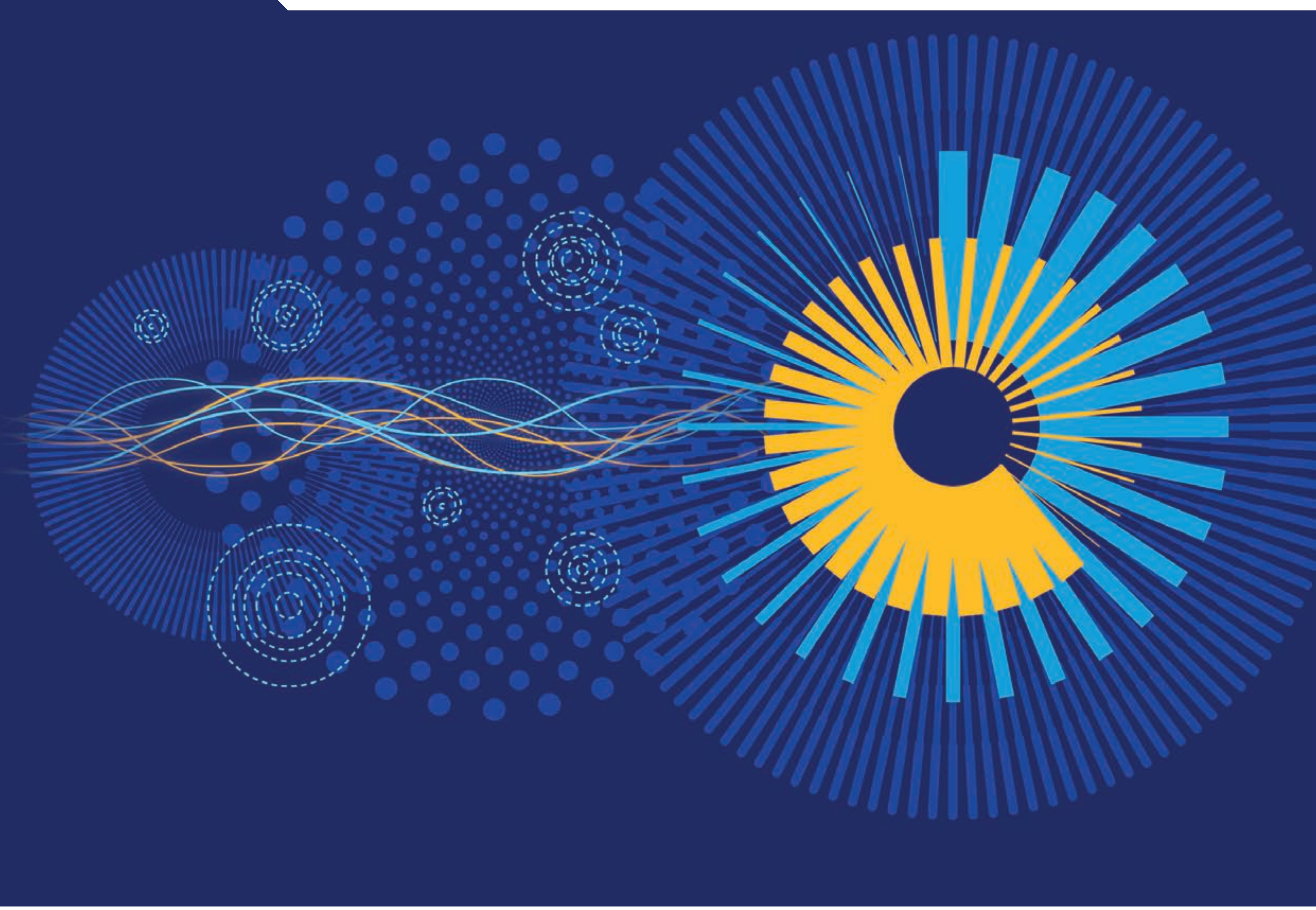
OECD Science, Technology and Innovation Outlook 2016



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OECD Science, Technology and Innovation Outlook 2016

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BETTER POLICIES FOR BETTER LIVES

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Foreword

The OECD Science, Technology and Innovation Outlook 2016 *is the eleventh in a biennial series designed to review key trends in science, technology and innovation (STI) in OECD countries and a number of major non-member economies: Argentina, Brazil, China, Colombia, Costa Rica, Egypt, India, Indonesia, Lithuania, Malaysia, Peru, the Russian Federation, South Africa and Thailand. It aims at informing policy makers, business representatives and analysts about recent and anticipated changes in the global patterns of science, technology and innovation and about the current and possible future implications for national STI policies both at global and national level.*

The STI Outlook 2016 *takes a more forward-looking perspective compared to previous editions. Chapter 1 considers* **megatrends** *that are expected to have a strong impact on the global economy and on the financing of innovation, on our future society and its relationship with STI, and on the modern state and future STI policy. Chapter 2 discusses* **ten key emerging technology trends** *that not only are the most promising and potentially the most disruptive but which also carry significant risks. The technologies covered are big data, the Internet of Things, artificial intelligence, additive manufacturing, nano/microsatellites, neurotechnologies, synthetic biology, nanomaterials, advanced energy storage technologies and blockchain. Chapter 3 presents* **future trends in science policy** *over a 10-15 year horizon and takes a forward-looking approach to issues related to multidisciplinarity, excellence, targeted funding, open science, the digitalisation of science and the attractiveness of research careers.*

The STI Outlook 2016 *also presents recent trends in STI in light of the fragile economic recovery, the scarcity of funding for innovation and entrepreneurship, mounting fiscal pressure, globalisation and major societal challenges (climate change, ageing societies and growing inequality). Chapter 4 presents an* **overall assessment of recent developments and the outlook for STI and policies** *across countries. It introduces a series of thematic* **STI policy profiles** *that provide a cross-country comparison of specific STI policy orientations, instruments and governance in the OECD area and beyond. The* **STI country profiles** *offer insights into national innovation systems: their structural characteristics, their STI performance benchmarked against selected harmonised indicators, and recent important developments in national STI policy. The focus of the profiles is on national STI priorities and initiatives introduced from 2014 to 2016.*

The STI Outlook 2016 *draws on the OECD's most recent empirical and analytical work in areas related to innovation and innovation policy. It makes use of the responses of member countries and non-member economies to the joint* **European Commission/OECD International Survey on Science, Technology and Innovation Policy (STIP)**, *formerly the biennial STI Outlook policy questionnaire. It builds on a statistical framework of over 300 STI-related indicators, drawing on the OECD's long-term efforts to build a system of internationally comparable metrics to monitor STI policy and on recent efforts to develop more experimental STI indicators.*

Finally, the STI Outlook 2016 *is one of the main pillars of the OECD-World Bank Innovation Policy Platform (IPP), a web-based interactive space that provides access to open data, learning resources and opportunities for collective learning about innovation policy.*

Acknowledgements

The *STI Outlook* is prepared under the aegis of the OECD Committee for Scientific and Technological Policy (CSTP), with input from its working parties. CSTP Delegates contributed significantly through their responses to the joint European Commission/OECD International Survey on Science, Technology and Innovation Policy (STIP), formerly the biennial STI Outlook policy questionnaire, and through their comments on the draft chapters.

The *STI Outlook 2016* is a collective effort and takes a horizontal approach, co-ordinated by the Science and Technology Policy (STP) Division of the OECD Directorate for Science, Technology and Innovation (DSTI). It is produced under the guidance of Dominique Guellec. Sandrine Kergroach served as the overall co-ordinator and Sylvain Fraccola as the administrative co-ordinator.

Chapter 1, "Megatrends affecting science, technology and innovation", was prepared by Michael Keenan and Sandrine Kergroach, with Sylvain Fraccola designing the infographics. Ozcan Saritas of the Moscow Higher School of Economics, Barrie Stevens of the OECD International Futures Programme and Gabriel Velloso of the Karlsruher Institut für Technologie provided valuable contributions. Thanks to Vincent Finat-Duclos of the OECD Public Affairs and Communication Directorate (PAC) for his insights on visualisation.

