156,157] and mistakes made by AI through biased data and non-diverse, non-inclusive workforces creating AI algorithms and products.[158] Another issue is privacy in urban environments when facial recognition becomes widespread and in smart communities where the activities of individuals are tracked.

The fact that AI decisions cannot be accounted for and explained to or interpreted by humans is also a major concern. There is a pressing need for decisions made by AI systems to be easier to explain and interpret. Key to solving these problems are approaches like conveying AI intermediate decisions in a manner that is understandable to humans and providing justification for final decisions.[159] A related issue is a need for privacy-preserving AI (e.g., differential privacy mechanisms in which AI models when the underlying data is subject to privacy constraints).[160] At a more fundamental level, today's AI technologies cannot determine causality (e.g., going beyond finding patterns in data to understanding causal relationships to answer questions about why particular outcomes are occurring), resulting in Explainable Artificial Intelligence (XAI).

Robustness, Resilience, Security, and Privacy

Society is becoming ever more dependent on digital technologies and infrastructure. As a result, the negative impacts of damage to or a loss of this infrastructure, or a loss, damage, or misuse of data, are become potentially more significant.[161–163] There is a pressing need for more research and policy work to improve the robustness and resilience of physical digital infrastructure against accidents, extreme weather events, and malicious acts, either by physical means or by cyber-attack. Similarly, urgent attention needs to be given to

protecting data of all kinds, including private and personal data.

Growing Environmental Impact of Digital Technologies

Today's digital infrastructure, including data centers and telecommunications networks, consumes approximately 10% of the world's electricity.[164] Some of this energy consumption is offset by savings in other areas, such as reduced travel by telecommuters. In addition, continuous advances in digital technology lead to the rapid obsolescence of the hardware underpinning the global digital infrastructure and end-user devices. The resulting large volume of e-waste across the world is a major environmental issue.[165,166] There is a lack of global attention to these two related environmental impacts of the Digital Revolution.[121,122]

4.B CRITICAL TRANSITIONS AND THEIR IMPACTS

Analysis of the complex global landscape of digital technology research capacities and current policy priorities indicates significant impacts to the Digital Revolution stem from five Critical Transitions: environmental changes, demographic shifts, rising inequality, emerging infectious diseases, and rapid technological advances.

The Digital Revolution is driven by the need for advanced, secure, and resilient infrastructure in the face of system shocks due to extreme weather events, health crises, geopolitical conflicts, and the rapid development of digital technologies. At the same time, the rapid development, distribution, and adoption of digital technologies are driving key developments in human rights, inclusiveness in society, privacy, data transparency, algorithmic fairness, ethics, and a changing societal landscape.[1]

The S20 Digital Revolution Task Force explored evidence of how the resulting impacts from these emerging critical transitions might be mitigated or achieved through advances in digital technology research and policy and the application of structured Foresight approaches.

The following report sections examine the potential impacts of these key critical transitions on the Digital Revolution and assess our capacity to predict, develop, and execute effective, cross-cutting digital technology research and policies.

4.B.1 RAPID TECHNOLOGICAL ADVANCES

As we have seen, rapid advances in readily available technologies have led to considerable benefits to society. But there have also been negative consequences. One particularly significant example is the emergence of deeps fakes, rapidly and widely spread misinformation, and fake news. There has been a dramatic rise in algorithmics to generate and disseminate fake identities and misinformation. Online algorithms can be manipulated to disseminate misinformation, limit access to factual data, and cause permanent damage to data. This affects how humans perceive new information: data credibility and accuracy can become questionable and lead to social unrest. Such interference might reinforce certain views and suppress any opposing positions. This kind of activity could be exacerbated during geopolitical conflicts where it becomes especially difficult to validate information and identity.

Rapid technological advances have also resulted in an over-reliance on digital tools and platforms, increasing the digital footprints of governments, institutions, and individuals. This is creating another critical vulnerability for the Digital Revolution that is specifically affecting data. We are witnessing an increasing frequency of cyberattacks, data theft, and fraud, which in turn increase the threat to an organization›s or a country›s valuable assets such as data, money, and critical infrastructure. They also reduce trust in the digital infrastructure. Recent cyber-attacks worldwide have left individuals and organizations more aware of the importance of cybersecurity, privacy, and data protection.

Rapid technological advances have also illuminated an ongoing problem of digital literacy, and the COVID-19 pandemic has further increased awareness of the importance of a minimum standard of digital and cybersecurity literacy among citizens and highlighted data security and privacy tradeoffs. It has also incentivized organizations to collect and share a large volume of data with researchers and analysts to provide a better understanding of COVID-19 and future pandemics. This has accelerated the deployment of solutions for COVID-19 related data collection and remote data handling. In general, however, governments, organizations, and individuals are not equipped for such rapid transformation to digital tools and platforms, many of which are vulnerable and may not comply with data security and privacy regulations.

Rapid technological advances also couple with geopolitical conflicts to reduce trust between countries, raising the potential for state-backed cybercrimes, data thefts, identity misuse, and leaks. This will increase the reliance on decentralized solutions (e.g., SSI and other blockchain solutions). Interstate tensions can slow down the advancement of data sharing in «going FAIR» (Findability, Accessibility, Interoperability, and Reuse). In the context of data governance, adopting the wrong public policies is almost as dangerous as not having any. In circumstances where there is a major failure of digital infrastructure (e.g., due to natural and made-made disasters), it can be challenging to prevent cyberattacks and maintain the confidentiality, integrity, and availability of the data.

4.B.2 ENVIRONMENTAL CHANGES

Extreme weather events, whether natural or man-made disasters, can lead to more extreme connectivity disruptions. Terrestrial telecom infrastructures are particularly vulnerable to weather events, and it often takes a long time to rebuild this infrastructure once it is destroyed. This typically leads to a quick and sudden loss of essential information and communication technology (ICT) services that are taken for granted. As such, places and regions frequently affected by natural disasters must make significant efforts to develop technologies that give rise to resilient telecommunication networks. In addition, these extreme but rare events offer potential opportunities for better prediction of these events through IoT sensors and AI-based predictive models and the development of more resilient networks with robust performance. Furthermore, extreme events are an additional incentive to develop technologies to connect the unconnected since these same technologies can be deployed and can serve in emergency and disaster situations.

4.B.3 DEMOGRAPHIC SHIFTS

Major demographic shifts are contributing to an ever-changing societal landscape often amplified by socioeconomic divisions caused by geopolitical factors (e.g., involuntary migration), climate change effects (e.g., water and food scarcity), and environmental disasters (e.g., forest fires and Earthquakes). For example, the ongoing COVID-19 pandemic has changed the professional landscape of many public and private organizations. In addition to causing unusual levels of unemployment and under-employment, it gave rise to a large increase in tele-work (i.e., working from home) which has been facilitated by progress in ICT, digitization of paperwork, and ease of data privacy and associated compliance regulations.

Digital technology is the biggest driver of this societal change. Internet-enabled social platforms are becoming increasingly popular and are changing society's norms; for example, privacy is changing quickly. Digital technology has also created new industries (e.g., Uber and Airbnb) and digitally skilled occupations. For example, digital technology is affecting how healthcare is structured and administered via increased use of telehealth consultations and virtual aid. The COVID-19 pandemic has further accelerated this change, causing shifts in the professional landscape via job elimination and outsourcing that particularly affect vulnerable groups such as women and some groups of unskilled workers.

Another demographic shift driving change is ongoing, rapid urbanization. By 2050, we expect 7 billion people or two-thirds of the world population to live in urban environments. Increased migration to megacities caused by environmental and geopolitical factors affects the already underserved rural areas and causes a heavy load on urban operations and resources. A sustainable solution to this ever-growing challenge is to transform environments digitally to create smart cities. Approaches include developing greater public transportation options to combat city congestion, pollution, and parking scarcity and the deployment of autonomous and semiautonomous vehicles. This solution also includes smart grid technology and enabling renewable energy production (e.g., wind and solar production) to bring improved security, reduced peak loads, and lower operational costs.

Financial burdens and legacy systems could prevent countries from developing and upgrading smart cities. International conflicts and competitions could impede knowledge sharing and the advance of digital transformation across borders, preventing equitable development of smart communities.

4.B.4 RISING INEQUALITY

One of the significant challenges worldwide is to eliminate the Digital Divide by developing the wide availability of broadband connectivity and provide access to genuine information. Eliminating the Digital Divide will require reducing variability in internet connectivity across regions and countries while concurrently increasing the level of and access to knowledge and training in digital technologies worldwide. The problem is primarily one of economics—the low average revenue per user of broadband services slows down the development of the Digital Revolution in regions where incomes are low. However, the ideal of broadband access for all is a goal worth pursuing given the large number of people that could benefit from being connected in order to have access to (i) distribution of food, (ii) transfer of financial benefits, and (iii) monitoring of employment opportunities. This also presents an extra incentive to invest in technological solutions that affordably connect the unconnected.

Unfortunately, we are witnessing the emerging impacts of broader social divides on access to and use of digital technologies. Furthermore, a skilled workforce shortage in low-resource regions may further impede the introduction of some technologies (e.g., smart homes and smart mobile applications), increasing both digital and social divides. These problems are likely to be further exacerbated in low-resource regions of the world subject to extreme events.

4.B.5 EMERGING INFECTIOUS DISEASES

The ongoing COVID-19 pandemic has highlighted the importance of access to reliable broadband internet connections. The unusual significant increase in demand on networks has led in some instances to a reduced overall quality of service and stretching bandwidth limits in certain residential areas. On the other hand, the massive move on-line during COVD-19 has helped people and governments to understand the importance of reliable and secure connectivity for (i) fighting the pandemic (e.g., monitoring the spread via electronic tracing, healthcare automation, and virtual education and conferencing) and for (ii) supporting the economy (e.g., via telework, automation of industries and supply chain, and e-commerce).[145,138] This has also accelerated, globally, the short- and long-term plans for upgrades to currently available infrastructure and deployment of additional infrastructure to sustain network traffic demands and improve the connectivity services for e-learning, e-health, tele-work, and other applications.

4.C CHALLENGES

Scientists and policymakers will need to overcome significant challenges as they navigate critical transitions on the pathway to achieving universal connectivity, sustainability, security, and resilience. Informed by analysis of the digital technology trends and anticipated impacts, the S20 Digital Revolution Task Force identified a set of priority challenges that may be effectively addressed through cross-sectoral research and policy solutions advancing digital technologies.

In the following sections, these challenges are assessed, and potential solutions are identified in the context of the global spectrum of institutional, political, technological, financial, ethical, and environmental frameworks, and with attention to the barriers and opportunities for international collaboration across the G20 nations.

4.C.1 INSTITUTIONAL

Across G20 nations, there is a significant lack of standardized policies, protocols, organizations, and institutional frameworks to advance digital technologies while ensuring that public values are maximized. For example, a lack of standardized frameworks for data collection and sharing slows the implementation of effective data management and governance. Similarly, there is a lack of proactive steps being taken to create educational, training programs, and professional degrees on technologies that underpin the Digital Revolution and the management and governance of data. Solutions to these challenges can be difficult due to the complexity of the systems. Some decentralized approaches are needed, but increasingly focused international collaborations are also important.

A variety of institutional barriers are holding back the implementation of digital technologies in society. For example, officials associated with the planning and management of smart communities and smart cities are often unaware of the benefits of using the IoT and digitally interconnected infrastructures. They are not working as effectively on developing smart infrastructure as they might. Similarly, due to the limitations in adequate skills, experiences, and resources, experts in next-generation devices are expensive and hard to find. As a result, small businesses and municipal authorities prefer to use older technologies.

Another institutional challenge facing the introduction of advanced digital technologies is the question of managing expectations. An example is in AI: unsubstantiated claims over its potential may encourage implementing AI in domains where it is not suited. In turn, failures cause disappointment and a lack of trust in the real promise of this technology. Similar challenges occur in some public health initiatives, such as the recent introduction in many countries of smartphone applications for contact tracing of people who contract COVID-19. Some of these applications have been less successful than initially expected, resulting in negative reactions from the public.

4.C.2 POLITICAL

Politicians are not always aware of the primary importance of the underlying technologies that drive the Digital Revolution or the dynamic nature of technology innovations. In this context, limited budgets and high-priority needs are severe constraints for governments to invest more in advancing these technologies. There is often a lack of political will to support innovations such as new broadband telecommunications infrastructure or smart community developments, which may demonstrate few immediate advantages over standard technologies and may require a timeframe that exceeds the electoral cycle. Critical issues such as broadband policies and radio frequency (RF) spectrum allocation have become politically charged in some countries, with attitudes, policies, and decisions divided along party lines. This has led, in some cases, to non-coherent divergent policies. Policy initiatives for data privacy and how to use data are other areas where attitudes and actions often diverge along party lines. In general, there is a need for cross-party agreement on approaches to improving infrastructures, collecting data efficiently, avoiding data loss, defeating security threats, and handling big data-related technologies. International collaboration is also important because our digital society does not stop at the borders of countries.

One problem is that policymakers sometimes think a particular solution is not possible due to a lack of detailed technology knowledge. For example, differential privacy mechanisms are hard to grasp, but they do work well, and they are needed.

Another concern expressed by some politicians is the potential political contribution of incorporating digital technologies, especially those based on Artificial Intelligence, on the displacement of jobs and the worsening of the income inequality gap.

4.C.3 TECHNOLOGICAL

In many G20 countries, there is insufficient interaction between university laboratories working on digital technologies and solutions and the industrial sector that builds commercial digital products. This lack of interaction is holding back the advancement of some technologies. Part of the problem is cultural in that university laboratories tend to work on more esoteric and long-term aspects of some technologies, while industry tends to look for technology innovations that solve immediate problems and generate a revenue stream. Another problem is a lack of adequate infrastructure in university laboratories. A related problem is that many universities and companies have difficulty in finding the talent they need. This problem is so acute that it might even result in geo-conflicts and discrimination in situations where some people are not welcome, whereas talent is.

While Big Data and algorithmic processes are used to solve problems in business, government, and the broader community, their use for automated decision-making raises concerns that many of these solutions are impervious to the impact on the users affected. This lack of transparency and the appearance of unfairness risk damage to meaningful analysis and accountability and is one of the key challenges facing the widespread integration of digital technologies into the fabric of society. A related challenge is to ensure fairness and evenness of opportunity to all people affected by the Digital Revolution and avoid incorporating bias, political orientation, and discrimination into algorithmic systems, either inadvertently or intentionally.

The public value issues of fairness, accountability, and transparency are especially relevant to AI. AI can provide recommendations, but automated AI processes cannot explain their decisions to humans. While this is acceptable in certain situations with high degrees of uncertainty and technical complexity, such as cybersecurity, the ability to explain AI outputs is vital in domains where members of the public are intimately involved in the process, such as finance, banking, and healthcare. Second, due to the ever-growing need for distributed databases (e.g., to maintain the privacy of user data and reduce the impacts of unauthorized access), the need for more capable distributed AI learning is rising.

As noted earlier in this report, there is a growing need for more interdisciplinary work on the application of digital technologies in society in which public values and user-centric development are taken as a starting point. Indeed, a new technological innovation that is not easy to use or does not adhere to the societal and user requirements may become a technological failure. Undertaking more interdisciplinary research is essential in smart communities, where the impact of digital technologies is highly visible to the public.