Chapter 2, "Future technology trends", was prepared by Andrés Barreneche, Steffi Friedrichs, Hermann Garden, Claire Jolly, Sandrine Kergroach, Jim Philp and Jakob Pruess, under the guidance of Michael Keenan. It is based on work carried out by the OECD Working Party on Innovation and Technology Policy (TIP), the OECD Working Party on Biotechnology, Nanotechnology and Converging Technologies (BNCT) and the OECD Space Forum. Contributions were also provided by Charlotte van Ooijen of the DSTI, Alexandra Mogyoros of the University of Oxford and Darja Vrščaj of the Eindhoven University of Technology. Anne Carblanc and Molly Lesher shared comments on the basis of the current activities of the OECD Committee for Digital Economy Policy (CDEP).

Chapter 3, "The future of science systems", was prepared by Michael Keenan and Sandrine Kergroach, and research assistance was provided by Alexandra Mogyoros of the University of Oxford and Darja Vrščaj of the Eindhoven University of Technology. This chapter also benefited from the observations of several external experts: Wiebe Bijker of Maastricht University, Philip Boucher of the European Parliament Science and Technology Options Assessment Foresight Unit (the EC JRC Foresight and Behavioural Insights Unit at the time he was interviewed), Arie Rip of the University of Twente, Tsjalling Swierstra of Maastricht University, Barend van der Meulen of the Rathenau Institute, Harro van Lente of Maastricht University, Geert Verbong of the Eindhoven University of Technology, Werner Wobbe of the EU Directorate General for Research and Innovation (DG RTD) Foresight Unit (at the time he was interviewed) and Sally Wyatt of Maastricht University. Their insights were collected during face-to-face interviews conducted by Darja Vrščaj in preparation of the *STI Outlook 2016*.

Chapters 1, 2 and 3 were designed and prepared following a forward-looking exercise conducted in 2015-16 and co-led by Michael Keenan and Sandrine Kergroach. In the framework of this exercise, a series of internal and external workshops were organised involving DSTI colleagues but also various OECD Directorates and bodies beyond the DSTI: the Centre for Entrepreneurship, SMEs and Local Development (CFE), the Directorate for Education and Skills (EDU), the Directorate for Employment, Labour and Social Affairs (ELS), the Environment Directorate, the Directorate of Public Governance and Territorial Development (GOV), the Trade and Agriculture Directorate, the Office of the Secretary-General, the Global Science Forum (GSF), the International Energy Agency, the International Futures Programme and the International Transport Forum. The forward-look chapters also benefited from discussions held during dedicated workshops involving country delegates of the CSTP, the TIP and the GSF. Mini-workshops were also organised in Korea, the United States and China with the help of, respectively, Byeongwon Park (STEPI – Science and Technology Policy Institute of Korea), Susan Fridy (OECD Washington Center) and Mu Rongping (Institute of Policy and Management, Chinese Academy of Sciences). Interviews with several OECD experts helped gather further knowledge. Thanks also to the following DSTI colleagues: Koen de Backer, Mario Cervantes, Chiara Criscuolo, Fernando Galindo-Rueda, Hermann Garden, Dominique Guellec, Alistair Nolan, Caroline Paunov, Mariagrazia Squicciarini, Vincenzo Spiezia, Carthage Smith and David Winickoff.

Chapter 4, “Recent international trends in STI policies”, was prepared by Sandrine Kergroach based on recent CSTP and TIP activities. It draws on country responses to the 2016 EC/OECD International STIP Survey.

As in the past, the STI Outlook policy profiles were prepared with a collaborative approach. Policy profiles and their analytical framework were designed by Sandrine Kergroach, who ensured co-ordination and consistency.

Chapter 5, “STI Policy Profiles: Governance”, was prepared by Mario Cervantes, Steffi Friedrichs, Michael Keenan, Sandrine Kergroach, Philippe Larrue, Jakob Pruess, David Winickoff and Pluvia Zuniga on the basis of work conducted by the TIP and the BNCT and experience obtained through the OECD Country Reviews on Innovation Policy. Marco Daglio (GOV) prepared the STI policy profile on public sector innovation.

Chapter 6, “STI Policy Profiles: Globalisation of innovation policies”, was prepared by Koen de Backer based on work conducted by the OECD Committee on Industry, Innovation and Entrepreneurship (CIIE) together with Fernando Galindo-Rueda and Sandrine Kergroach based on work conducted by the CSTP and its Working Party of National Experts on Science and Technology Indicators (NESTI) and Frederic Sgard of the GSF. Gwénaël Jacotin and Stéphan Vincent-Lancrin (EDU) prepared the STI policy profile on the internationalisation of universities and public research.

Chapter 7, “STI Policy Profiles: Facing new societal and environmental challenges”, was prepared by Andrés Barreneche, Mario Cervantes and Jim Philp based on work done by the TIP and the BNCT, Elettra Ronchi on the basis of work conducted by the CDEP and Caroline Paunov on the basis of TIP and more general OECD activities on inclusive innovation.

Chapter 8, “STI Policy Profiles: Innovation in firms” was prepared by Silvia Appelt, Mario Cervantes, Sylvain Fraccola, Fernando Galindo-Rueda, Sandrine Kergroach and Jakob Pruess on the basis of work conducted by the CSTP, NESTI and TIP. Lucia Cusmano, Marco Marchese and Jonathan Potter (CFE) prepared the STI policy profile on start-ups and entrepreneurship.

Chapter 9, "STI Policy Profiles: Sectoral innovation", was prepared by Giulia Ajmone-Marsan, Sarah Box, Mario Cervantes, Hermann Garden, Claire Jolly, Alistair Nolan and Jim Philp, all of the DSTI, on the basis of work conducted by the CSTP, the TIP, the BNCT, the CDEP and the OECD Space Forum. Valérie Paris (ELS) and Prof. Dr. Philippe Gorry of the Research Unit in Theoretical and Applied Economics of the University of Bordeaux prepared the policy profile on health innovation for rare diseases.

Chapter 10, "STI Policy Profiles: Universities and public research", was prepared by Giulia Ajmone-Marsan, Andrés Barreneche, Mario Cervantes, Caroline Paunov, Frederic Sgard and Carthage Smith on the basis of work conducted by the CSTP, the TIP and the GSF.

Chapter 11, "STI Policy Profiles: Skills for innovation", was prepared by Andrés Barreneche, Sandrine Kergroach, Richard Scott and David Winickoff on the basis of work conducted by the CSTP, the TIP and the BNCT.

Chapter 12, "STI country profiles: Assessing STI performance", was co-ordinated by Sylvain Fraccola and Sandrine Kergroach. The methodology was designed by Dominique Guellec and Sandrine Kergroach. Country profiles were prepared by Giulia Ajmone-Marsan, Koen de Backer, Andrés Barreneche, Stefano Baruffaldi, Sarah Box, Qian Dai, Sylvain Fraccola, Steffi Friedrichs, Dominique Guellec, Gernot Hutschenreiter, Michael Keenan, Sandrine Kergroach, Philippe Larrue, Alistair Nolan, Daehyun Oh, Caroline Paunov, Jakob Pruess, Carthage Smith, Yana Vaziakova, David Winickoff, Gang Zhang and Pluvia Zuniga, all of the DSTI, based on information gathered through the EC/OECD STI Policy Survey and drawing on TIP activities and the OECD Country reviews on innovation policy.

All components of the *STI Outlook 2016* have been reviewed by and received valuable comments from the editorial board: Dominique Guellec, Dirk Pilat and Andrew Wyckoff of the DSTI.

Sandrine Kergroach supervised the development of the policy infrastructure (EC/OECD STIP database) and the statistical infrastructure (IPP.Stat). Sylvain Fraccola, Chiara Petroli, Jakob Pruess and Charlotte van Ooijen provided research assistance in processing the 2016 country responses. Thanks to Julien Chicot, Naoya Ono, Inmaculada Perianez-Forte, Chiara Petroli and Tomomi Watanabe for their pivotal work in implementing the former versions of the EC/OECD STI Policy database. Thanks to colleagues of the European Commission's DG RTD for their help in preparing country information for the 2016 survey. Sylvain Fraccola and Blandine Serve provided co-ordination and statistical assistance respectively and supported the entire survey process.

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Acronyms

BERD	Business enterprise expenditure on R&D
CO_2	Carbon dioxide
CSTP	OECD Committee for Scientific and Technological Policy
EPO	European Patent Office
EU	European Union
FDI	Foreign direct investment
FTE	Full-time equivalent
GBAORD	Government budget appropriations and outlays for R&D
GDP	Gross domestic product
GERD	Gross domestic expenditure on R&D
GOVERD	Government intramural expenditure on R&D
GVCs	Global value chains
HERD	Higher education expenditure on R&D
HRST	Human resources in science and technology
HEI	Higher education institution
ICT	Information and communication technology
IA	Impact assessment
IMF	International Monetary Fund
IP	Intellectual property
IPC	International patent classification
IPR	Intellectual property right
ISCED	International Standard Classification of Education
ISCO	International Standard Classification of Occupation
ISIC	International Standard Industrial Classification
IT	Information technology
JPO	Japan Patent Office
KIPO	Korean Intellectual Property Office
MFP	Multifactor productivity
MNE	Multinational enterprise
NGO	Non-governmental organisation
OA	Open Access
OD	Open Data
OHIM	Office for Harmonization in the Internal Market
PCT	Patent Co-operation Treaty
PPP	Purchasing power parity
PPP	Public-private partnership
PRI	Public research institution
R&D	Research and development

RTA	Revealed technological advantage
SDG	Sustainable Development Goals
S&E	Science and engineering
S&T	Science and technology
SIPO	State Intellectual Property Office of the People's Republic of China
SME	Small and medium-sized enterprise
SSS	Smart specialisation strategy (also known as 3S)
STEM	Science, technology, engineering and mathematics
STI	Science, technology and innovation
STIP	Science, technology and innovation policy survey and database
USD	United States dollar
USPTO	United States Patent and Trademark Office
VC	Venture capital
WIPO	World Intellectual Property Organization

Abbreviations

ARG	Argentina	Argentine peso	ARS
AUS	Australia	Australian dollar	AUD
AUT	Austria	Euro	EUR
BEL	Belgium	Euro	EUR
BRA	Brazil	Brazilian real	BRL
CAN	Canada	Canadian dollar	CAD
CHE	Switzerland	Franc	CHF
CHL	Chile	Chilean peso	CLP
CHN	People's Republic of China	Yuan renminbi	CNY
COL	Colombia	Colombian peso	COP
CRI	Costa Rica	Colón	CRC
CZE	Czech Republic	Koruna	CZK
DEU	Germany	Euro	EUR
DNK	Denmark	Krone	DKK
EGY	Egypt	Egyptian pound	EGP
ESP	Spain	Euro	EUR
EST	Estonia	Estonian kroon	EEK
EU	European Union	Euro	EUR
FIN	Finland	Euro	EUR
FRA	France	Euro	EUR
GBR	United Kingdom	British pound	GBP
GRC	Greece	Euro	EUR
HUN	Hungary	Forint	HUF
IDN	Indonesia	Rupiah	IDR
IND	India	Indian rupee	INR
IRL	Ireland	Euro	EUR
ISL	Iceland	Króna	ISK
ISR	Israel	New Israeli sheqel	ILS
ITA	Italy	Euro	EUR
JPN	Japan	Yen	JPY
KOR	Korea	Won	KRW
LTU	Lithuania	Lithuanian litas	LTL
LUX	Luxembourg	Euro	EUR
LVA	Latvia	Latvian lat	LVL
MEX	Mexico	Mexican peso	MXN
MYS	Malaysia	Malaysian ringgit	MYR
NLD	Netherlands	Euro	EUR

NOR	Norway	Krone	NOK
NZL	New Zealand	New Zealand dollar	NZD
PER	Peru	Peruvian nuevo sol	PEN
POL	Poland	Zloty	PLN
PRT	Portugal	Euro	EUR
RUS	Russian Federation	New Russian ruble	RUB
SVK	Slovak Republic	Koruna	SKK
SVN	Slovenia	Euro	EUR
ZAF	South Africa	South African rand	ZAR
SWE	Sweden	Krona	SEK
THA	Thailand	Thailand baht	THB
TUR	Turkey	Turkish lira	TRY
USA	United States	United States dollar	USD
ZAF	South Africa	South African rand	ZAR

Country groupings

BRICS	Brazil, Russian Federation, India, People's Republic of China, South Africa
BRIICS	Brazil, Russian Federation, India, Indonesia, People's Republic of China, South Africa
EU28	European Union (Austria, Belgium, Bulgaria, Croatia, Cyprus[1], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, United Kingdom)
OECD	Total OECD

1. Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

Note by all European Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

Executive summary

Tomorrow's world is set to be of another kind. Powerful forces, rising from deep socio-economic, environmental, technological and political trends – so-called "megatrends" – are influencing developments in economies and societies, shaping our future, often in unexpected ways. These multidimensional, mutually reinforcing and sometimes opposing megatrends will affect the direction and pace of technological change and scientific discovery and influence future STI activities and policies.

Megatrends are shaping future STI capacity and activities

Ageing societies, climate change, health challenges and growing digitisation are, among other factors, expected to shape future R&D agendas and the scope and scale of future innovation demand. Novel markets are likely to emerge, creating new skills needs and new growth and job opportunities. New approaches to sustainable growth, e.g. through the circular economy, are making their way.

The fast pace of economic development in emerging economies, coupled with the cross-border activities of multinationals and a further fragmentation of global value chains, will also favour a broader distribution of STI activities across the planet. Global competition for talent and resources will most likely intensify, as will the production and diffusion of new knowledge. Existing centres of excellence may benefit from this competition, further concentrating the best talent and resources at the expense of less competitive places.

STI activities could however be confronted with strong resource constraints. Possibly insufficient growth in developed and emerging economies, as well as competing policy priorities and agendas, may limit the financial resources available. This could compromise the role of STI to address future challenges. Similarly, an ageing population, together with changing patterns in migration, will have uncertain consequences for the availability of STI skills.

The megatrends raise urgent issues that demand policy responses, but the capacities of governments to intervene will likely face major constraints, including high public debt, increasing international security threats, a possible erosion of social cohesion, and the rise of influential non-state actors that challenge their authority and ability to act.

Technology is set to disrupt societies, with uncertain outcomes

Future developments in STI could accelerate, intensify or reverse megatrend dynamics. But these developments also have the potential to offer solutions to the challenges we face. For example, globalisation will be further enabled by advances in communications and transport technologies; income growth will be increasingly driven by STI developments; reductions in CO_2 emissions will depend on the development of new, cleaner energy technology; and improved health outcomes and increasing life expectancy will heavily depend on health technology innovation.

On the other hand, emerging technologies carry several risks and uncertainties, and many raise important ethical issues, too. STI developments could exacerbate inequalities without wider innovation diffusion and skills acquisition. Developments in artificial intelligence and robotics raise concerns around future jobs; the Internet of Things and big data analytics around privacy; 3D printing around piracy of intellectual property; synthetic biology around biosecurity; and neurosciences around human dignity.

Still, emerging technologies are expected to have wide impacts across several fields of application and will often depend on other "enabling" technologies for their development and exploitation. Technology convergence and combination could be further helped by cross-disciplinary working arrangements and skills training.

Public science has a central role to play, provided it can manage its own transition

Public sector science will continue to play pivotal roles in developing knowledge and skills for exploitation in the wider economy. But it will also undergo its own transformation. Emerging technologies are opening up a new age for research. Big data and algorithms are generating huge amounts of data, changing scientific methods, instruments and skills requirements and creating new fields of research.

Open science is the next frontier. Open data access practices are increasingly widespread. Encouraging the sharing and re-use of research data could generate more value for public money. Science is also becoming a less institutionalised endeavour, with citizens conducting their own research alongside the scientific community. However, deep changes in academic culture will be necessary to realise the full potential of a more open science.