Finally, applications using AI and robotics can be quite vulnerable to adversarial attacks. As the Digital Revolution advances, society has an increasing reliance, perhaps even an over-reliance, on digital infrastructure that is assumed to be always working perfectly. One often-cited example is the potential of disruption of critical infrastructures, such as manufacturing systems relying on robotics, the electricity network, and transport systems. Another is the image classification scheme in self-driving cars, which could be tricked by interference with road signs. The solution here is improved defenses against cyber-attack. In fact, defense against cyber-attack is a critically important topic central to the orderly future of the Digital revolution.

4.C.4 FINANCIAL

Investment in infrastructure to connect people in remote areas or with low average revenue per user is often economically unviable. Another challenge is that the diffusion of new technologies is often delayed in developing countries, which creates difficulties in implementing up-to-date systems. Providing connectivity to rural, remote, and low-income areas should not be considered a burden and a challenge to developed societies; instead, it should be viewed as a great humanitarian opportunity to improve access to critical resources such as health and social services.

On another front, funding typically follows the attention a humanitarian effort would generate: the initial investment could end up funding ideas to improve connectivity in dense or lucrative urban environments. Therefore, there should be an increase in investments and research funding in this strategic area using subsidies from the government or long-term alliances between government and companies.

Developing smart communities is financially challenging, as there is a need to demonstrate the return on investment (ROI) and show how it is rewarding to pursue on the economic level.

The high costs associated with technology development and deployment, together with the long gestation period of some advanced technologies, means that some advances take a considerable time to find their way into practical application. In general, there is a need for more sustainable financial resources to support research, development, and deployment of digital infrastructure. In this context, COVID-19 has had a substantial negative impact on R&D budgets. Due to the high cost of developing smart communities, there are few investments in digital services and tools related to smart communities at this time.

4.C.5 ETHICAL

As pointed out above, public values are centrally important to considerations of the Digital Revolution. Among these values are ethics. Ethical challenges considered by the Digital Revolution Task Force include AI-based decision-making in life-threatening or life-altering situations, such as credit lending, medical diagnosis, collision avoidance in autonomous vehicles, and mass surveillance and its implications for criminal justice. Automated-decision systems must avoid unethical outcomes, including bias, discrimination, and privacy invasion. Without having the proper controls in place, AI can amplify pre-existing biases or even introduce new ones. Arguably, humans should remain in control. The concept of "meaningful human control" of AI is a way to deal with the adverse effect of AI and is one way to avoid some of the ethical problems associated with AI.

Other examples of unethical practices are cyber-attacks, theft of private information, and the generation of fake news content. One difficulty here is a lack of standard definitions of privacy and ethics across different cultures and differing attitudes to balancing privacy issues, approaches to information sharing, and public good when adopting technology.

Ethical issues related to smart communities are dependent on opportunities to exchange data among populations. Public concerns about surveillance systems highlight issues related to privacy, data protection, and security. Some members of the public are also concerned about possible health issues associated with wireless technologies. In addition, there are no global and uniformly accepted ethical norms and rules that can be applied nor any agreements on the ethical implementation of smart communities.

A final area of ethical challenges in the Digital Revolution is environmental. Digital technologies consume large amounts of electricity, which in turn contributes to climate change. Therefore, a key challenge is to design, implement, and deploy new digital services with a focus on minimizing their environmental footprint. These challenges range from the design of energy-efficient data centers and communications networks to developing low-power computing techniques for AI and other data processing. A related challenge is to minimize e-waste that accumulates worldwide as technology service providers and consumers move from one generation of electronic devices to the next.

4.C.6 INTERNATIONAL COOPERATION

Global trade disputes and wide gaps in technological maturity among nations cause fragmentation and fractures in technology standardization efforts. This could lead to multiple standards for technologies, thus depriving the world of the benefits of economies of scale.

The availability of network hardware, software, bandwidth, and end-user devices like laptops, mobiles, and tablets at affordable cost could be adversely affected by a lack of international cooperation. Therefore, digital connectivity infrastructure planning should be done by keeping international cooperation in mind and implementing the UN Sustainable Development Goals roadmap for digital connectivity for achieving universal connectivity by 2030.

Smart communities are adapted to local conditions. However, international cooperation may improve smart communities in different countries. Today this cooperation is limited as there are substantial differences in technological developments, making it difficult for countries to cooperate due to market competition and the lack of trust. This may lead to segregation of data movement and lack of interoperability, hindering smart communities› development rather than enabling it. Moreover, the difference in protocols and connectivity management and the confidentiality of high-end technologies, because of their potential use in military activities, increase the challenge.

Fostering a spirit of cooperation across countries can be challenging when there exists a general perception of an ongoing "AI race" to attract talent and even a cyber-war to seize intellectual property rights and use the technology for purposes that are not universally agreeable, such as surveillance and lethal automated weapons, instead of focusing on improving the welfare of humankind. The challenge can be particularly severe when ethical matters are perceived differently in different societies. This lack of cooperation is a major threat to the progress of this field.

4.D RECOMMENDATIONS

Five Policy Recommendations and corresponding Policy Actions aim to maximize the benefits of the Digital Revolution to benefit the global community.

4.D.1 BRIDGE THE DIGITAL DIVIDE

RECOMMENDATION

Bridge the emerging digital divide by developing policies and actions to ensure that all people on the planet have access to digital technologies and, the Internet.

RATIONALE

The COVID-19 pandemic has highlighted the digital divide in our society between those who have capability and have access to digital technology, especially the internet, and services enabled by it, and those who do not. Internet access is a basic or fundamental right for every citizen. Narrowing the gap between the 'haves' and the 'have nots', between the under-connected regions and hyper-connected regions is, therefore, a critical challenge.

POLICY ACTIONS

1. Promote inclusive education and literacy programs to ensure digital education opportunities for all, especially for women, and assist disadvantaged communities in participating in the digital economy.
2. Develop ICTs suited to deployment in disadvantaged communities and regions with limited infrastructure.
3. Promote international strategies to encourage funding of broadband connectivity and digital infrastructure for those people and communities that are presently not serviced.
4. Develop end-user devices that operate effectively in remote locations and areas with limited access to the power grid.
5. Develop strategies to use digital technologies to promote equity in education and economic development opportunities across the globe.
6. Establish international strategies to close the technology gap in less-developed countries by the exchange of expertise and knowledge services.

4.D.2 ENHANCE GLOBAL LINKAGES IN DIGITAL TECHNOLOGIES

RECOMMENDATION

Establish a global platform to enhance collaboration in the field of science and technology to accelerate exchanges of data and facilitate advances in digital technologies.

RATIONALE

Collaborations across nations are critical to the development and implementation of digital technologies. While there are significant commercial investments in digital technologies, there are gaps in the funding for certain technologies and a lack of international collaboration and sharing of data across borders. To accelerate the Digital Revolution, it is critical to define how data is collected, processed, secured, shared, and destroyed.

POLICY ACTIONS

1. Promote sustainable financing programs that enable technical and economic collaboration between universities and research institutes at the international level.
2. Promote greater funding for international research and development projects that focus on the development of open-source platforms and interoperability between technologies.
3. Develop simplified and internationally accepted approaches to standards and policies for data collection, protection, sharing, processing and destruction among different parties, such as governments and the private sector, with clear enforcement mechanisms while accommodating differing cultures and policy priorities among nations.
4. Promote open data access in government and private sectors by establishing frameworks for data collection, analysis, and access, while protecting the privacy and personal information of individuals.
5. Support initiatives for data sharing and building testbeds and allow for collaborations in real-world application settings.
6. Encourage development and adoption of AI regulations or development of a Global Artificial Intelligence Association (GAIA) through interdisciplinary research to ensure human safety, standardized liability and accountability, and governance laws while considering ethical, legal, and potential for inappropriate use of AI systems.

4.D.3 EMBED DIGITAL TECHNOLOGIES ACROSS ALL OF SOCIETY

RECOMMENDATION

Plan for a future digitally enabled society, in which digital infrastructure is seamlessly and ethically embedded across the entire social, political, business, and cultural landscape in a way that enhances public values, preserves individual freedoms, and protects against disinformation.

RATIONALE

There is a growing need for businesses and governments to take sociological and ethical considerations into account when developing digital technologies and related policies. For example, AI is increasingly being deployed to make crucial decisions that affect human beings, such as in e-health, and digital services are increasingly impacting people as they go about their daily lives. Similarly, the spread of disinformation across digital platforms has the potential for major societal disruption. It is becoming imperative that digital technologies and their applications are co-designed with relevant social and cultural considerations.

POLICY ACTIONS

1. Support value-sensitive design (VSD) principles, in which public values like transparency and fairness, are embedded in the design from the start.
2. Support funding for multidisciplinary research into societal aspects of digital technology, interlinking social sciences, the humanities, ethics, engineering, and natural and computer sciences.
3. Enhance the quality of digital education and training for all stakeholders, from the public to the workforce and decision-makers and define and enforce a compulsory basic level of digital and cyber literacy in all educational curricula.
4. Develop strategies to address the societal impact of the use of digital technologies such as AI, facial recognition, drones, and 5G as well as concerns about negative health impacts from wireless technologies and potential unemployment due to widescale automation.
5. Develop technologies and processes that facilitate rapid detection and blocking of deep fake, fake news, and disinformation.
6. Invest in research and development of trustworthy and explainable AI (XAI) in critical domains, such as finance and healthcare.
7. Develop methodologies and protocols for the incorporation of ethical behavior into automated systems such as AI, autonomous vehicles, robots, and related technologies.

4.D.4 REDUCE VULNERABILITIES IN DIGITAL INFRASTRUCTURE

RECOMMENDATION

Reduce vulnerabilities and enhance the security, robustness, and resilience of current and future digital technologies and infrastructure.

RATIONALE

Existing digital infrastructures are vulnerable to all kinds of disruptions, including pandemics, climatic disasters, and cyber-attacks. It typically takes a long time to rebuild this infrastructure once damaged or destroyed. Despite the strong need for resilience, most nations refrain from investing in building more redundancy into networks, as that would require significant investments as well as political will, while the results of such investments may not be tangible.

POLICY ACTIONS

1. Leverage the scientific community in developing plans to upgrade current digital infrastructure, and deploy additional infrastructure (e.g., low orbit satellite internet) to sustain increasing network traffic demands and improve the connectivity services for remote digital services

(e.g., e-learning, e-health, home office) along with contingency plans to ensure continued availability, even during disruptions.
2. Enhance the infrastructure to quickly recover from disruptions and failures and to be resistant against cyber-attacks.
3. Dedicate more resources to promote research and development of robust and resilient AI algorithms that are less susceptible to random failures and malicious attacks.
4. Support research and development of more robust cryptographic protocols and regulations to protect sensitive and private digital information.
5. Expand research into cybersecurity and promote international cooperation on work to defend against cyber-attacks.

4.D.5 IMPROVE ENERGY EFFICIENCY AND SUSTAINABILITY OF DIGITAL INFRASTRUCTURE

RECOMMENDATION

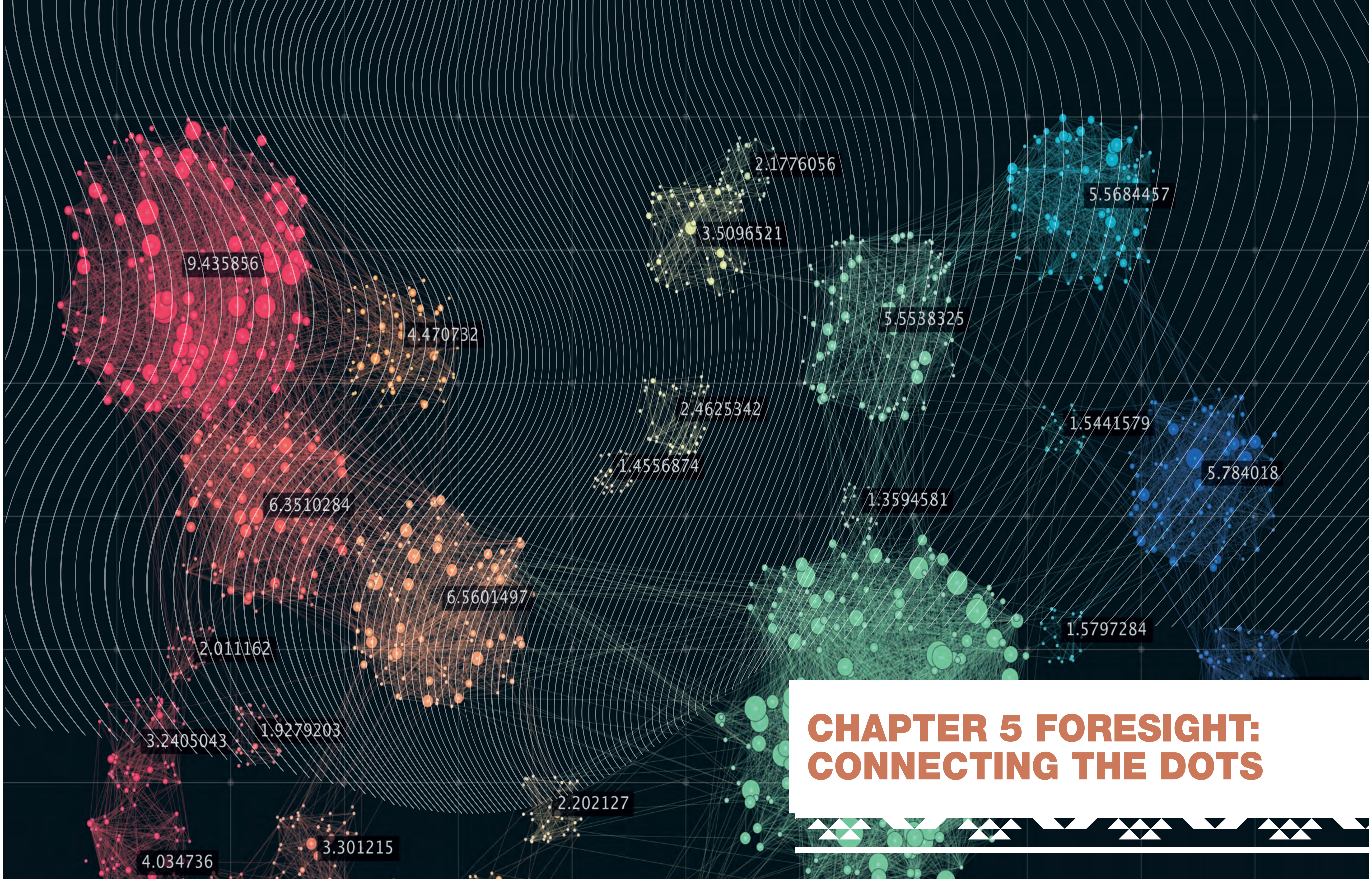
Improve the energy efficiency of digital infrastructure, including end-user devices, reduce the volume of electronic waste through cradle-to-grave lifecycle considerations, and improve opportunities for digital technologies to contribute to a cleaner environment and greenhouse gas reductions.