Funding issues will evolve. The proportion of public spending that goes to R&D is unlikely to increase, and a decline in the public funding of universities is already noticeable in many countries. Public science will need to find new sources of funding, including from philanthropists and private foundations, and this will have impacts on future public R&D agendas. Research careers will also remain precarious, especially for women, with consequences for attracting future generations of researchers.

Today, policy attention remains focused on immediate economic imperatives and efficiency gains

The recent financial crisis hit STI activities hard, and the subsequent rebound has remained weak. Financial conditions for innovation and entrepreneurship remain difficult, especially for SMEs.

OECD countries and non-OECD economies have placed considerable emphasis on supporting firms' capacity to innovate. Many countries have sought to consolidate their business support programmes to make them more accessible and more cost-efficient. Several governments have also adopted a "no-spending" approach in supporting innovation, e.g. through extensive use of fiscal incentives and public procurement. Many countries have also adjusted their policy portfolios to assist SMEs and start-ups, especially for accessing global markets. There is emerging evidence of a trade-off in the allocation of public support between firms on the one hand and public research on the other, with a growing share of the total budget going to the business sector.

The picture nevertheless differs across countries, and the gap between countries on a low-growth path and those on a high-growth path is widening. Even within Europe, noticeable cross-country differences in investment profiles signal a growing threat to the cohesion of the European Union. Governments are seeking to improve the efficiency and impact of their STI policy mix, giving increasing attention to policy evaluation and new data infrastructures to improve the policy evidence base.

Governments will increasingly work with wider society to shape and exploit STI

Governments are increasingly managing the risks and uncertainties around emerging STI developments by adopting more "responsible research and innovation" (RRI) policies. RRI principles have diffused into policy agendas, funding programmes and governance arrangements, integrating ethical and social considerations "upstream" in the innovation process.

Chapter 1

Megatrends affecting science, technology and innovation

This chapter describes and analyses the main global "megatrends" that are set to have a strong impact on societies and economies, including science, technology and innovation (STI) systems, over the next 10-15 years. Megatrends are large-scale social, economic, political, environmental or technological changes that are slow to form but which, once they have taken root, exercise a profound and lasting influence on many if not most human activities, processes and perceptions. Such relative stability in the trajectory of major forces of change allows some elements of a likely medium-to-long term future to be envisioned, at least with some degree of confidence. The megatrends covered in this chapter are clustered into eight thematic areas as follows: demography; natural resources and energy; climate change and environment; globalisation; the role of government; economy, jobs and productivity; society; and health, inequality and well-being.

Introduction

Our future is uncertain, shaped by a multitude of powerful, complex and interconnected forces, and eventually altered by improbable, unpredictable and highly disruptive events. Seen over a time horizon of say 10-20 years, some of the big trends we see unfolding before us are in fact quite slow-moving. These are megatrends – large-scale social, economic, political, environmental or technological changes that are slow to form but which, once they have taken root, exercise a profound and lasting influence on many if not most human activities, processes and perceptions. Examples are global population growth and urbanisation, or the ageing of societies in many parts of the world; the warming of the planet and rising sea levels or the acidification of our oceans and seas; the deepening of globalisation; and the growing momentum of digitalisation, big data and bioengineering.

The relative stability in the trajectory of these major forces of change allows us to envision at least some elements of our likely medium-to-long term future with some degree of confidence. What often tends to shake that confidence, at least temporarily, are disruptive events. These come in a multitude of forms and include natural disasters and catastrophes and events related to human intervention, e.g. sudden peaks of violence, large-scale accidents, and economic and political crises. Such events are difficult to build into trend projections, and so are often treated in forward-looking exercises as "wild cards", defined as high-impact events that are unpredictable or unlikely to happen. Potentially disruptive scientific and technological innovation frequently find a place in forward trend studies, not least because they often occur as an extension of, or as a marked departure from, existing science and technology (S&T) trends. Ultimately, it is how megatrends and disruptive trends – especially in the field of S&T – interact that will set the scene for the coming decades. It is for governments, business, researchers and citizens in general to reflect on what the interplay of such trends means in terms of opportunities to be seized and challenges to be met.

In this regard, foresight can be a useful tool for developing and implementing forward-looking research and innovation policies. Analysis of future trends, whether derived from extrapolations, simulations, projections or scenarios, can provide important insights for the future. Foresight can offer support and guidance for decision makers and investors, and alert policy makers, the business community, researchers and society more generally to important upcoming issues. The interpretation of future trends, however, always needs to be done with care: they do not foretell the future, but merely indicate how the future might evolve under certain conditions and in a given subject area. By bringing together and closely examining the interplay between trends in different subject areas, it is possible to assemble a somewhat fuller picture of possible futures. This can strengthen the basis for developing narratives or storylines, which in turn can enrich our view of where the world is heading and what challenges and opportunities may lay on or beyond the longer-term horizon.

This chapter covers those megatrends that are expected to have a strong impact on science, technology and innovation (STI) systems. The megatrends covered are clustered into eight thematic areas, as shown in Figure 1.1. While the time horizon adopted in this

STI outlook is 10-15 years, several megatrend projections presented below stretch somewhat longer into the future. This in part reflects the availability of data. It also reflects the fact that large discernible changes for some megatrends are best seen over longer time horizons of 20 years or more. Irrespective of the time horizons adopted, there are implications for STI policy today. Indeed, this focus on the need for policy (re)orientation has guided the choice of megatrends featured below.

By way of overview, some of the main megatrends covered include the following:

- **Demography:** The world population will continue to grow in the 21st century and is expected to nudge the 10 billion mark by mid-century. Africa will account for more than half of this growth, which will generate significant youth bulges. Elsewhere, including in many developing countries, populations will significantly age, and those over 80 will account for around 10% of the world's population by 2050, up from 4% in 2010. With a declining share of the population in work, ageing countries will face an uphill battle to maintain their living standards. International migration from countries with younger populations could offset this decline. At the same time, technologies that enhance physical and cognitive capacities could allow older people to work longer, while growing automation could reduce the demand for labour.
- **Natural resources and energy:** A growing population coupled with economic growth will place considerable burdens on natural resources. Severe water stress is likely in many parts of the world, while food insecurity will persist in many, predominantly poor, regions. Energy consumption will also rise sharply, contributing to further climate change. Global biodiversity will come under increasing threat, especially in densely populated poorer countries.
- **Climate change and environment:** Mitigating the considerable extent and impacts of climate change will require ambitious targets for the reduction of greenhouse gas emissions and waste recycling to be set and met, implying a major shift towards a low-carbon "circular economy" by mid-century. This shift will affect all parts of the economy and society and will be enabled by technological innovation and adoption in developed and developing economies.
- **Globalisation:** The world economy's centre of gravity will continue to shift east and southwards, and new players will wield more power, some of them states, some of them non-state actors (such as multinational enterprises and NGOs) and others newly emerging megacities. Driving and facilitating many of these shifts in power and influence is globalisation, which operates through flows of goods, services, investment, people and ideas, and is enabled by widespread adoption of digital technologies. But globalisation will inevitably face counter-currents and crosswinds, such as geopolitical instability, possible armed conflict and new barriers to trade.
- **Role of government:** Governments will be compelled to respond to the many grand challenges arising in the future in a context marked by mounting fiscal pressure, eroding public confidence in government and the continuing transition to a multipolar world, with the consequent potential for growing instability.
- **Economy, jobs and productivity:** Digital technologies will continue to have major impacts on economies and societies. Over the next 15 years, firms will become predominantly digitalised, enabling product design, manufacturing and delivery processes to be highly integrated and efficient. The costs of equipment and computing will continue to fall, while the rise of open source development practices will create further communities of

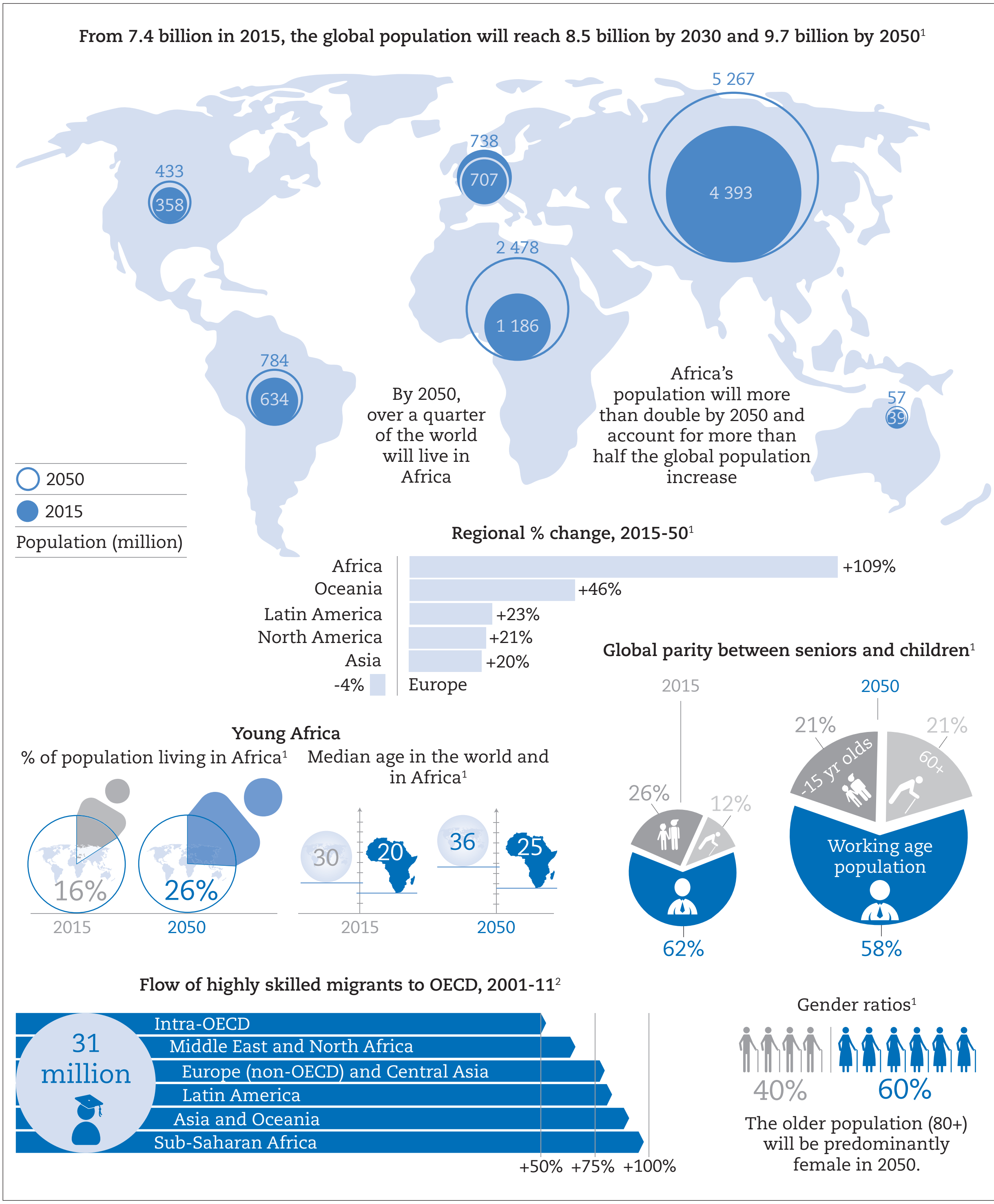
developers. There will be greater opportunity for entrants – including individuals, outsider firms and entrepreneurs – to succeed in new markets. At the same time, the decreasing cost of computing power and advances in machine learning and artificial intelligence will further disrupt labour markets, with one in ten jobs in OECD countries at high risk of being automated over the next two decades.

- **Society:** The future will see striking changes in family and household structures in OECD countries with significant increases in one-person households and couples without children. Access to education and acquisition of skills will be one of the most important keys to improving life chances. Growth in female enrolment at all levels of education will continue, and will have important implications for labour markets and family life. The global population will be increasingly urban, with 90% of this growth occurring in Asia and Africa. Urbanisation could bring several benefits to developing countries, including better access to electricity, water and sanitation. But it could also lead to extensive slum formation with negative consequences for human health and the environment.
- **Health, inequality and well-being:** The treatment of infectious diseases that affect the developing world disproportionately will be further compromised by growing antibacterial resistance. Non-communicable and neurological diseases are projected to increase sharply in line with demographic ageing and globalisation of unhealthy lifestyles. Inequalities will grow in many developed countries, as will poverty rates and the profiles of those at risk of poverty.

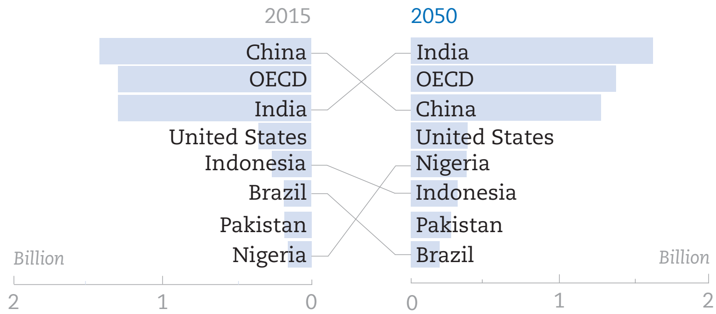
In this changing world, STI can work as a double-edged sword. On the one hand, technological advances have the potential to reinforce the destabilising effects of many of the megatrends described here. On the other, they have the potential to improve humankind's response to many of the global challenges facing the planet. Either way, they will have a major influence, often in unexpected ways.

Eight megatrend areas covered in this chapter

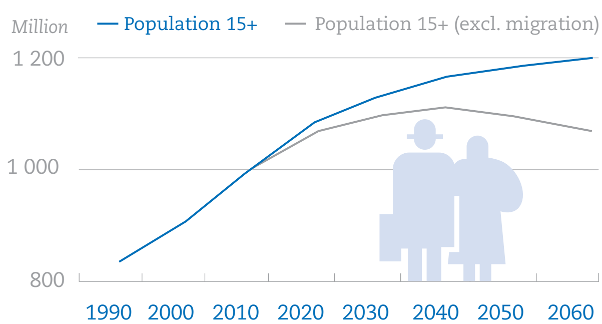
Demography


From 7.4 billion in 2015, the global population will reach 8.5 billion by 2030 and 9.7 billion by 2050[1]
433
358
738
707
5 267
4 393
2 478
1 186
784
634
57
39
By 2050, over a quarter of the world will live in Africa
Africa's population will more than double by 2050 and account for more than half the global population increase
2050
2015
Population (million)
Regional % change, 2015-50[1]
Africa +109%
Oceania +46%
Latin America +23%
North America +21%
Asia +20%
-4% Europe
Global parity between seniors and children[1]
2015
2050
26%
12%
62%
21%
21%
-15 yr olds
60+
Working age population
58%
Young Africa
% of population living in Africa[1]
16%
26%
2015
2050
Median age in the world and in Africa[1]
30
20
36
25
2015
2050
Flow of highly skilled migrants to OECD, 2001-11[2]
31 million
Intra-OECD
Middle East and North Africa
Europe (non-OECD) and Central Asia
Latin America
Asia and Oceania
Sub-Saharan Africa
+50% +75% +100%
Gender ratios[1]
40%
60%
The older population (80+) will be predominantly female in 2050.