RATIONALE

The global digital infrastructure and the associated billions of end-user devices consume vast amounts of energy and make a significant contribution to global greenhouse gas emissions. Smart cities are helping to reduce energy consumption by adopting smart technologies for better management and operation of the urban environment and transportation. However, these developments are hindered by the many standards and protocols for smart city technologies, many of which rely on proprietary technologies. A lack of interoperability will place financial and operational burdens on city administrators when deploying technologies and could result in closed systems that are difficult to upgrade.

POLICY ACTIONS

1. Accelerate initiatives aimed at improving the energy efficiency of digital technologies and focus on the use of renewable energy sources, where appropriate.
2. Increase commitments to the development of smart cities and smart communities to improve resource sharing and to increase activities aimed at energy efficiency and using electronic resources and applications to reduce overall greenhouse emissions by travel replacement.
3. Promote sharing of know-how, best practices, and experiences in the development of sustainable smart communities among nations.
4. Increase awareness of the advantages of smart communities and encourage government support for building digital infrastructures for smart communities in both rural and urban settings.
5. Provide targeted investment and resources toward developing less intensive computational methods, such as lite AI and edge computing, which would reduce costs and energy consumption.
6. Develop standardized tools and frameworks for continual evaluation of digital technologies to maximize efficacy in their usage and to maximize their useful lifetime.



CHAPTER 5 FORESIGHT: CONNECTING THE DOTS

CHAPTER 5 FORESIGHT: CONNECTING THE DOTS

5.A INTRODUCTION TO FORESIGHT

The coming decades will witness a convergence of multiple transitions for our global society, and these transitions must be navigated correctly if disruptions in economic and political stability are to be avoided. Each of these transitions is a challenge, yet there are also key synergies and interconnections between these transitions that must be carefully appreciated. These key transitions and their interconnected complexities compel G20 attention and foresight planning.

The need for the G20 to focus on foresight planning is not new: the G20 was founded in response to Critical Transitions affecting the G7 and, in turn, the entire global community.[167] In 1999, in the wake of five years of country after country failing to pay its debts, the G7 agreed to meet the crisis by extending direct coordination and consultation to the ministries of finance from twenty leading economies.[167] Nearly a decade later, the interconnected global financial system was disrupted by the financial crisis of 2007-08, with international financial institutions facing insolvency and the economies they supported facing collapse. In response, the G7 expanded its coordination of finance ministries across twenty countries to full consultation and coordination across governments: the G20 was established.[167]

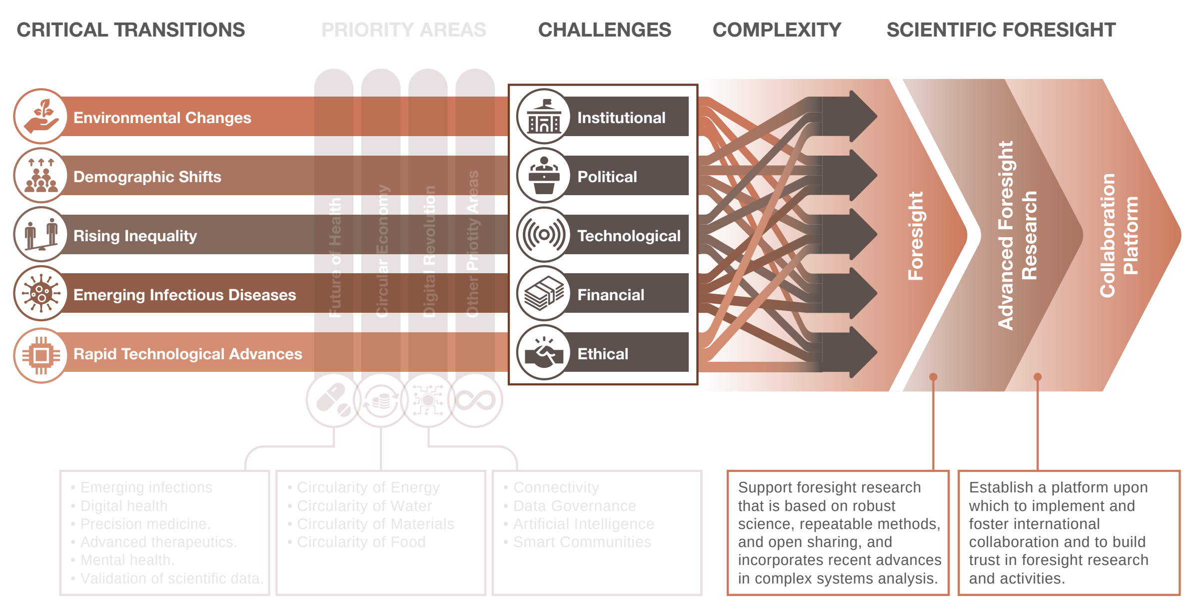


Figure 5.1: The S20 Foresight Framework for analysis, highlighting the Foresight priority area and its components of analysis.

The G20 was therefore founded in response to Critical Transitions with a goal not only to coordinate response and mitigate consequences of harmful Critical Transitions but also to mitigate the occurrence of harmful Critical Transitions and drive the development of beneficial Critical Transitions. This concluding chapter of the Report argues that the mechanism by which the G20 will accomplish these goals is by embracing and improving the world's capacity to apply foresight. To chart that path, the chapter reviews the challenges presented by Critical Transitions and the role of foresight in addressing those challenges. Current foresight methods, gaps in methods, and the state of the use of foresight are analyzed to develop actionable recommendations.

5.B CURRENT FORESIGHT METHODS

Foresight starts from a belief in human self-determination and freedom of action: the future can be actively influenced, built better, or even entirely re-created. For the purpose of discussion, we begin with a succinct definition:

Foresight is a collection of plausible stories of the future based on creative engagement with a diverse group of stakeholders that is used to guide decision-making and mobilize action.

This provisional definition highlights three key elements that characterize foresight work. First, foresight aims to explore plausible, alternative futures and identify their challenges and opportunities. Plausibility stems from taking into account technological, economic, environmental, political, social, and ethical factors. Foresight helps us understand the forces shaping a system, how the system could evolve, and what surprises could arise. There is not just one future, but a range of alternative futures and the stories we tell each other about the future generate cultural resonances as deep as the stories we tell ourselves about the past. Such analysis provides a valuable context for developing policies and strategies that are robust across a range of plausible futures. It also provides a solid foundation for building a vision of the future.

Second, a foresight process demands engagement with and active participation by individuals and groups with a wide range of skills and perspectives. Cross-fertilization of ideas, and democratization of the process, enrich the visions of the future, breaks the constraints imposed by the past, and confers legitimacy on the outputs of the process.

Third, foresight processes should be aligned with action implementation and monitoring of outcomes. Visions of the future must be brought into sharp nearer-term focus to identify policy actions that work to bring about the future we wish to see. Foresight provides a context for strategic management and coherence of policy across governments and organizations. Foresight identifies risks and opportunities to innovate and helps to prioritize policy actions and adapt current operations to increase resilience in the face of the range of futures envisioned.

The objective of this section is to lay the theoretical foundation for further and more in-depth analysis of the selected world trends in the following section. To meet this goal, it is expedient to review the meaning and importance of the terminology of foresight and global trends.

Foresight is a purposeful process of developing knowledge about the future of a given unit of analysis or a system of actors, which is aimed at action in the form of public or private policy making, strategizing and planning, and that foresight is frequently a participatory, involved and collaborative process.

This broad definition of foresight can be broken down into two parts. It could be concluded that "foresight is: 1) an organized social process; an intervention (in an organization), 2) to create actionable and domain/ context-specific information or knowledge about the future." [168]

Foresight is often defined as

...an approach and a process which requires broad thinking and results in the generation of multiple scenarios and ideas. Some of these ideas must then be further developed and implemented into policy and subsequent action.[169]

The European Foresight Platform[170] further describes foresight work as

...a conceptual framework for a number of forward-looking approaches to informed decision making that includes long term considerations". Alternatively, it was defined as "a systematic, participatory, prospective and policy-oriented process which, with the support of environmental and horizon scanning approaches, is aimed to actively engage key stakeholders into a wide range of activities "anticipating, recommending and transforming" (ART) "technological, economic, environmental, political, social and ethical" (TEEPSE) futures.

We, therefore, propose a working definition of Scientific Foresight for this Report:

Scientific foresight is a structured, systematic and participatory process, using the scientific method, to explore multiple alternative visions of the future, taking into account technological, economic, environmental, political, social and ethical factors to guide and inform present-day decisions and mobilize actions

The methods for Scientific Foresight can be broadly organized along two axes: firstly, the level of subjectivity that the method allows compared to the use of evidence, and secondly, the reliance on expertise versus the degree of interaction between (for example) a set of stakeholders.[171] Consideration of the interplay between these two elements allows the organization of a wide range of foresight methods into the 'Foresight Diamond.'[172]

An example of a common foresight method is "Horizon Scanning", which can be used as part of risk management strategies, emerging issues analysis, and identifying wild cards (events with low probability, potentially high-impact risks). The European Commission defines it as "the systematic outlook to detect early signs of potentially important developments. These can be weak (or early) signals, trends, wild cards or other developments, persistent problems, risks, and threats, including matters at the margins of current thinking that challenge past assumptions. Horizon Scanning can be completely explorative and open or a limited search for information in a specific field based on the objectives of the respective projects or tasks. It seeks to determine what is constant, what may change, and what is constantly changing in the time horizon under analysis. A set of criteria is used in the searching or filtering process. The time horizon can be short-, medium- or long-term.

Therefore, horizon scanning represents a valuable tool for assessing and anticipating future developments. The provisions for horizon scanning can be desk research, automated and semi-automated literature search, bibliometric, patent searches, text mining, science maps, conference scanning, environmental scanning, expert opinions, scenarios, storytelling, matrices, platforms, social media scans, and much more. For example, this method has been used in the King Abdulaziz City for Science and Technology (KACST) to develop strategic intelligence studies and identify/ predict future global science and technology demands and trends. Table 5.1 briefly defines this and other common foresight methods.Foresight methods span a wide range of approaches, driven by the time horizon to be assessed, the topic being analyzed, and the use that will be made of the analysis, in addition to the types of data available and the amount of data available. However, even though the advancements made in foresight methods are significant, there are still gaps that are ever increasing, especially for the application of foresight for critical transitions.

Before addressing these gaps, let us recognize one of the main issues for foresight: the complexity of our modern world. One of the biggest gaps is the oversimplification of the systems under analysis. In a complex system, simple questions about past events, such as the cause of a specific effect, become difficult, let alone questions about the future. Therefore, the first gap is the lack of methods for handling the complexity of interconnected systems.

Foresight Method	Definition	Scale and Mode	Main use
Horizon Scanning	Searching for clues to future challenges in early signals today	Think tanks, policy institutes, universities, regional and national governments, etc.	Guide policy at the national level, e.g., on public infrastructure, education, and contingency planning (pandemics, natural disasters, monetary policy)
Trends analysis	Extrapolation of established patterns	Think tanks, policy institutes, universities, etc.	Resource planning, economics, commerce, communications
Delphi	Repetitive sampling to identify trends, assess commonalities of response, and pool ideas to seek convergence to a consensus	Polling institutions, political parties, private companies	Public policies, fiscal regimes (taxes, tolls & tariffs), market services, establish common assumptions for use in scenario planning
Others: Dynamic Argumentative Delphi	Established boundary conditions and transition forces combined with Delphi surveys to create targeted future scenarios	Universities, Think Tanks, public & private research groups	Public policies, technology projects (public and private)
Others: Scenario Planning	Plausible stories built on known facts plus creative ideas in internally consistent and plausible systems	Finance & defense ministries, technical departments & directorates, project planning	Public policies, major projects (public and private)
Others: Prediction Markets	Aggregation of individual forecasts to improve combined accuracy (mitigate biases, add useful information)	Technical departments & directorates, public institutions, private companies	Public policies, major projects (public and private)
Others: Road Maps	Identification of major stakeholders and network elements in an industry or emerging technology, and outline of possible futures	Technical departments & directorates, public institutions, private companies	Public policies, major projects (public and private), often combined with modeling

Table 5.1: Common Foresight methods

In addition, in recent times, the number of available data sets has grown exponentially. One of the biggest gaps in many of the traditional foresight methods is their inability to fully analyze (quantitatively), integrate, and use the amount of data available. This issue, combined with oversimplifications of the systems under analysis, significantly hinders traditional methods' progress towards critical transition foresight.

Finally, no one method alone can provide foresight; instead, it is the combination of a multitude of methods that has the hope of succeeding. Hence, a significant feature of promising foresight methods is their complementarity or compatibility. Sadly, the results of many traditional methods do not lend themselves to being easily combined to form a cohesive analysis,their quantitative approaches are incompatible and cannot be integrated to form a more robust, insightful picture.

All this is to say that there needs to be more thought put into curating a list of complementary methods that could be combined to help tackle the challenge of foresight, and become a beacon for scientists to rally around, both enhancing and utilizing them more than ever before towards the unified objective of foresight.

5.C THE COMPLEXITY OF CRITICAL TRANSITIONS

As discussed in the Introduction of this Report, Critical Transitions are a rare category of shifts in the state of ecosystems and norms that occur when conditions pass a tipping point. Not all rare events are created equal: Critical Transitions are special because they have a high impact if they occur, cause long-lasting effects, and are unique and different from previous events.

The complexity of the systems involved often drives the shifts occurring with Critical Transitions. Although it is difficult to provide a single definition of a complex system suitable for all situations, typically, a system is said to be complex if it is composed of multiple individual elements but exhibits, or gives rise to, behavior that cannot be understood simply by analyzing the constituent parts themselves. Such behavior is said to be emergent: it emerges at the system level through the interactions among the individual units and cannot be explained simply through analysis of one unit at a time. Couplings between the units give rise to feedbacks, rapid amplification of fluctuations (for example, the bullwhip effect in supply networks[173]), and enable the system to show self-organizing behaviors.

The existence of positive, reinforcing feedbacks allows a complex system to support multiple internal states under the same external environmental driving forces. This is a key observation: in most cases, we assume that knowledge of the external environment uniquely determines the internal system state, but this is not necessarily true for a complex system.

Further difficulty emerges when applying such complex systems thinking to systems containing human actions and responses in addition to the natural environment. In most social and engineered systems, a key source of additional complexity is the stratification of the system into layers that interact with and prescribe the possible behaviors of other layers. Frequently, failures in complex systems that are most visible at the task and technical layer (e.g., airplane crashes) have their origins in failures in the governance or management layers.[174] Understanding the interaction between regulation and oversight mechanisms, corporate management, and operations-level performance is a central challenge in analyzing complex systems involving human actions.

The complexities in the systems in which Critical Transitions occur often result in abrupt shifts. Even gradual Critical Transitions, such as climate change and urbanization discussed in Chapter 1 of this Report, often contribute to and culminate in abrupt shifts. The abrupt shifts can be beyond our control, but our focus here is on the large number of Critical Transitions that human decisions and actions can influence. Critical Transitions can lead to harmful outcomes, and we seek to prevent or mitigate their effects. By contrast, Critical Transitions can be desirable, and we seek to realize and enhance their beneficial impacts.

In the last sixty years, the world has witnessed examples of systems in which complex, interconnected events resulting in abrupt, harmful critical transitions at regional and global scales. In the 1960s, the Soviet Union initiated an agricultural engineering project to increase cotton production that had complex, unintended consequences with global impacts on human health, the economy, and the environment. At the start of the 21st century, the fragility of a regional power system was revealed through a series of interconnected failures that rippled and echoed through the network resulting in catastrophic failure across borders. And as this report is being written, the world is living through a pandemic that has global impacts on health, economies, and international relations.

An investigation of each of these examples shows that the information and analytical methods would have been available to decision-makers to allow them to anticipate and prevent the harmful impacts. Although hindsight is 20/20, Foresight could have been 20/20 as well. Therefore, the case studies below illustrate aspects of Critical Transitions in the domains of health, environment, and digital systems that are directly relevant to the S20 and that must be considered in the development of a vision and actionable recommendations for Foresight.

5.C.1 CASE SUMMARY—COVID-19 PANDEMIC

The ongoing COVID-19 pandemic indicates the challenges faced in developing foresight for the future of health. With international flights transporting people across continents within hours, the virus spread more quickly than could be matched by the global response. Within less than a year, over 56 million people were infected, and 1.3 million had died, with those numbers still increasing. This pandemic impacted most major systems with highly complex interactions and dynamics, including, but not limited to, the health care systems, transportation systems, manufacturing, and supply chain systems, and political and nation-state systems. COVID-19 pandemic emerged unexpectedly in December 2019 and spread quickly. Little was known about the virus, its viral dynamics, or its impacts, most of which are being learned as the events are unfolding. Although the events that triggered the pandemic were difficult to predict, and its spread mechanisms were difficult to control, the viral pandemic's fundamental dynamics and its impacts were possible to model and study in advance. The reality of our negligence to the interconnectedness of the modern world and its systems caught us by surprise, however.

Given the nature of interconnectedness and complexity, the most challenging impacts of the pandemic and the decisions that we continue to refine were independent and far removed from any particularities of the virus itself or its triggering events, as can be noted from the following paragraphs. Representative complex models and analysis could have been conducted in advance, which could have spared the world the need to learn and strategize on the spot.

The capacity of the healthcare system, and intensive care units (ICUs) in particular, constitutes one of the major critical detrimental factors for this pandemic. The risk of death increases non-linearly with the reduction in patient capacity in ICUs. The healthcare system and ICUs are shared systems used to serve COVID-19 patients in addition to other demands. Managing the competing demands for healthcare in these systems requires careful, complex planning and coordination between people and all segments and levels of leadership to control the severity of the damage from the pandemic. Some of the significant measures include attempts to keep the healthcare system operational, quickly increase its capacity, and reduce the risk of infection and spread of the virus.

These decisions have complex interactions and, in most cases, are managed by distributed actors and decision-makers. Public health strategies and shutdowns of major systems represented common strategies for reduction of risk of infection and spread of the virus. However, these same major systems are required to keep the healthcare system operational and needed to drive the needed increase in its capacity. For instance, the transit system, associated with an increased risk of infection, is detrimental in some cities for healthcare workers' commutes. Public health strategies such as the use of personal protective equipment (PPE) prevailed, creating shortages and competitions that required balancing. Several manufacturers shifted production to support the spontaneous increase in demand for PPEs, and sales of these available PPEs required prioritization for frontline workers.

Social distancing and shelter-at-home orders to contain the spread of the virus were widespread across the world. These orders targeted flattening the curve, with the initial hope that restrictions could be eased once that goal was achieved. However, these measures changed the dynamics of virus spread and hence changed the system itself. Easing restrictions destroys the achieved flatness of the curve, creating difficulties for policymakers as they plan to reopen.

Complex temporal dynamics associated with social distancing and shelter-at-home orders were observed beyond the targets of the health sector, the primary sub-theme of the decision. The demand for the transportation system dropped significantly in general, leading to a significant reduction in greenhouse and carbon emissions. On the other hand, consumer behavior and demand pattern shift have been observed across different transportation models, for instance, from public transit to personal vehicles. This behavioral shift is expected to increase congestion on the road and the potential to reverse and exacerbate the initial reduction in congestion and emissions.

5.C.2 CASE SUMMARY—THE ARAL SEA DISASTER

The Aral Sea disaster continues to harm the affected region and illustrates challenges in foresight that are analogous to those faced as nations seek to advance the circular economy to conserve energy, enhance sustainability, and mitigate environmental impacts from industrial activity.

The Aral Sea, located then in the USSR and now spanning the border between Kazakhstan and Uzbekistan, was the fourth largest lake in the world before 1960. It hosted a thriving aquatic ecosystem, represented an important source of seafood for the USSR, and played an important role in the economy of the surrounding communities. The lake's water level was maintained by two primary feeding rivers around an otherwise arid part of the world. Water from these feeding rivers was redirected starting in the early 1960s for agricultural purposes: for irrigation of cotton fields and other crops that require excessive amounts of water to grow. The redirection of feeding water sources to the lake triggered a sequence of complex impacts that soon dried out the lake and transformed the region's livelihood for a long time to come.

Critical transitions can be triggered by human-driven activity, such as large-scale projects and environmental interventions. The Aral Sea disaster is an environmental/agricultural project that dried up a lake, destroyed aqua life, destroyed fertile grounds, destroyed a fishing industry, caused a spread of diseases, and increased mortality rate. In contrast to the COVID-19 pandemic, the Aral Sea disaster triggering events (redirection of water supply to the lake) were humanly controllable (avoidable). The real disaster was in the consequences of this redirection, which resulted from a lack of foresight. As can be noted from the following paragraphs that outline the consequences and their interconnectedness, complex models of this interconnectedness could have provided the foresight to mitigate these consequences or provided guidance for better and more timely interventions.

In this disaster, as the water level in the lake continued to decrease, the surface area of the Aral Sea decreased and was replaced by a desert full of salt. Moreover, the salinity of the water continued to increase. This disruption directly impacted the aquatic ecosystem, the eco-diversity within the lake itself, and the ecosystem in the region. Wind started to carry the dust and salt now exposed from the newly created desert into the surrounding regions. Fertile grounds around the lake started to become infertile. Agricultural regions around the lake needed more water to compensate for the salt they received from the air. To contain the salinity, groundwater was used, causing a significant decrease in the levels of aquifers. Eventually, the lake lost 90% of its original water volume.

People who lived and depended on this lake and its aquatic life were impacted in complex ways too. Air polluted by dust and salt affected people's health: cancer, anemia, hepatitis, and other diseases increased in the population. The child mortality rate reached 75 per 1000 newborn. The decrease in the water level and water quality impacted people's access to drinking water. A significant amount of drinking water was polluted by pesticides and fertilizers. 40% of vegetation around the lake diminished, causing a decline in agricultural productivity. Twenty fish species that once populated the lake disappeared, crippling a fishing industry that once sourced 1/6th of all the fish in the Soviet Union and employed more than 40,000 people.

The impacts of this spread much farther than the areas near the lake. Wind carried salt for hundreds of kilometers and to mountain tops. Agricultural activity within a wide radius was affected, and mountain top glaciers started to melt. For disasters at this scale, once the domino effect is in motion, the cascade is difficult to stop, and the impacts are difficult to reverse. Efforts to restore water levels in the Aral Sea started in the early 2000s. Conditions of the lake on the Kazakhstan side have been improving. However, on the Uzbekistan side, no plans are in motion for restoration. In Uzbekistan, restoration efforts are challenged by a lack of funding and the need for river water for the cotton fields currently central to that region's economy.

5.C.3 CASE SUMMARY—THE AUGUST 2003 BLACKOUT

The global digital revolution is no less subject to foresight challenges than complex environmental systems. Digital, energy, and human systems must operate in concert within operations rooms to ensure safe generation and distribution of power at a country scale. Power system infrastructure is monitored and controlled by supervisory control and data acquisition (SCADA) systems and human operators in the loop. A failure of this interconnected system at a small power generation plant at Eastlake, Ohio in 2003 triggered a cascade failure leading to a power outage throughout the Northeastern and Midwestern United States and the Canadian province of Ontario. The outage affected more than 50 million people for several days.

Critical transitions could blow out of proportion with impacts far removed from the local triggering challenge. The August 2003 blackout was triggered by a computer system challenge at a local power generation station leading to a massive international blackout and a shutdown of most life-critical systems such as water, food, and transportation. At the heart of this was a cascading chain reaction in a feedback loop system. Although this and similar triggering events are routinely foreseen, whether from space weather, terrestrial weather, grid attack, or accidents, traditional foresight methods were challenged by their inability to model the extent of the impact of such incidents and their inability to trace-back the source of an interconnected system shutdown. The following paragraphs describe the propagation of the disaster from the triggering events all the way to the massive damage it caused.

The sequence of events started developing slowly on 14 August 2003, leading to a broken feedback loop between the SCADA system, its alarms, and the human operator. The broken feedback loop blocked the proper handling of a local powerline failure that occurred the same day. This local powerline failure caused a transfer of power load to neighboring power generation stations. This transfer of load initiated a cascade of power-overload tripping within the interconnected power network, which quickly led to the massive blackout that was difficult to stop or recover from. Within a system as large and complex as this digital, energy, and human sub-systems spanned several states and countries: as the events unfolded, no one knew where the cascade of events started or what was causing the blackout. Moreover, the same operators who had to attend to the blackout had to address incoming phone calls reporting the blackout, further depleting available resources to handle the situation.

This cascade failure turned out to be only the beginning of more challenging days to come. The power system itself is interconnected to operate cities and maintain many aspects of modern life. Within large cities affected by the blackout, such as New York City, people were stuck inside or outside their skyscraper homes and offices, for which power-driven elevators were vital. People located at high grounds and cities such as Cleveland, Ohio lost access to water, which is power pumped, and they lost access to toilets and other life-critical infrastructure. Power supported food preparation systems such as microwaves, electric stoves, refrigerators, and freezers affected edible food supply. The transportation system was crippled, and electric powered subway systems, which were vital for several cities, were down. The economy was shut down during this time, and manufacturing depending on electric power to operate lost productivity.

5.D CHALLENGES OF FORESIGHT

Elements of Complex Systems

- Composed of multiple individual elements but exhibits behavior which emerges at the system level through the interactions between the individual units and cannot be understood by analyzing the constituent parts themselves
- Exhibit the existence of positive, reinforcing feedbacks
- Demonstrate stratification into layers which both interact with and prescribe the possible behaviors of other layers
- Includes interaction between regulation and oversight mechanisms, corporate management, and operations-level performance

Informed by the discussion of the current trends driving change in foresight, the Task Force identified a set of key challenges in six main categories for which recommendations and corresponding policy actions need to be developed: institutional, political, technological, financial, ethical, and international collaboration challenges.

5.D.1 INSTITUTIONAL

Institutional challenges include a limited focus on infrastructure encompassing foresight and a lack of collaboration and coordination among relevant stakeholders and authorities at national and international levels. A variety of institutional barriers are impairing the advancement of foresight, such as the lack of scientific research, understanding, and adaptation of foresight in strategic plans and projects.

Another institutional barrier is the limited access to data, intellectual property, and know-how. The lack of data sharing and exchange will slow the implementation of foresight, specifically in less developed countries.

Shortages of an adequately trained scientific workforce were highlighted as the main institutional challenge that needs to be addressed. The Task Force emphasized the need to address the lack of researchers with specialized training and advanced skills to conduct work in the various areas of foresight. This challenge is further compounded by the limited opportunities for international scientific exchange and mentoring. Encouraging governments to invest in training and continuing education opportunities for early career researchers is one way to address this challenge.

The limited investment in infrastructure to implement foresight technologies continues to be a significant challenge in many countries. A compelling case for the return on government investment in expanding the infrastructure to support the implementation and use of foresight technologies needs to be made to address this challenge.

The lack of institutional commitment to long-term planning and preparedness was another challenge highlighted by the Task Force. Limited and uncoordinated funding and research support to meet institutional foresight needs and limited training opportunities in foresight science and methods were highlighted as key factors contributing to this challenge. Education and training opportunities are needed to build institutional capacity in foresight methods and best practices. Additionally, there is a need for heightened awareness of the necessity of aligning institutional long-term strategic plans with foresight insights.

5.D.2 POLITICAL

Difficulties in resource allocation and prioritization decisions were the primary political challenge identified. Scarcity of resources, competing priorities, and frequent changes in governments and mandates further complicate this challenge by restraining policymakers and planners' ability to integrate foresight into long-term strategic plans.

Unclear policies and uncertainties in the regulatory environment around new technologies, in general, are an additional, significant challenge. The uncertainty among policymakers concerning whether to support these technologies and their reluctance to develop policies to regulate their development and use can hinder the speed of scientific progress in these areas. Open and frequent communication between researchers and politicians about the implications of advanced foresight technologies for patients and societies is needed to properly educate policymakers about the potential risks and benefits involved. This will allow the policymaker to expedite the decision-making process when developing policies that would govern the advanced foresight field.

5.D.3 TECHNOLOGICAL

Although the methods used for foresight have been adapted to analyze varying time horizons and subjects using a range of data quality and serving different goals, there are still significant methodological challenges, especially for the application of foresight for critical transitions.

One of the main challenges is the complexity and interconnectedness of our modern world faced with a limited toolset of foresight approaches (as shown in Table 5.1), which often leads to the oversimplification of the systems under analysis. In a complex system, simple questions about past events, such as the cause of a specific effect, become difficult, let alone questions about the future. Therefore, the first gap is the lack of methods for handling the complexity of interconnected systems.

Given the complex interconnectedness of today's world and the ever-increasing enhancements and adoption of IoT smart city technologies, which produce an immense amount of data, in order to predict something about any part of a city (e.g., critical impacts of renewable technology adoption), far from critical transition foresight, you would need to expand the definition of what is or isn't exogenous and include a large number of systems (socioeconomic, future energy requirements, and even future climate trends) to have a somewhat accurate prediction. Traditional foresight methods do not suitably handle the complexity of these interconnected systems, neither are they able to fully harness the immense data produced by all of the various infrastructures, and it is a challenge to combine their results in a cohesive way to be applied to the problem at hand.

Another big challenge in many of the traditional foresight methods is their lack of suitability for quantitative analysis. The traditional methods supporting quantitative analysis are challenged by the recent exponential growth in available data sets. This issue, combined with oversimplifications of the systems under analysis, significantly hinders the progress that traditional methods can make towards critical transition foresight.

Many developed foresight approaches and methodologies are not actually advancing the field of foresight as their repeatability is questionable due to the lack of providing adequate structural information and details. Reproducibility of foresight research and methodology can be improved by promoting transparency of the research process and practices. Furthermore, developed countries need to be motivated to share and publish foresight experiences with developing and emerging countries.

Last but not least, no single method alone is capable of providing foresight: multiple methods must be combined in order to succeed. However, the traditional methods do not lend themselves to be easily combined with the results of one another to be combined into one cohesive analysis, i.e., they don't have quantitative synergies that could allow their analyses to be integrated together easily.