Most populous countries[1]

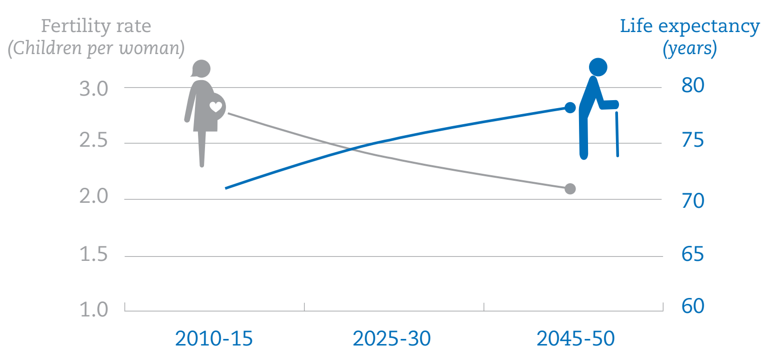


Population and migration
OECD, 1990-2060[3]



Migrant workers will be an important factor to mitigate the effects of ageing in most OECD countries.

Fewer births and longer life spans[1]



The population in all major regions of the world is ageing.

Growing global population

- A larger global population, together with increased educational attainment and economic development, will likely translate into more consumers, innovators and researchers at a global level.
- The demands and needs of the centres of largest population growth, e.g. in Africa, could increasingly shape innovation agendas. These areas will also further develop localised research and innovation capabilities.
- A greater focus on technology transfer to centres of largest population growth will likely be needed to help them manage the multiple development challenges they face.

Ageing societies

- Ageing societies could see slower economic growth and resources diverted to social and health spending. This could draw resources away from STI spending.
- Ageing implies changes in lifestyle and consumption patterns, which will influence the types of products and services in demand and the direction of innovation.
- Ageing-related illnesses, including cancer and dementia, will increasingly dominate health research agendas.
- New technologies, e.g. robotics and neurosciences, could help the elderly live longer, healthier and more autonomously.

Labour and international migration

- Fewer people of working age will affect the labour market for STI skills and could lead to an ageing research workforce in OECD countries.
- The flow of highly skilled migrants into OECD countries is likely to intensify, further contributing to the STI labour force.
- Though much debated, new technologies, e.g. robotics and artificial intelligence, could alleviate expected labour shortages in the wider economy.

Sources: 1. UNDESA (2015a). The population refers to persons aged 15 and above. Iceland is excluded from OECD destinations when comparisons between 2000-01 and 2010-11 are made.; 2. OECD (2015a); 3. Westmore, B. (2014).

Population growth in less developed countries

The world's population is expected to grow during the 21st century, though at a slower rate than in the recent past, reaching 8.5 billion by 2030 and 9.7 billion by 2050. Growth will take place almost entirely in less developed countries and Africa will account for over half of the expected increase. Population size in much of the developed world will stabilise and many countries will even experience a population decline. In Japan and much of Central and Eastern Europe, for example, populations are expected to fall by more than 15% by 2050.

Global population growth will place unprecedented pressures on natural resources, e.g. food, energy and water, and STI will continue to be called upon to play essential roles in enhancing their production and conservation. In general, a larger global population, together with continuing economic development, should translate into more research and innovation activities. At the same time, research and innovation agendas may be significantly influenced by the multiple development challenges faced by countries with large population growth. New international STI co-operation and agreements – for example, around the UN's SDGs and COP21 Paris Agreement – will seek to accelerate technology transfer to these countries to augment existing channels of diffusion through trade, foreign direct investment (FDI), and the acquisition of capital goods. Developing countries will need to expand and deepen their own research and innovation capabilities if they are to absorb and adapt these technologies for their own needs.

Ageing societies

A combination of low fertility rates and longer life spans will lead to future ageing in all major regions of the world. At current rates, there will be almost global parity between the number of over-60s and the number of children by 2050. This is a significant change from the past and present: while there are around 900 million over-60s in the world today, their number is projected to increase to 1.4 billion by 2030 and 2.1 billion by 2050. Europe is expected to have the largest proportion of over-60s (34% in 2050 compared to 24% in 2015). But rapid ageing will occur in other parts of the world as well, particularly in Asia (UN, 2015a). Almost 80% of the world's older population will live in what are currently less developed regions. The People's Republic of China (hereafter "China") will have about 330 million citizens aged 65 or more, India about 230 million, and Brazil and Indonesia over 50 million by 2050 (UN, 2011). Globally, the number of over-80s is expected to multiply threefold by 2050 (from 125 million in 2015 to 434 million in 2050 and 944 million in 2100). The over-80s group accounted for just 1% of the OECD population in 1950, but its share rose to 4% in 2010 and is projected to be close to 10% by 2050.

Ageing implies changes in lifestyle and consumption patterns, and this will have significant implications for the types of products and services in demand. New markets will emerge as part of a flourishing "silver economy" (OECD, 2014a), while more traditional ones may have to adapt or will even disappear, all of which will have implications for innovation. At the same time, ageing societies could see slower economic growth. High old-age dependency ratios, together with more prevalent non-communicable diseases and increased disability among the elderly, will place considerable burdens on healthcare and other services. The resulting fiscal pressures could draw public spending away from other areas, including STI. Ageing-related illnesses, including cancer and dementia, may also increasingly dominate health research agendas. As the world grows older together, including many emerging economies, international research co-operation on tackling age-related diseases could intensify.