5.D.4 FINANCIAL

Advancing Foresight requires investment in data acquisition, R&D, and diffusion of practice. Data acquisition encompasses various endeavors such as remote sensing, online data gathering, and macroeconomic tracking and reporting. In almost all cases, the data used in Foresight is a byproduct of collection for other purposes. While in one sense this may appear to lower the cost of Foresight, significant expense is involved in adapting this "second-hand" data to the needs of Foresight, and investment is needed to gather data for Foresight where gaps exist.

Likewise, Foresight research and development (R&D) requires significant investment as a dedicated pursuit. Foresight methods and the technologies to use them are often created for research with goals other than Foresight. This is complicated by the lack of financial incentives and direct support for research collaborations across public and private sectors. The lack of dedicated Foresight R&D funding results in a slow advance of Foresight at a time when it is critically needed.

Even when compiled data and emerging methods are adequate to advance and apply Foresight to mitigate harm, there is very little investment in making these capacities available to the countries and regions that may need them most. The diffusion and adoption of advanced Foresight in emerging economies are critical to mitigating harm to human health, the environment, and socioeconomic systems. Diffusion and adoption of Foresight require investment in developing the capacities of the science and engineering ecosystems in emerging economies, supporting international collaborations, and gathering high-quality local and regional data needed for meaningful analysis.

5.D.5 ETHICAL

The primary ethical challenges in the use and development of foresight fall into four categories: 1) capacity to access the benefits of foresight; 2) intentional withholding of Foresight benefits; 3) privacy of information in data sets; and 4) embedding and perpetuation of social and cultural biases in AI and related modeling approaches.

Access to the benefits of foresight may be unequal due to the high variability in national economic resources to carry out foresight, the availability of the full spectrum of expertise needed for foresight, and the political will to carry out foresight and take action in response to foresight analysis. Analogous to the development of a vaccine during a pandemic, countries must collaborate and share resources to extend the benefit of foresight to the largest number of people.

Another potentially unethical aspect of access to foresight would be the intentional withholding or monopolization of insights gained from Foresight analysis due to economic competition (or, potentially, political differences), particularly when the foresight could prevent human suffering.

Inherent to some types of traditional foresight analysis is the compilation of large data sets from multiple sources and potentially from multiple countries. Depending on national laws, and the variability in adherence to laws, data may be aggregated that have not all been obtained ethically. A parallel ethical concern would be the temptation to exploit the relatively lax privacy ethics in one or more countries to obtain information that cannot be ethically obtained in the country or region where the Foresight analysis is taking place. A requirement for broadening international collaboration in the domain of foresight is the adoption of rigorous standards for privacy and ethics in data collection and use.

Finally, in the cases where emerging use of AI and related modeling methods might be used in foresight analysis, the AI-based modeling may inadvertently amplify the problem of data sets that embed social and cultural biases. When large data sets are ingested for AI analysis seeking patterns and correlations, systemic biases can distort the predictions made and lead to results that, if acted upon, reinforce inequities based on discrimination. Although the AI methods used might be entirely neutral and essentially incapable of bias on their own, they are entirely subject to the quality of data fed into them. It would therefore be unethical to conduct Foresight analysis via AI or modeling without consideration for biases that may be present in the data used.

5.D.5 INTERNATIONAL COLLABORATION

Despite the numerous foresight activities, projects, and initiatives around the world, creating foresight for the future requires rigorous and effective global and regional collaboration on multiple fronts. Most of these activities remain domestic rather than transnational because collaboration is not encouraged systemically, its benefits may not be recognized, or it may be inhibited by competitiveness.

Indeed, international cooperation and collaboration are needed for better foresight research. For example, the COVID-19 pandemic has provided the central incentive to break silos for healthcare professionals, engineers, scientists, policy and decision-makers, and leaders worldwide. In fact, given the wide disparities among developed and developing nations in terms of research capabilities and financing, international collaboration on Foresight scientific research, innovation, and funding is needed. International collaboration on foresight research naturally flows from the growing interconnectedness of the world and resonates with SDG 17, 'Revitalizing the global partnership for sustainable development'. Advancing foresight research and international collaboration in foresight activities holds the promise of fulfilling the potential of our best minds to avoid and mitigate future suffering and achieve greater health, stability, and prosperity.

Likewise, cross-disciplinary collaborations, including multidisciplinary, interdisciplinary, and transdisciplinary foresight research approaches, while essential for building effective foresight capabilities, seem insufficient and calls for adequate intervention measures to be taken.

Global competition, economic stability objectives, and increasing nationalism drive a desire to maintain the confidentiality of data within countries, and barriers are also in place to protect citizens. These types of barriers restrict research quality over time and limit the level of international collaborations. There is a growing need for more awareness that many challenges across the globe are highly interconnected and that long-term solutions require increased trust and cooperation driven by recognition of these common challenges. Governments can help by carefully reviewing existing and planned laws to balance data accessibility with security and privacy.

It is also critical to facilitate the collective exchange of foresight reports, data, best practices, and information on foresight initiatives conducted around the world, and with a mandate to provide scientific and policy recommendations for global challenges. It is important to note that the proposed solutions to address such gaps and challenges should be holistic but actionable by governments, guiding them in establishing policies that create conducive environments and promote actions and collaboration.

5.E FORESIGHT FOR NAVIGATING FUTURE CRITICAL TRANSITIONS

5.E.1 NEW AND EMERGING METHODS

The gaps in existing foresight methods illustrate the factors driving the development of new foresight methods. A review of diverse, quantitative example methods demonstrates the diversity and complementarity of the methods that are emerging to serve the field, highlighting the importance of enhancing both the different methods themselves and the science of combining them together.

Given the complexity of the task, it is fitting that the first field of science that we discuss would be complexity science, or the science of complex systems. This field is vast, but quite a few concepts are key for foresight, such as emergent behavior, chaos theory, nonlinearity, system dynamics, and interconnected systems. These all provide the right guidelines for how to approach the problem of foresight in a world with interconnected nth order effects that are hard to navigate and that might be better mitigated with the right approaches. Another group of methods that would prove extremely useful is holistic ones that try to understand the complete system under analysis, using methods that deconstruct, analyze, connect, and visualize a system in order to build up enough knowledge and understanding for accurate foresight. These include methods such as network science, e.g., in analyzing countries' exports to evaluate their economic complexity and predict their ability to produce more complex products in the future,[175] without going into other more widely applied methods such as mathematical representations with linear algebra, e.g., the use of singular value decomposition on power grid analysis and management[176] and probability theory/statistical analysis to avoid the painful pitfall of treating a "Heavy-tailed distribution" system in a normal/gaussian way[177] which can be argued to be one of the reasons for the 2008 financial crash. Finally, one of the fields that is more recently becoming crucial for many science areas, Artificial Intelligence, and many of its methods that can be very impactful.

To further explore emerging methods relevant to foresight, let us then take a few key science fields and delve into the various methods within them that are relevant for our objective.

Complexity Science. In a complex system, cause and effect can become vague, let alone n^{th} order causes and effects and the exponentially enhanced difficulty caused by parts of the system possibly being "chaotic," which brings chaos theory into play. That is not to say that the objective is not possible, but to highlight that the goal should not be to build an oracle but to build a "Monte Carlo oracle" that would enable the user to predict the possible futures in order to better plan for black swan critical transitions. Methods such as Agent-based Modeling can be a great tool for such an objective: they allow us to build the complex system in question from the ground up (i.e., never needing to understand the macro features and connections, as long as the micro parts are modeled correctly with their connections and details), sometimes even leading to many emergent behaviors that the modeler even didn't know about. However, such methods face challenges when it comes to data requirements and details that historically were lacking, but with the future's sensors being in every pocket and every pipe, that challenge is dwindling.

Systems Dynamics. A method that takes the opposite approach to Complexity Science is System Dynamics, which focuses on macro details and interconnections, modeling them directly using empirical data that informs the equations for those relationships. This approach, on the other hand, requires data on various historical scenarios in order to model the relationships correctly, or a priori, have knowledge of what those equations are.

Network Science. Network Science is one of the fields that contains many robust tools to assist in achieving our objective. Incorporating Network analysis in foresight methods can help disentangle complex systems data to reveal hidden structures, relationships, and trends. After representing the complex system as a network, simply quantifying different network characteristics such as connections degree, edge strengths, centrality measures, etc. can reveal valuable information (e.g., detecting undesired connections, short cuts, and even dangerous bottlenecks), not to mention algorithms such as community detection of a network that help detect influential factors and groups that could be crucial to detect, analyze and understand. As for the interconnectedness of systems, Multidimensional Networks are networks that define multiple layers, each layer representing one system, while the different layers themselves having connections across each other, which allows for a better representation of the real world. In addition, algorithms that simulate diffusion on networks can be extremely useful, for example, in assessing the propagation of a risk, estimating how a pandemic might spread between people, neighborhoods, or cities to help make a fast decision to intervene early and limit the spread.

The previous three methods can be thought of as focusing predominantly on space, but we can continue the list with methods focusing predominantly on time: methods of understanding the past, current, and future, using techniques such as pattern recognition, time-series analysis, causal analysis, probability theory, uncertainty quantification and risk mitigation to help navigate the future and detect possibilities that are low probability but high impact (i.e., Critical Transition) tipping points. However, since our focus is on the future segment of time (i.e., prediction), the field recently making a huge push in prediction by consuming huge amounts of data is Artificial Intelligence.

Gamification is a method of adding game mechanics into a non-game environment in order to benefit from the collaborative, innovative, and engaging experience often associated with it. Gamification can be beneficial within the decision-making process as it encourages different decision-makers to engage collaboratively in order to maximize their collective benefits, instead of motivating individual rewards. Thus, when it comes to foresight, this behavior can not only cause various collaborators to come up with new insights on various predicted scenarios, but it also motivates stakeholders to think about optimized solutions with the most holistic benefit. Furthermore, gamification and playing serious games can encourage users to "think outside the box" when it comes to planning or tackling problems, as gamification can motivate players to engage in exploratory behavior without a definitive objective in mind. Thus, it can provide insight into unconventional outcomes. Such exploration can also allow stakeholders to create multiple scenarios, outweigh their drawbacks and benefits, and iterate through multiple phases to exercise various possibilities from an initial scenario. Furthermore, gamification heavily depends on feeding players with a reward function that promotes behavioral changes to maximize the possible rewards. Rewards can vary from being digital benefits that exist within the realm of the game itself, or for a more realistic representation, it can equate lower costs, maximized outputs, and improved optimization within a system. Both of these rewards heavily incentivize users to reform their decision-making process in order to target a determined outcome. In conclusion, gamification promotes a collaborative decision-making process between players to foresee an optimal outcome, or to test multiple scenarios based on current metrics, while also incentivizing users towards such outcomes through a determined reward system.

Game theory, on the other hand, is the field of study which focuses on the modeling of strategic interactions among rational decision-makers (i.e., agents). The agent broadly can be any persistent entity interacting with other entities such as humans or market participants. Game theory focuses on modeling competing behaviors of these interacting agents in a dynamic multi-agent system. It helps in predicting individual agents' actions and the resulting payoffs and analyzing equilibria (e.g., Nash equilibrium). Besides modeling competitive games, game theory also includes the modeling of cooperative games in which the joint actions of groups, their form of coalition, and the resulting collective payoffs are predicted. Among many examples of its applications is modeling utilities' actions in the markets, autonomous cars' actions in traffic, and human actions during epidemics in the cities.

Decision Support Systems (DSSs) are computerized programs that are used to support choices, judgments, and courses of action in an organization. DSSs crunch and analyze huge amounts of data, compiling comprehensive information that can be used to solve problems, including those from decision theory, economics, econometrics, statistics, computer-supported cooperative work, database management, linguistics, management science, mathematical modeling, operations management, cognitive science, psychology, user interface management, and others in decision-making.

However, since our focus is on the future segment of time (i.e., prediction), the field recently making a huge push in prediction by consuming huge amounts of data is Artificial Intelligence.

Artificial intelligence. Artificial Intelligence can be used to construct multidimensional, semantic, and dynamic worlds from raw and limited sensory data using approaches such as building latent models from images, translating from LiDAR to objects, or the use of digital twins methods. AI can also learn models and abstraction beyond the raw data. It is often the case that we do have access to vast amounts of raw and partially complete datasets. Learning and constructing models and abstractions from these datasets is a crucial step toward capturing and simulating the dynamics of the real world. Methods such as latent-models learning and digital twins provide us with constructs that are more useful in simulation and projection.

We can also Interactively and efficiently select data to be gathered or annotated using active learning approaches, and we can automatically fill gaps and improve our data. Our ability to respond to certain events is related to our previous encounters with them or events that are analogous in some respect. Active learning methods facilitate smarter sampling of data for the learning process. By consciously selecting events that we are uncertain of, we allow for more light to be shed on low probability occurrences and data that in the normal sense would be deemed negligible.

There are even methods that can be used to find solutions without fully specifying the objective (self-play, adversarial networks, competitive multi-agent reinforcement learning). In many real-world problems, it is often the case that the objective we desire to achieve is well defined, but we lack the means to optimize and evaluate solutions to the objective. If it is feasible to define the counter objective of our goal, then methods such as adversarial networks, self-play, and competitive multi-agent reinforcement learning can jointly optimize and find solutions for both objectives.

A fitting AI method to end with is the approach of learning the optimal by combining the results of multiple models (i.e., Ensemble methods). For solving specific problems through machine learning, multiple models can exist with their basis features being different from one another. These models independently can produce varying results. They capture specific segments of the problem at hand that the others might not consider. Ensemble methods allow for combining these multiple models that rely on different features of the problem to produce better results.

This last point leads to our final method, which is the culmination of all of the above with some of the traditional foresight methods that are complementary

> **To make this work, we need a couple of changes in our systems. We need to have much more broadly available data...you need to break up the departments and silos...research should be motivated by problems, not by disciplines...holistic, data-rich science focused on real problems is the thing that I would like to see the G20 and S20 come out strongly for.**
>
> **Professor Alex 'Sandy' Pentland**
> **Massachusetts Institute of Technology (MIT)**

would therefore become "Scientific Foresight," i.e., the science of combining a wide range of synergistic quantitative methods to provide foresight of critical transitions.

5.E.2 THE NEED FOR SCIENTIFIC FORESIGHT

Although the magnitude of harm avoided or benefit achieved from Critical Transitions is profound, they have historically been difficult to model, study, monitor, or predict. The challenge of global critical transitions is exacerbated by the complexity and globalization of contemporary civilization. Up to this point in history, exercises for navigating the future have largely been conducted by policy analysts in think tanks, corporations, multilateral organizations, and governments. Science has been an ad hoc resource for most foresight studies. However, profound global challenges and Critical Transitions require insightful leadership and vision to transform these traditional foresight exercises through evidence-based foresight research. In turn, the scientific knowledge base and tools necessary for rigorous analysis that is sufficient for an acceptable level of readiness and response is still fragmented. We, therefore, argue in this Report for the advancement of Scientific Foresight and its applications to help prepare for and navigate these transitions.

The argument for Scientific Foresight stems from the fact that critical transitions involve interactions between systems, areas of expertise, players, and stakeholders. Actors during these transitions often operate with varying levels of visibility, information availability, information quality, and level of authority and control. Systematic and rigorous approaches to facilitate cross-disciplinary collaborations and allow for robust, quick, and agile discovery and planning at large scale are thus required. This could help provide unified views to support coordinated learning and coordinated action.

The primary objective of Scientific Foresight is thus to build the strong basis needed for future planning. Future planning has been happening through scattered tools and activities; however, we believe that these are mature enough and that it is the time to push the boundaries and attempt to make it more rigorous.

Scientific Foresight

The use of the scientific method to conduct a holistic system's view of our complex interconnected world, in order to guide and inform present-day decisions taking into account the complexity that arises from the investigation of various possibilities of the future

With gaps in foresight described and emerging methods reviewed to address those gaps, we turn our attention to the current state of foresight around the world and the institutions and governments applying it.

5.F FORESIGHT ACTIVITIES AND THE NEED FOR COLLABORATION

5.F.1 ONGOING AND EMERGING FORESIGHT ACTIVITIES AND EXPERIENCES

Countries increasingly realize that focusing analysis in one policy arena or looking through the lens of a single academic discipline is rarely successful in confronting emerging challenges. Rather, it is becoming increasingly clear that multidisciplinary, interdisciplinary, and transdisciplinary foresight research approaches are much more useful in addressing upcoming challenges and capturing opportunities in today's uncertain environment. The concepts associated with foresight, relevant foresight methods, and the applications of those methods are continuously evolving in what is a relatively new focus area for many countries. Foresight methods are used to varying degrees by governments, public institutions, think tanks, corporations, and other groups with a common interest in assessing the future. At a national level, governments usually rely on a dedicated foresight organization that may be established formally within the government (e.g., the Horizon Scanning Programme Team in the UK Cabinet Office) or external to it (e.g., NITI Aayog in India). Some government Ministries have established a well-developed foresight capability dedicated to their needs (e.g., the Ministry of Economy and Planning in Saudi Arabia and the Ministry of Science, Technology and Innovation in Argentina). Foresight capabilities are also established within many national parliaments, higher education organizations, or independent think tanks.

In the following, we provide a representative sample of foresight activities and experiences from various countries around the world, grouped based on the world regions. This survey allows us to better understand the geographical differences and the diversity of foresight practices, as there are several differences in the way foresight is leveraged. It is important to mention that the discussed activities and experiences are by no means comprehensive, nor it is intended to be, as the ones discussed only represent sample types and are intended to stimulate discussion of the issues that require immediate attention to maximize the potential benefits of foresight (see [34,178–183] for a more comprehensive summary and review).

AT THE NATIONAL LEVEL

North America. In the US, several foresight activities are very much dominated by industry-sector technology road-mapping exercises. The Expert and Citizen Assessment of Science and Technology (ECAST) network brings together academic research, informal science education, citizen science programs, and non-partisan policy analysis to engage citizens. ECAST creates peer-to-peer deliberations to inform citizens about and solicit their input on science and technology policy issues in an effort to inform decision-making more fully. Formally launched in April 2010, ECAST has conducted large-scale public deliberations in the United States on policy issues related to biodiversity, space missions, and climate and energy. The National Research Council (NRC) of ***Canada*** has identified seven topics/areas that will become important to the country in the future through its Gamechanger study, which sought to show which technology ''game changes'' bring revolutionary impacts on Canadian well-being and economic growth. The methods used included horizon scanning and the Delphi method of Subject Matter Expert (SME) consultations. This study helped justify the launch of certain key programs by the NRC in these areas—advancement of manufacturing, cities of the future, game-changing technologies, autonomous surface transportation, big data, supply chain security, and aging in place. In ***Mexico***, the National Development Plan is generated through a participatory process in which people from different sectors put forward ideas and proposals that are condensed into a Plan that guides sectoral policy programs. In addition, institutions such as the National Council on Science and Technology (CONACYT), the Mexican Academy of Sciences, and the Center for Research and Teaching in Economics (CIDE) offer policy foresight capacities to design and implement policies for national and subnational governments. Specific examples are CIDE's research program on Industry 4.0, with a focus on producing relevant scientific knowledge to promote prospective and innovative technology and knowledge, and the National Public Policy Laboratory's work on cities and Sustainable Development Goals and regional long-term planning processes with subnational governments.

Europe. The ***UK's*** foresight project operates under the Government Office for Science. The project also collects foresight information from government agencies, academic and research entities, think tanks, and corporate foresight units. Thus, it represents a network of professionals with a foresight capability to enable decision-makers to build evidence-informed policies. Other foresight projects include Global Migration, International Dimensions of Climate Change, and Global Food and Farming Futures, which help shape future policies in national security, urban planning and development, and food security and agriculture. The Parliamentary Office of Science and Technology in the UK surveyed more than 1,100 experts to answer the question: What data or information do experts want the UK Government to release during the COVID-19 outbreak? Their responses were analyzed and synthesized into 15 reports in different areas. In ***Italy***, the National Research Program is defined every five years by the Ministry of University after consultation with universities, research institutions, and other stakeholders. The objective is to identify the key areas to support and develop to meet the social and economic needs of the country. The general objectives are to reinforce internationalization, invest in human capital, develop research infrastructures, and foster private-public cooperation in the field of research. The twelve areas of central relevance are aerospace, agri-food, cultural heritage, blue growth, green chemistry, design, creativity and Made in Italy, energy, digital factory, sustainable mobility, health, smart and inclusive communities, and technologies for living environments. ***Germany*** leverages publicly supported and independent organizations in foresight activities. Several committees and scientific councils are linked to the ministries that require foresight capabilities. Likewise, in ***France*** and ***Finland***, the foresight systems are fragmented by the presence of various players from academia, public and private sectors.

Asia. In ***Japan***, the AI-Based Policy (ABPI) uses AI to eliminate subjective and skewed perceptions and helps local and federal governments make policy driven by data. Key Performance Indicators (KPIs) were analyzed by AI to forecast how Japanese societies can be sustainable and promote the happiness of people until the year 2050. Around 20,000 scenarios were provided, and they were merged into seven groups. The two main future scenarios were: 1) concentration on the city areas and 2) distribution to local areas. The conclusion drawn was that Scenario 2 provides better sustainability, health, and happiness for the population. Future policies within this scenario should include environmental tax, renewable energy, transportation requirements, culture and ethics, and social security. ***China's*** technology foresight program, initiated in 2005, provides key technology selection for the next 20 years, choosing strategic priorities and launching science and technology action plans, adjusting the input mechanisms, and improving the efficiency of resource allocation. The primary method is Delphi questionnaire surveys, in which technology importance, expected realization time, realization probability, and research/development level are compiled to derive a list of key technologies. The Fourth Industrial Revolution Intelligence Center at ***Korea*** Advanced Institute of

Science and Technology (KAIST) uses foresight to predict the impact of "Industry 4.0" (a merger of the physical, digital and biological worlds fusing advances in AI, robotics, the Internet of Things, 3D printing, genetic engineering, quantum computing, etc.) and shape policymaking. Methods used included scenario planning, forecasting, and pilot analysis, and the objective is to assist and focus leadership attention on the 4th industrial revolution. In the late 1980s, ***Singapore*** established scenario planning in the Ministry of Defense, which predicts how the world could evolve and identifies future potential challenges and opportunities. Singapore approved scenario planning in 1993 as a long-term strategic and policy development tool. Around 2013, several foresight-oriented centers and units in the government were established. For example, the Centre for Strategic Futures was founded to develop capabilities in foresight to help the government entities, including advanced analytical approaches to help better understand complex systems and environments. ***India's*** Planning Commission, with the aid of the Center for Study of Science, Technology, and Policy, produced in 2013 the document' Scenarios: Shaping India's Future' to promote new initiatives and policies by both the general public and the scientific community, that could shape India's future.

Middle East. Vision 2030, supported by the Council of Economic and Development Affairs, used foresight to help build more robust national programs for ***Saudi Arabia*** to reduce dependence on oil, diversify its economy and develop public service sectors, in addition to promoting public service sectors such as health, education, infrastructure, recreation, and tourism. The primary method was horizon scanning, assisted by existing global scenarios, and the outcome was thirteen programs called Vision Realization Programs, which aim for a more diverse and sustainable economy. Another example is the Global Energy Macro-Econometric Model (KGEMM) built by the King Abdullah Petroleum Studies and Research Center (KAPSARC), a non-profit institution for independent research into global energy economics. This uses computerized modeling and simulation to develop economic frameworks to help achieve effective alignment between energy policy objectives and outcomes. King Abdulaziz City for Science and Technology (KACST) established the Technology Foresight Center, which is responsible for the long-term plan of R&D in KACST and the Kingdom at large. In ***Turkey***, The Parliamentary Research Commission on the Effects of Global Warming and Sustainable Management of Water Resources raised awareness on the effects of these topics on behalf of the Turkish Grand National Assembly. The commission gathered information and statistics, comparing and categorizing compared to previous years, emphasizing marginal changes, and making scientific inferences and suggestions. The objective was to present scientific data to the public and to enact scientifically reasonable recommendations.

Australia/Oceania. The futures community linked to the World Future Society and the World Futures Studies Federation has guided many foresight activities in this region. ***Australia*** successfully established a circular economy innovation network to connect industry, government, communities, and scientists together and create a pathway to transition the newly developed solutions for the circular economy into applicable methods for industry. Several similar activities are conducted by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, the Ministry of Research, Science and Technology (MoRST), and the Ministry of Housing in New Zealand.

South America. In general, the foresight activities are limited but increasing in South America. For example, Argentina, Brazil, Chile, Colombia, and Venezuela have launched several foresight-oriented initiatives and activities. It is worth mentioning here that international organizations (e.g., UNIDO and the Andres Bello Agreement) have significant contributions to many of these initiatives. The BLUE BOOK – 4th National Conference on Science, Technology, and Innovation (STI) was held in ***Brazil*** in 2010; it used foresight to build a national STI policy for federal and state governments, with local, municipal, state and national discussions, seminars, forums, meetings, and lectures (with the participation of researchers from abroad). Thousands of people from a wide range of societal sectors participated: academia, government, industry, workers syndicates, social movements, indigenous people, etc. This conference led to the development of policies and legislation to improve the national STI system. In ***Argentina***, the National Plan of Science, Technology and Innovation 2020-2030 (MinCyT) established national targets for R&D actions in the next decade. Multi-stakeholder consultations and expert-led assessments were used to define specific areas where opportunities could be present for the country to become a world player.

Africa. The ***South African*** Foresight Exercise for Science Technology Innovation (STI) 2030 used foresight to contribute towards the development of a new decadal plan for STI in government, higher education institutions, business, and civil society. The exercise used STI domains and thrusts as a basis for formulating new priorities. Furthermore, South African government entities outsourced many foresight projects to their private sector to help develop and implement national policies that are effective and informed by evidence.

AT THE INTERNATIONAL AND REGIONAL LEVELS

While relative to national-level foresight activities, the international- and regional-level activities are much fewer in quantity, they seem to be more effective, efficient, and to have a greater impact. In the following, we discuss some of the most recent ones.

European Union. There are several foresight activities conducted by the European Union. For instance, FOR-LEARN is considered to be a knowledge-sharing project of European Foresight, and it operates under the Institute for Prospective Technological Studies of the European Commission's Joint Research Centre. European Foresight initiated several foresight initiatives, projects, and studies within the European context, and it is considered the first reference for European countries as it focuses on common issues emerging from national exercises within Europe.

NATO. NATO upgraded its intelligence and crisis anticipation capabilities to better guard against risks and threats. For example, a joint civilian-military Strategic Analysis Capability (SAC) provides NATO with strategic foresight scenarios about future developments of strategic relevance for the Alliance. SAC collaborate with NATO partner countries, external foresight teams (including those outside the Allied capitals), and with some international entities.

UNESCO. In 2012, UNESCO focused its foresight efforts on the development of Futures Literacy and the Discipline of Anticipation in over 20 countries to explore locally rooted anticipatory assumptions. Further, 8 UNESCO chairs have been initiated in Finland, Greece, Italy, Malaysia, Netherlands, Tunisia, United Kingdom, and Uruguay to develop Futures Literacy Centers championing innovative foresight methods and approaches working closely with stakeholders in public and private sectors in these countries.

OECD. OECD invested in Foresight capacity-building activities (e.g., foresight conferences, workshops, and training). The OECD offers support to governments to establish their foresight capacity through advice, interventions, and studies. For example, OECD provided advice and support through Iceland's Futures Committee and strategic foresight upgrade, the Slovenia National Development Strategy, the Slovakia national priorities for Agenda 2030, and Estonia's 2035 strategy.

FAO. FAO provided several foresight studies and publications in food and agriculture for the purpose of increasing understanding of the challenges that agriculture, rural development, and food infrastructure and systems are facing now and will be facing into the 21st century. Also, to provide long-term projections on food demand and supply, study the development of global food markets, and to assess how socioeconomic fluctuations, climate change, and investment payoffs could affect future global food demand.

UNIDO. UNIDO is carrying out a global initiative on technology foresight to establish the foresight capability required for designing policies and strategies that exploit emerging and critical technologies for the benefit of developing and emerging countries. For example, UNIDO has several initiatives in Asia, Latin America, Central and Eastern Europe (CEE), and the Newly Independent States (NIS) to promote sustainable and innovative development, fostering economic, environmental, and social benefits at the regional level.

World Bank. The World Bank has several foresight-oriented activities, studies, and initiatives in climate and disaster-resilient development that the bank believes are essential to help eliminate extreme poverty and achieve shared prosperity. For example, the 'Building Resilience: Integrating Climate and Disaster Risk into Development' report targets development practitioners and national policymakers who face the challenge of addressing a potential increase in disasters caused by gradual changes in climatic means and extremes, and it contributes to the loss and damage discussions under the United Nations Framework Convention on Climate Change.

5.F.2 THE NEED FOR COLLABORATION IN SCIENTIFIC FORESIGHT

Although a wide range of work employing foresight has been accomplished and is ongoing across the G20 countries, a scan across the above analysis reveals a set of gaps:

- Work is too frequently carried out in disciplinary silos. In a large number of cases, an economic analysis dominates foresight exercises, even when the institution conducting the analysis is not exclusively focused on economic issues. However, even when a non-economic technical perspective is used, it is very frequently not balanced with input from a range of complementary disciplines. And further, even in the cases where foresight may be transdisciplinary across economics and the physical sciences, for example, the social and psychological aspects of acting on the Foresight analysis may not be considered, thereby hindering the effectiveness of actions taken.
- Advanced methods are not employed where applicable. While advanced methods are under active development in universities and research institutions and are often documented in the published literature, the pathway is poorly developed for new methods to move from the lab (so to speak) into widespread practice. Information flow, adaptation of new methods to a variety of contexts, and continuing education for those leading Foresight studies all need to be developed or improved.
- The development of new methods is not consistently pursued. Although new methods are being developed, as discussed in the previous point, they are not developed systemically to address critical gaps. Because foresight is not yet a well-established academic discipline in its own right, there is not the same disciplinary focus and coordination on resolving identified gaps in knowledge that a mature and established field may have. Many advances in foresight are the by-products of research in other disciplines. Strengthening and establishing foresight as a discipline in its own right, and respecting its transdisciplinary nature, would significantly resolve the problem.
- There is inconsistent data quality, gaps in data, and poor systems and practices of data sharing. To some extent, these issues are a symptom of the lack of international collaboration on foresight and the lack of recognition and attention to foresight as a discipline. If collaboration and status for foresight improve, more attention and resources would be available to improve data quality and sharing.
- There are inadequate working knowledge and institutional structures. Foresight is frequently a one-off activity or carried out by a committee or group that is peripheral to an organization's main purpose. Both the expertise to carry out foresight and its institutional role must be much better integrated in order to achieve the benefits of foresight.