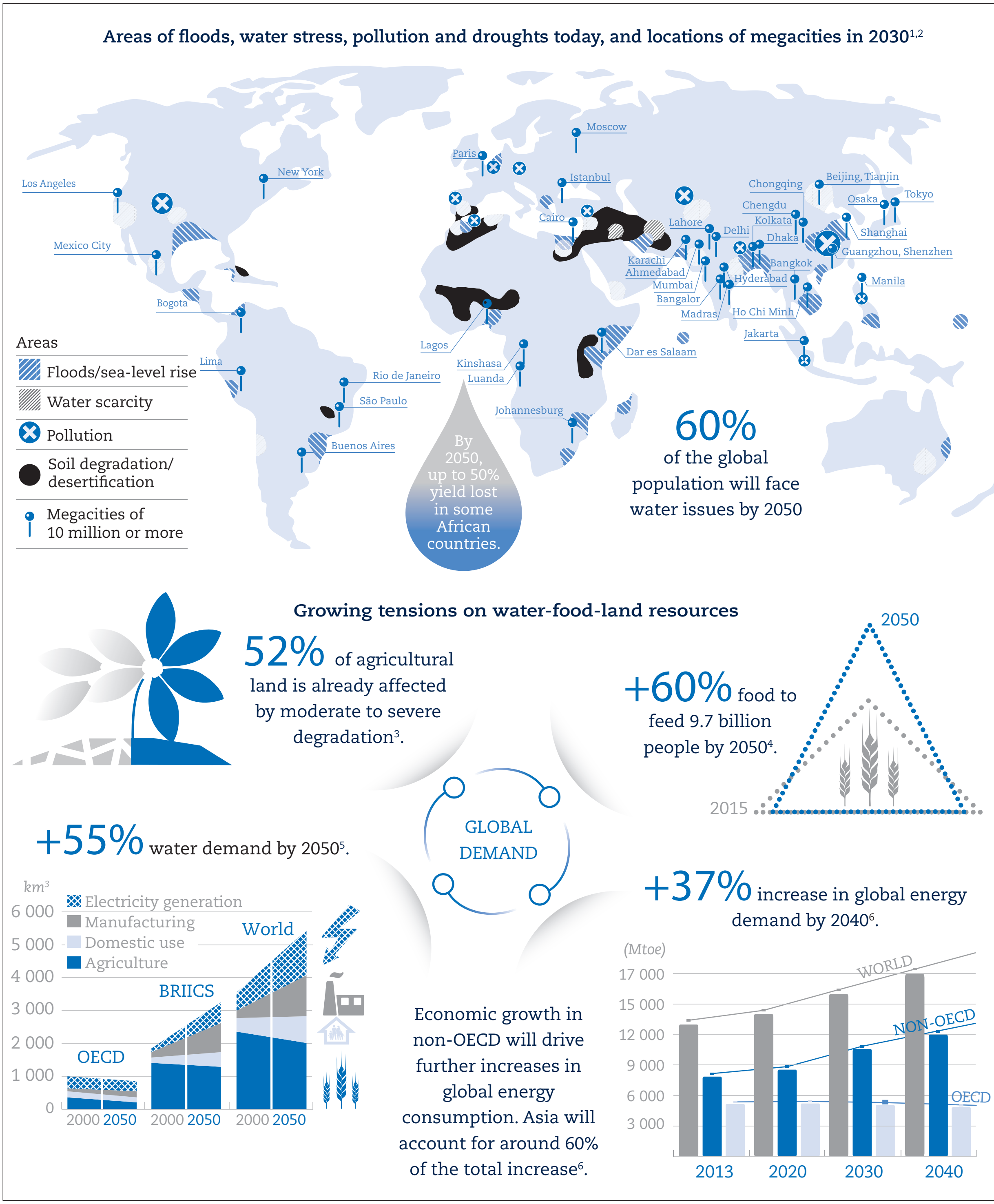
International migration

The smaller proportion of working-age people in the population will affect the labour market for STI skills in many OECD countries. The size of the working-age population (15-64) is currently at an historical peak and will very soon begin to diminish. This means the size of the dependent population (currently defined as younger than 15 and older than 64) relative to the working-age population that provides social and economic support will increase. While the ability of elderly citizens to remain active and continue working beyond official retirement age is set to increase, this alone is expected to be insufficient to meet workforce shortages. However, estimations of future workforce shortages should also consider technological change as an important determining factor, particularly the impacts of robotics and artificial intelligence. Though much debated, these technologies may reduce the demand for labour and help balance future skills mismatch. Such technologies and others (e.g. neurotechnologies) may also enhance physical and cognitive capacities, allowing people to work longer in their lives.

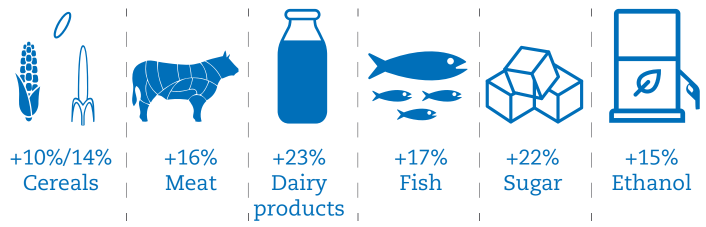
International migration may help reduce anticipated labour and skills shortages in receiving countries. The central scenario in the OECD's long-term growth projection assumes that inflows of migrant workers will be an important factor to mitigate ageing in most OECD countries (Westmore, 2014). All the signs point to a further strengthening of factors pushing and pulling migratory flows in the decades to come. Youth bulges in some parts of the developing world are creating conditions ripe for outward migration: a likely lack of employment opportunities and growing risks of internal conflict will force many to seek better lives and safety elsewhere. Climate change may also have more of an influence on future international migration flows (European Environment Agency, 2015).

Many migrants bring qualifications and skills with them. There were 31 million highly educated migrants in OECD countries in 2011, and high-skilled migration increased by 72% over the previous decade (OECD, 2015a). In Europe, over the past decade, new immigrants represented 15% of entries into strongly growing occupations, such as science, technology and engineering as well as the health and education professions. In the United States, the equivalent figure is 22% (OECD and EC, 2014). However, migrants' skills are not fully utilised in the labour markets of destination countries, and close to 8 million migrants with tertiary education in OECD countries are working in low- and medium-skilled jobs (OECD, 2015a). This is also a loss to origin countries facing "brain drain", particularly developing ones, and compromises their ability to develop the indigenous research and innovation capabilities needed to address their development challenges. A further concern is the growing size and importance of ethnic minority communities in destination countries, some of which may be poorly integrated and economically disadvantaged, which could give rise to tensions and instability (OECD, 2016a).

Natural resources and energy

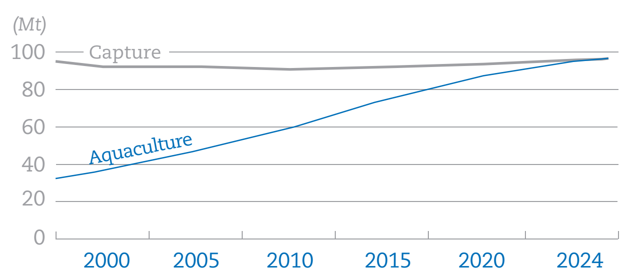


Agricultural production outlook in 2025[7]



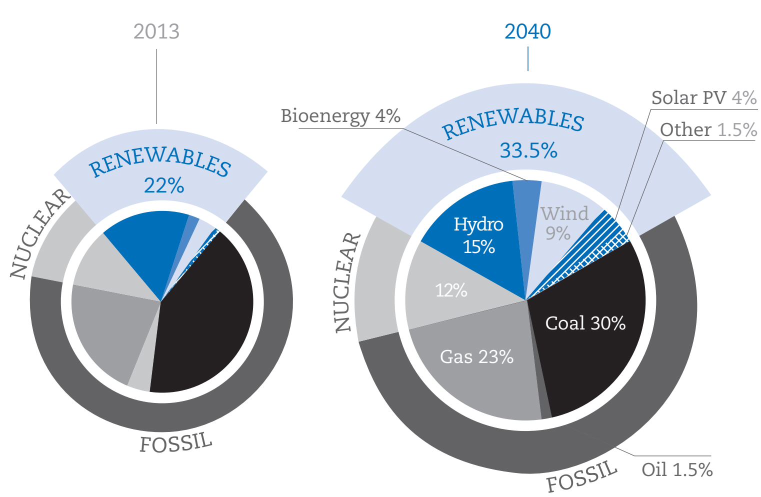
Price increases for most agricultural commodities will likely affect the poorest populations the most.

Aquaculture driving the expansion of global fish supply[7]



South and East Asian countries will continue dominating overall aquaculture production, with China, India, Indonesia and Viet Nam accounting for the majority of projected growth.

New markets for renewables
Energy supply mix (% of electricity generation)[8]



The promise of innovation

- New STI knowledge could improve the monitoring, management and productivity of natural resources and, ultimately, decouple economic growth from their depletion.
- Technology diffusion efforts will be as important as developing new technologies and should promote wide adoption of best available technologies for efficient resource use.

Agriculture, food and water

- In agriculture, as in other sectors, innovation is the main driver of productivity growth. New innovative agricultural technologies and methods could help increase land productivity in a more sustainable way.
- New technologies will play a central role in adapting agricultural practices to climate change and more extreme weather-related conditions.
- Improvements in irrigation technologies and new agricultural practices should help better monitor water use and slow groundwater depletion.
- A new generation of wastewater treatment plants using advanced technologies will be needed to deal with the challenge of micro-pollutants from medicines, cosmetics, etc.

Energy

- Onshore wind and solar photovoltaics are ready to be mainstreamed, but high levels of deployment will require further innovation in energy storage and smart grid infrastructure to increase their adaptability to weather variability.
- The Internet of Things and advanced energy storage technologies offer opportunities to better monitor and manage energy systems. Cities could play a leading role in deploying these smart innovative approaches.

Sources: 1. FAO (United Nations Food and Agricultural Organization) (2015). By 2050, up to 50% yield lost in some African countries if no significant improvement is achieved in production practices.; 2. UNDESA (2015b); 3. UNCCD (2014); 4. FAO (2012); 5. OECD (2012a); 6. IEA (2015a); 7. OECD/FAO (2016b). Cereals include wheat (10%), rice (13%), and maize (14%).; 8. IEA (2015a).

Natural resources and energy

Natural resources are a major – if not the primary – foundation of economic activity and thus ultimately of human welfare. Water, air, land and soil provide food, raw materials and energy carriers to support socio-economic activities. Their extraction and consumption affects the quality of life and well-being of current and future generations. Their efficient management and sustainable use are key to economic growth and environmental quality (OECD, 2014b).