If the G20 can provide global leadership in addressing these gaps, then Scientific Foresight can be developed and employed for the benefit of all member nations.

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5.G RECOMMENDATIONS

In consideration of the analysis in this Report, our recommendations focus on 1) the need to accelerate the development of methods, and 2) the need to significantly improve the state of multilateral collaboration in the use of foresight.

5.G.1 ADVANCE FORESIGHT RESEARCH

RECOMMENDATION

Support foresight research that is based on robust science, repeatable methods, and open sharing, and incorporates recent advances in complex systems analysis.

RATIONALE

Foresight research must transform in consideration of recent major advances in network and complexity science, AI, machine learning, big data analytics, and advanced computing (e.g. quantum computing).

POLICY ACTIONS

Ensure that foresight research is based on robust science and repeatable methods that are openly shared. Such research would involve the intersection, interaction, and/or combination of scientific and engineering methods, technologies, trends and drivers, as well as the contexts in which these are embedded. Such enhancement would strengthen the reliability of foresight research and would promote trust in the use of and outcomes from these applications.

5.G.2 MAKE FORESIGHT A FOCUS OF INTERNATIONAL COLLABORATION

RECOMMENDATION

Establish a platform upon which to implement and foster international collaboration and to build trust in foresight research and activities.

> **If policy makers keep going on and keep becoming more nationalistic, more polarized, and diving more identity politics, then we are doomed. We need leaders like the G20. We need science-leading collaborative like S20, which bring across the message that this is about collaboration within the country, within the region, and globally.**
>
> **Dr. Flavia Schlegel**
> **Special Envoy for Science in Global Policy, International Science Council**

RATIONALE

Challenges that are global in nature often involve different pathways in different regional, national, or local contexts, and effective intervention options are also likely to vary according to context. Global cooperation offers a rich collaborative space for developing appropriate methods that use cutting-edge developments in network and complexity sciences, AI, and big data with the goal of promoting foresight research.

POLICY ACTIONS

Encourage international organizations (such as the UN) to establish a global clearinghouse and knowledge-sharing platform, as well as a global scientific advisory body to strengthen scientific foresight research, to foster international collaboration and collective exchange of foresight reports, data, best practices, and information on foresight initiatives conducted around the world.

This will complement and leverage existing (mostly) regional foresight efforts by encouraging international dialogue on the need for foresight research and capabilities to understand the complexity and interconnectivity of global systems and by assuring that this international cooperation fosters acceptance and tolerance of various cultures and social norms.

Such efforts should also help to develop protocols, technologies, and regulations to ease data sharing, both locally and cross-border, to allow open access to data among relevant stakeholders.

And finally, these efforts should help to prioritize programs that heighten the awareness of foresight to the broader society and policymakers and to establish strategies for communicating different futures to diverse audiences.

CONCLUSION

CONCLUSION

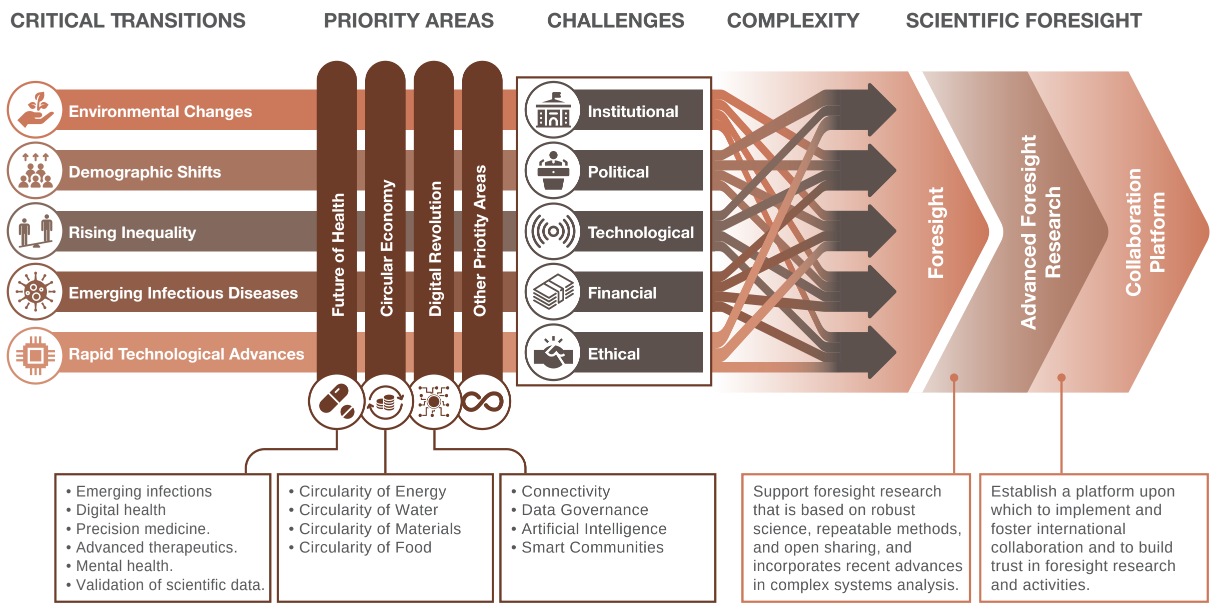


Figure C.1: The S20 Foresight Framework for systemic analysis of critical transitions, S20 priority areas, challenges, and complexity leading to a vision for Scientific Foresight and actionable recommendations to achieve that vision.

The analysis in this report, developed by more than 170 representatives of the National Academies of Science of G20 nations together with international experts, emphatically demonstrates that issues of planet and people must be viewed holistically and with full appreciation of their complexity and interconnectedness. This lesson emerges from a systematic examination of critical global transitions in health, environment, and technology, punctuated by a real-time example of a globally disruptive event, the COVID-19 pandemic. This viral pandemic laid bare the health, economic, social, and educational vulnerabilities of societies and exposed the lack of foresight that resulted in ill-equipped responses on multiple fronts.

In 2008, the world experienced a global financial crisis, a critical transition that warranted the G20 discussions to be elevated to include G20 leaders.[2] Twelve years later, we are faced with another critical transition of far-reaching impact in COVID-19. These transitions are abrupt shifts in the state of our ecosystems[184] and become critical when they have global or far-reaching impacts. The global impacts of these Critical Transitions could be negative and avoidable, negative, and unavoidable, or positive and desired. Five cross-cutting Critical Transitions have been identified across health, environment, and digital sectors, and are now occurring at an unprecedented pace and magnitude:

1. Environmental Changes
2. Demographic Shifts
3. Rising Inequality
4. Emerging Infectious Diseases
5. Rapid Technological Advances

The world's leading economies, represented by the G20 countries, must have the capacity to alleviate system-level economic and societal disruptions that can happen during and from such Critical Transitions. The science and engineering community must help governments identify impending risks and opportunities, but they must also provide evidence-based advice to policymakers to explore the "solution space" for addressing these risks or optimizing the opportunities. An excellent example of the importance of this is the ongoing COVID-19 pandemic and the role that Critical Transitions have played in its global impact.

COVID-19 is the latest in a long line of infectious disease outbreaks that have increased both in frequency and diversity over the past several decades, a period coinciding with population doubling, urbanization, globalization, and climate change.[185] Repeated outbreaks and prolonged pandemics will probably become more common in the future and will demand sustained and data-driven foresight research. Holistic approaches, such as One Health[186], must be contextually understood as complementary to the basic provision of access to healthcare and to broad support for the United Nations Sustainable Development Goals (SDGs).[187] Another health and socioeconomic related Critical Transition is due to the significant demographic shifts many countries are facing due to changing birth rates, aging populations, migration, and urbanization. Aging represents a significant demographic shift affecting many developed nations. The potential implications include increased vulnerability to infectious diseases, rising healthcare expenditures, and increased demands for healthcare services for the elderly including mental health. Furthermore, the way healthcare is practiced is going through a transition. Conventional therapeutic approaches face several challenges, mainly related to their lack of specificity and associated toxicity. Multiple approaches have recently emerged to overcome these limitations such as multi-omics technology, tailored cellular therapy, specific immunotherapy, gene therapy, and nanomedicine. However, inadequacy of talent, institutions, regulations, and funding have hampered progress in these areas. While the COVID-19 pandemic has accelerated the application of telehealth and other digital health applications, it has also revealed serious gaps in digital infrastructures and digital literacy especially among vulnerable populations. This is further exacerbated by the lack of uniform regulatory and legislative structures as well as the absence of real-time data sharing mechanisms that also maintain data privacy and security.

The disruptions caused by the COVID-19 pandemic seem to have temporarily slowed many environmental impacts caused by human activity.

Yet, we continue to damage the environment by following the traditional linear economic model based on "take-make-consume-throw away" practices. This has created a situation where we are using our natural resources unsustainably and generating enormous waste. The traditional linear economic model and associated downsides could be mitigated through a circular economy that is based on 'reduce, reuse, repair, refurbish, and recycle', while maintaining focus on economic development that includes green jobs. However, technological challenges and insufficient incentives for upscaling and adoption have been barriers to the swift transition to circular economic designs. Moving towards a more circular economy would seamlessly complement existing global climate and environmental efforts to deliver opportunities including reduced pressures on the environment, enhanced security of the supply of raw materials, and increased numbers of jobs. These will further contribute to the attainment of multiple SDGs. Increasing greenhouse gas emissions are driving a critical transition of climate change and consequent damage to land and marine ecosystems, which in turn pose threats to human health and lives. Efforts to reduce emissions and enable carbon circularity will support global commitments for responsible development while also reducing environmental pressures from hyper growth and urbanization. Limited awareness of available approaches and of opportunities to reduce emissions and to adopt carbon circularity continues along with a lack of economic and regulatory incentives to drive change. The need for such change is central to attaining SDGs related to making cities resilient and sustainable, combating climate change and its impacts, and conserving oceans and marine resources.

The COVID-19 pandemic has underscored the divide in our society between those who have capability and access to digital technology, especially the internet and services enabled by it, and those with limited or no access. The present pandemic has further reinforced the notion that internet accessibility must be considered a basic or fundamental right of every citizen. Furthermore, the existing telecom infrastructure is vulnerable to disruptions by Critical Transitions such as climatic disasters, cyberattacks, and pandemics. Despite the strong need for resilience, most nations are economically and politically constrained from investing in the network redundancy that provides resilience. These vulnerabilities in connectivity and data are shaking trust in digital technology. This mistrust has been compounded recently by the emergence of deep fakes, misinformation, and fake news. We are witnessing a changing societal landscape across multiple domains. Digital technology is disrupting traditional industries and giving rise to novel ones. In turn, this disruption is changing the professional landscape via job elimination and outsourcing and is particularly affecting vulnerable groups including women. Geopolitical factors, involuntary human migration, and climate change are resulting in increased urbanization. By 2050, two-thirds of the world's population are expected to live in urban areas, causing a heavy load on cities' operations and resources. While smart city technologies could offset this, we are not able to harness their full potential due to the lack of interoperability between competing proprietary technologies. Furthermore, global digital infrastructure and the associated billions of end-user devices consume vast amounts of energy and significantly contribute to global greenhouse gas emissions. More needs to be done in helping to reduce energy consumption and e-waste.

COVID-19 not only illustrates the role of Critical Transitions but also the Challenges the G20 faces in addressing global problems. This Report identifies six categories of challenges hindering solutions in the S20 focus-areas of health, environment, and digital systems: institutional, political, technological, financial, ethical, and international cooperation. The S20 Task Force process identified the significant aspects of each of these challenge categories that must be resolved for the G20 to advance progress in the S20 focus areas and to advance Foresight:

Institutional challenges fall into three categories: human capacity, infrastructure, and policy/practice. Common human capacity challenges include the lack of an adequately prepared scientific/technical workface needed for institutions to fulfill their responsibilities. This is exacerbated by limited or non-existent mentoring or in-service professional training opportunities and can lead to very limited research in areas where an institution may have significant national responsibility. A lack of acquisition and maintenance of infrastructure is also a challenge limiting responsiveness to critical transitions. Largely independent of these factors are the challenges posed by policies and procedures: institutions do not collaborate well with each other; they lack a commitment to long-term planning and preparedness; and they are subject to broader governmental policies on funding that further drive short-term and often crisis mode thinking. In some cases, the challenges posed by poor policy and practice are compounded by the lack of standardization of policy among institutions that have (or should have) a complementary or collaborative relationship.

Political challenges include both internal and international barriers. Internal political roadblocks may include a lack of political will for needed investments or research allocations or disagreements between political parties on funding priorities. Frequent changes in government leadership can further complicate funding priorities. Additionally, arcane and strict regulatory laws and policies can also serve as major deterrents to innovation and deployment. Lastly, uncertainty and reluctance among policymakers to develop policies to fairly regulate development and use can slow the rate of innovation. International complications such as geopolitical conflicts can also present a major problem for adoption, as they can result in destabilizations of nations and regions and alter both the availability of resources for development as well as the political priorities of a government.

Technological challenges generally involve limitations that hinder the current state-of-the-art. Sometimes, the technology available does not have the level of functionality necessary to solve certain problems. Additionally, access to technology can present itself as an issue of equity within and between countries. Unfortunately, this is a consequence of expenses related to patent-protection of technologies. Other significant challenges include infrastructural constraints and lack of adequate standards and systems needed for information sharing. Digital technologies in particular can also be accompanied by increased vulnerability, for example, to cyberattacks from malicious actors. Lastly, there is a perceived lack of transparency behind certain automated and algorithmic systems, and they are sometimes at risk of perpetuating bias.

Financial challenges consist of fiscal roadblocks to technology development, innovation, implementation, and adoption. The high cost of development and deployment combined with limited financial support for R&D is a recurring theme that stands in the way of application. Limited involvement from academia and/or the private sector, and lack of public-private investment is often a direct hindrance. Moreover, the financial disparity in lower income communities and countries often results in a slowed process of diffusion for new technologies. Lastly, the long period of gestation required for certain advanced technologies to find their way to practical application can often be associated with high costs.

Ethical challenges include the societal implications of technological developments. Privacy, vulnerability, and ownership of data is a major ethical concern within the realm of digital technology. A lack of ethical frameworks for new technologies is needed to avoid perpetuating socioeconomic inequities. Limited awareness among the public and policymakers as to the societal impacts can be another roadblock.

Additionally, misinformation and distrust in surveillance systems have increased substantially in recent times. Lastly, the environmental impacts of technology—in energy usage, for example—present yet another ethical challenge.

International cooperation challenges largely entail a lack of synergy and collaboration between countries. There is often a disconnect in standards and policies for technology between countries, which can make collaboration difficult. Moreover, there is a lack of effective models and agreements for international collaborations. Restrictions on data sharing present another barrier for countries looking to cooperate on technological projects. Unfortunately, global trade disputes and perceptions of competitiveness between nations further the divide between potential collaborators.

The current pandemic crisis has highlighted that Critical Transitions can have far-reaching impacts across the globe and that global challenges transcend societal, economic, political, and technological domains. The growing complexity and interconnectedness of systems make it increasingly difficult for policymakers to understand the impact of their decisions as they navigate the Critical Transitions we will face. The pathway to better government, policy, and action should be built on a whole-system approach.

FROM FORESIGHT TO SCIENTIFIC FORESIGHT

"Foresight is a purposeful process of developing knowledge about the future of a given unit or system of actors, which is aimed at action in the form of public or private policy making, strategizing and planning."[188] Yet, the on-going COVID-19 pandemic clearly shows that pandemic foresight was and still is a challenge requiring the convergence of medical, public health, socioeconomic, and complementary disciplines. Up to this point in history, exercises for navigating the future have largely been conducted by policy analysts in think tanks, corporations, multilateral organizations, and governments. Science has been an ad hoc resource for most foresight studies. However, profound global challenges and Critical Transitions require insightful leadership and vision to transform these traditional foresight exercises through evidence-based foresight research.

Shifting the paradigm from Foresight to Scientific Foresight would propel the science and engineering community into a needed central role to develop deeper, more accurate, and more comprehensive foresight methods to drive effective policymaking. There is a need for Scientific Foresight that can connect the dots, allowing the assessment of the impact and unintended consequences of decision options and leading to visionary actions at an international level.

International cooperation and collaboration are needed to advance Scientific Foresight. The pandemic has provided the central incentive to break silos for healthcare professionals, engineers, scientists, policy and decision-makers, and leaders worldwide. In fact, given the wide disparities among developed and developing nations in terms of research capabilities and financing, international collaboration on Scientific Foresight research, innovation, and funding is needed. International collaboration on Scientific Foresight naturally flows from the growing interconnectedness of the world and resonates with SDG 17: "Revitalizing the global partnership for sustainable development"[187]. Advancing Scientific Foresight and international collaboration in foresight activities holds the promise of fulfilling the potential of our best minds to avoid and mitigate future suffering and achieve greater health, stability, and prosperity.

RECOMMENDATIONS

The collective outcome of the work and dialogues of the S20 task forces produced over 130 policy and actionable recommendations. As demonstrated in this report, the results of S20 task forces' analysis of Critical Transitions affecting the planet and the needed role for Scientific Foresight was distilled into ten key recommendations that the S20 presented to the G20 Leaders in the S20's Communiqué. The ten S20 recommendations in the S20 priority areas of the Future of Health, the Circular Economy, and the Digital Revolution chart the path forward for the G20 in these priority areas and culminate in two critical recommendations to develop and strengthen Scientific Foresight:

1. **Advance existing pandemic preparedness towards an internationally collaborative framework to monitor and respond rapidly to emerging diseases and handle future pandemics.**

Establish an international research agenda to study the superposition of pandemic scenarios on existing health conditions, lifestyles, health impacts from environmental changes such as climate change, and social interactions using contemporary research methods. Such research will build on and work with existing global efforts to strengthen the response to a pandemic or similar health emergencies. The impact and feedback from social and behavioral research, mental health, and frontline-community interactions must be considered. To enable the application of foresight, data must be collected, shared, and analyzed, with results transparently communicated in a manner that ensures peer review, continuous knowledge sharing, data assimilation, and continuous quality improvement.

2. **Promote advanced therapies and precision medicine research to enhance personalized care, with a view to concurrently improve technology, cost, and accessibility.**

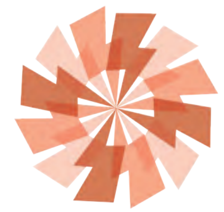
Enhance the development of techniques such as multi-omics technology, tailored cellular therapy, specific immunotherapy, gene therapy, and nanomedicine to complement the traditional healthcare industry. Promote vertical integration of multidisciplinary basic, translational, clinical, and ethical outcomes research, cutting across silo-based activities and taking into account the need for facilitating trans-national mobility and accessibility of scientists and clinicians through better exchange policies. Patients must be empowered to actively participate and collaborate in health research programs. The agenda must also incorporate development of low-cost and high-precision digital health solutions, leveraging predictive models to profoundly understand pathogenesis, identify new drug targets, and develop more personalized diagnostic and therapeutic modalities. Investments in research and training programs are needed to enhance human capital to support the development of and access to innovative diagnostics and therapeutics including vaccines.

3. Deploy policies and interventions to address the challenges arising from demographic shifts.

Account for global demographic, ethnic, and socioeconomic differences in health-related data analyses to allow more accurate data interpretation and decision-making, especially among vulnerable populations and systems with growing inequities. Similarly, conduct a comparative analysis of epidemic data collected from different countries using an agreed framework and appropriate samples in population surveys to provide added value. Among older adults, mental health issues resulting from social isolation, as well as other challenges related to higher risk of contracting diseases, limited digital literacy, and inadequate access to testing and treatment must be addressed.

4. Develop an integrated and efficient closed-loop systems approach to natural resource extraction, distribution, consumption, disposal, and recycling.

Establish the required legal and economic structure to promote large-scale acceptance and application of closed-loop systems and use of recycled and recovered products by businesses and consumers. Steps to encourage the development and adoption of closed-loop systems, especially among key sectors such as mining, manufacturing, construction, services, agriculture, and urban dwellings, should be undertaken. This will in turn stimulate research, development, and use of innovative waste reduction technologies. The design of circular economy systems should create new jobs and encourage community participation at the local level to reduce the use of virgin materials and to promote responsible consumption. Develop educational materials and programs on the circular economy to be included at all educational levels to raise awareness and open career paths to innovation, startups, and jobs in all aspects of the circular economy. Leveraging advanced digital technologies such as IoT, AI, big data, and blockchain will improve the efficiency, resilience, and circularity of natural resource use as well as enhance synergies of circularity in energy, water, materials, and food. Progress towards circularity and waste minimization must use standardized circular economy indicators to support establishment of targets for transitioning towards the circular economy.

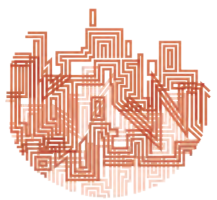


5. Promote circular design of materials and energy systems through advancing the 3Rs (Reduce, Reuse, Recycle) plus Renewables aimed at net zero carbon emission.

Promote renewable energy along with affordable and sustainable energy systems including storage, through market-based approaches and awareness programs, that will reduce societal dependence on fossil fuels. Conduct techno-economic feasibility studies and lifecycle assessment to determine the optimal mix of alternative energy technologies coupled with 3R related technologies in integrated societal systems that will best meet carbon neutrality goals. Assessment and promotion of emerging Carbon Capture, Utilization, and Storage (CCUS) technologies such as Bio-Energy Carbon Capture and Storage (BECCS), and conversion of CO^2 into products, including tests at test-bed sites, will be required to clarify their upscaling and implementation opportunities. Encouraging forest and marine ecology recovery and restoration as methods for carbon sequestration will simultaneously help restore biodiversity.

6. Bridge the emerging digital divide to ensure that all people on the planet have access and capability to use digital technologies and the internet, while ensuring privacy, resilience, and security of digital networks and devices.

Develop strategies to encourage funding of the digital infrastructure and development of communications technologies and devices suited for deployment and use in poor communities and remote locations with limited infrastructure. Inclusive education and literacy programs are required for all to ensure digital education opportunities, especially among women, minority groups and disadvantaged communities. Leverage the scientific community in digital infrastructure planning to upgrade current systems for improved resilience and increased network traffic demands. Dedicate more resources to promote data science for the public good, research and development for robust and resilient AI algorithms, stronger cryptographic protocols, and expanded regulations to prevent threats from random failures and malicious cyber-attacks.

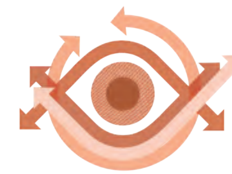


7. **Improve the sustainability of the digital infrastructure, including end-user devices, and improve opportunities for smart city technologies to contribute towards a cleaner environment.**

Accelerate initiatives aimed at reducing the environmental impact of digital technologies, including designing for energy efficiency, developing less intensive computational methods, and using renewable energy sources in place of non-renewables. Develop standardized tools and frameworks to maximize efficacy in the use of digital technologies and maximize their useful lifetime to reduce e-waste. Design smart cities and smart communities to be inclusive, optimize resource sharing, embrace interoperability, and reduce the emission of greenhouse gases and other pollutants. Promote collaboration and knowledge-sharing of best practices and experiences among policymakers, industry, community stakeholders, and the scientific community. Enhance public awareness of the environmental impact associated with use of digital technologies.

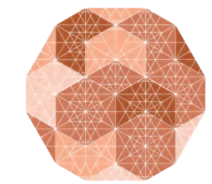
8. **Adopt a multi-disciplinary approach to plan for a human-centric, digitally enabled society of the future, in which the digital infrastructure is fully embedded in the entire social, educational, political, business, and cultural landscape.**

Strengthen focus on multidisciplinary education and research, interlinking science and engineering, social sciences, the humanities, and ethics, and enhancing the quality of digital education for all. Initiate a broad scientific and public discourse related to the societal and health impacts of digital technologies and engage in public education based on scientific evidence. Support the development of technologies and human-managed processes that allow for rapid detection and blocking of deep fakes, fake news, and disinformation, and empower users to identify and handle false and misleading information. Increase investment in research and development of trustworthy and explainable AI in high-stakes domains such as finance and healthcare and develop methodologies and protocols for the incorporation of ethical behavior into robots and related autonomous technologies.



9. **Support foresight research that is based on robust science, repeatable methods, and open sharing, and incorporates recent advances in complex systems analysis.**

Transform foresight research given recent major advances in network and complexity science, AI, machine learning, big data analytics, and advanced computing (e.g. quantum computing). Ensure that foresight research is based on robust science and repeatable methods that are openly shared. Such research would involve the intersection, interaction, and/or combination of scientific and engineering methods, technologies, trends and drivers, as well as the contexts in which these are embedded. Such enhancement would strengthen the reliability of foresight research and would promote trust in the use of and outcomes from these applications.



10. **Establish a platform upon which to implement and foster international collaboration and to build trust in foresight research and activities.**

Encourage international organizations (such as the UN) to establish a global clearinghouse and knowledge-sharing platform, as well as a global scientific advisory body to strengthen scientific foresight research, to foster international collaboration and collective exchange of foresight reports, data, best practices, and information on foresight initiatives conducted around the world. This will complement and leverage existing (mostly) regional foresight efforts by encouraging international dialogue on the need for foresight research and capabilities to understand the complexity and interconnectivity of global systems. Challenges that are global in nature often involve different pathways in different regional, national, or local contexts, and effective intervention options are also likely to vary according to context. International cooperation must foster acceptance and tolerance of various cultures and social norms. Global cooperation offers a rich collaborative space for developing appropriate methods that use cutting-edge developments in network and complexity sciences, AI, and big data with the goal of promoting foresight research. Such efforts should also help to develop protocols, technologies, and regulations to ease data sharing, both locally and cross-border, to allow open access to data among relevant stakeholders. These efforts should also help to prioritize programs that heighten the awareness of foresight to the broader society and policymakers and to establish strategies for communicating different futures to diverse audiences.

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APPENDIX I:

MEMBERS OF THE S20 LEADERSHIP TEAM

S20 Chair

- Anas Alfaris, Ph.D. (King Abdulaziz City for Science and Technology)

Executive Advisor

- Adnan Alsaati, Ph.D. (King Abdulaziz City for Science and Technology)

S20 Sherpa

- Amal Fatani, Ph.D. (King Saud University)

Chief Advocacy Officer

- Yara Al-Rajeh (King Abdulaziz City for Science and Technology)

Steering Committee

- Abdulaziz Almalik, Ph.D. (King Abdulaziz City for Science and Technology)
- Donal Bradley, Ph.D. (King Abdullah University of Science and Technology)
- Khalid Ibrahim Alhumaizi, PhD (King Saud University)
- Khalid M. AlKattan, Ph.D. (Alfaisal University)
- Mesfer M. Al-Zahrani, Ph.D. (King Fahd University of Petroleum and Minerals)
- Yusuf Abdulaziz Al-Turki, Ph.D. (King Abdulaziz University
- Areej AlKhalaf, Ph.D. ((Princess Nourah bint Abdulrahman University)

S20 Secretariat

- Jun Abrajano, Ph.D. (King Abdullah University of Science and Technology)
- Stine Büchmann-Møller, Ph.D. (King Abdullah University of Science and Technology)
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- Abdullah Binquayeed (King Abdullah University of Science and Technology)
- Mae Belle Noynay (King Abdullah University of Science and Technology)
- Gumana Habis (King Abdullah University of Science and Technology)

APPENDIX II:

MEMBERS OF THE S20 TASK FORCES

TASK FORCE 1: FUTURE OF HEALTH: PREVENTING PANDEMICS AND EXPANDING PERSONALIZED HEALTHCARE

Aws Alshamsan (King Saud University) **- S20 Future of Health Task Force Lead**

Helena Nader (Brazilian Academy of Sciences) - **S20 Future of Health Task Force Co-Lead**

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- Akiba, Suminori (Science Council of Japan)
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- Essack, Sabiha (Academy of Science of South Africa)
- Hofman, Karen (Academy of Science of South Africa)
- Keleştemur, Fahrettin (Turkish Academy of Sciences)
- Ju, Young Seok (The Korean Academy of Science and Technology)
- Koriyama, Chihaya (Science Council of Japan)
- Liu, Chenli (The Chinese Academy of Sciences)
- Martínez-Palomo, Adolfo (Academia Mexicana de Ciencias)
- Mehra, Narinder Kumar (Indian National Science Academy)
- Özer, Ali (Turkish Academy of Sciences)
- Park, Sang Min (The Korean Academy of Science and Technology)
- Patrono, Carlo (Accademia Nazionale dei Lincei - Italy)
- Rey, Rodolfo (The National Academy of Exact, Physical and Natural Sciences - Argentina)
- Spies, Claudia (German National Academy of Natural Sciences Leopoldina)
- Stacey, Dawn (The Royal Society of Canada)
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- Alhasan, Ali (King Abdulaziz City for Science and Technology)
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TASK FORCE 2: CIRCULAR ECONOMY: HOLISTIC SOLUTIONS FOR OUR ENVIRONMENT

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TASK FORCE 3: DIGITAL REVOLUTION: ACHIEVING UNIVERSAL CONNECTIVITY AND SMARTER COMMUNITIES

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TASK FORCE 4: CONNECTING THE DOTS

Ali A. Al-Meshari (Saudi Aramco) - **S20 Connecting the Dots Task Force Lead**

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