Future population growth, changing lifestyles and economic development will enlarge global demand for water, food and energy and increase pressures on natural resources. Agriculture will remain the largest consumer of water, affecting the quality of surface and groundwater through the release of nutrients and micro-pollutants. Several energy sources change the quality and quantity of water available (e.g. hydraulic fracturing, hydropower, and cooling techniques for thermal and nuclear power plants), so that future shifts in the energy mix have to factor in water management as well (OECD, 2012a). The growing demand for biofuels has raised competition on arable yields. Further reallocation of productive lands towards non-alimentary production will be driven by price volatility and relative profitability of food commodities but could challenge food security in the medium term.

Developments in STI are set to bring new knowledge, innovative solutions and enhanced infrastructures to improve monitoring, management and productivity of natural assets and, ultimately, to decouple economic growth from their depletion. Governments are expected to play significant roles, providing knowledge infrastructures (e.g. databanks, centres of technology convergence), sharing knowledge and best practices, and financing research on agriculture, energy and natural resource management.

Water

Severe water stress is likely in many parts of the world, as water demand has outpaced population growth during the last century (OECD, 2012a; 2014b). If current socio-economic trends continue and no new water management policies are implemented (a baseline scenario), water demand is projected to increase by 55% globally between 2000 and 2050. The sharpest increases are expected from manufacturing (+400%), electricity generation (+140%) and domestic use (+130%).

Groundwater is by far the largest freshwater resource on Earth (excluding water stored as ice), representing over 90% of the world's resource (UNEP, 2008; Boswinkel, 2000, cited in OECD, 2012a; OECD, 2015b). In areas with limited surface water supply, such as regions of Africa, it is a relatively clean, reliable and cost-effective resource. Yet, groundwater is being exploited faster than it can be replenished in many parts of the world. Its rapid depletion is a consequence of the explosive spread of small pump irrigation throughout the developing world. Such intensive groundwater use is not confined to the developing world, however, with the volume of groundwater used by irrigators in several OECD countries also substantially above recharge rates, e.g. in some regions of Greece, Italy, Mexico and the United States, undermining the economic viability of farming (OECD, 2012a). Improvements in irrigation technologies and the introduction of new agricultural practices and robotics in agriculture could help better monitor water use and slow groundwater depletion, though will need to be coupled with wider institutional changes to be effective (OECD, 2015b).

Surface and groundwater are also becoming increasingly polluted because of nutrient flows from agriculture and poor wastewater treatment. Surpluses of nitrogen in agriculture are projected to decrease in most OECD countries by 2050 with greater efficiency of fertiliser use. The trend is, however, expected to go in the opposite direction in China, India and most developing countries. In parallel, nutrient effluents from wastewater are projected to increase rapidly due to population growth, rapid urbanisation and the growing number of households connected to sanitation and sewage systems. The nutrient removal in wastewater treatment systems is also expected to improve rapidly, but not fast enough to counterbalance the projected rise in inflows. Micro-pollutants (e.g. medicines, cosmetics, cleaning agents, and herbicides) are particularly worrying because they enter water bodies of various types (urban drainage, agriculture, rainwater runoff), have negative and cumulative effects on organisms (e.g. interference with hormone systems, cancers, births defects) and are resistant to regular treatment technologies.

The consequences of degraded water quality will be increased eutrophication, biodiversity loss and disease (OECD, 2012a). The economic costs of treating water to meet drinking water standards are also significant in some OECD countries. Eutrophication of marine waters imposes high economic costs on commercial fisheries for some countries (e.g. Korea and the United States) (OECD, 2012a). Advances in synthetic biology, for instance, for crop genetics, and improved efficiency in water sanitation, will require more R&D and the implementation of new generations of wastewater treatment plants and sanitation and sewage systems, combining the use of sensors and nanotechnologies (see Chapter 2). Tapping alternative water sources, such as rain and storm water, used water, and desalinated sea, and encouraging successive uses of water to alleviate scarcity are also emerging innovative practices.

Water is likely to become a major political issue. Over 40% of the world's population (3.9 billion people) is likely to live in river basins under severe water stress by 2050, but, at the same time, almost 20% (1.6 billion) are projected to be at risk from floods. Most of the future growth in water demand will arise from developing countries where the degradation of environmental conditions is already well-advanced. By contrast, water demand across the OECD area is expected to fall in line with efficiency improvements in agriculture and investments in wastewater treatment (OECD, 2012a).

Food

Global food and agriculture systems face multiple challenges. More food must be produced for a growing and more affluent population that demands a more diverse diet. At the same time, competition for alternative uses of natural resources is increasing and agricultural practices and technologies will have to adapt to climate change and more extreme weather-related conditions.

It is estimated that 60% more food will be required to feed the world population by 2050 (OECD, 2013a). On a global level, food production should be able to support this demand and the proportion of people who are undernourished should drop slightly from 11% to 8% by 2025 (OECD/FAO, 2016). However, food and nutritional insecurity will persist in many, predominantly poor, regions where water scarcity and soil degradation will continue to damage agricultural lands (FAO and WWC, 2015). Today, around half of arable land is already affected by moderate to severe degradation. Desertification and drought are likely to transform around 12 million hectares of productive lands (the equivalent of Bulgaria, Honduras, or Nicaragua) into barren regions annually (UN, 2015b). If no significant improvements are achieved in production practices, the loss of yield may be as high as 50% in some African countries by 2050 (UNCCD, 2014). The situation in most OECD and BRIICS countries is, however, less severe, as continuing yield improvements will lead to more efficient use of land. Instead of agricultural land expansion, land abandonment is planned in many countries, which will allow ecosystems to partially recover and regenerate (OECD, 2012a).

Modern agricultural technologies and methods could help increase land productivity in a more sustainable way. In agriculture, as in other sectors, innovation is the main driver of productivity growth (OECD, 2013b). Innovation can also improve the environmental performance of farms and the quality of agricultural products. Sensors can help farmers manage their tractor fleet, reducing downtime and saving energy (OECD, 2016b). Some innovations (e.g. around irrigation, animal medicines, pesticides, improved seeds, and innovative risk management tools) have the potential to help farmers better deal with production and income uncertainties, and ultimately increase earnings. For instance, increased production, together with innovation in aquaculture, has significantly lowered production costs in fisheries, providing benefits to both consumers and producers (OECD, 2015c). In some regions, the challenge is to adapt agricultural production systems to more difficult natural environments, e.g. due to salinity, more frequent drought, etc.

Food consumption habits will likely change, reflecting growing living standards, higher participation rates of women in the labour force, and reduced time available for meals (OECD, 2013b). The prices of most agricultural commodities are projected to increase significantly by 2050, which will especially affect poorer populations (Ignaciuk and Mason-D'Croz, 2014). Innovation will have a key role to play in helping the agrifood sector produce more nutritious, diverse and abundant food, address changes in food diets, and provide raw materials for non-food use. At the same time, innovation should alleviate natural resource depletion and enable adaptation to the expected changes in natural conditions caused by climate change (OECD, 2013b).

Aquaculture will continue to be one of the fastest growing food sectors and, in 2025, is expected to provide over half the fish consumed worldwide. Fish consumption will expand in all continents, but particularly in Oceania and Asia, and South and East Asian countries, predominantly China, India, Indonesia and Viet Nam, which are projected to dominate production (OECD/FAO, 2016).

Energy

Energy consumption will rise sharply, driven by population and economic growth. Based on existing and planned government policies (the International Energy Agency's [IEA] so-called "New Policies Scenario"), global primary energy demand is set to increase by 37% between 2012 and 2040. Most of this increased demand can be ascribed to economic growth in OECD partner economies, particularly in Asia, which will account for around 60% of global energy consumption (IEA, 2015a). Growth in global demand is expected to slow down after 2025 as a result of price and policy effects, and structural shifts towards services and lighter industrial sectors (IEA, 2014a). However, industry will likely remain the largest consumer of energy in 2040, followed by transportation and commercial and residential buildings.

The global energy mix will be transformed, mainly on account of the growing use of renewables. This means that low-carbon sources and fossil energies (i.e. oil, gas and coal) will make up almost-equal parts in the world's energy supply mix by 2040. Worldwide, the largest share of growth in use of renewables for electricity generation will be from wind power (34%), followed by hydropower (30%) and solar technologies (18%) (IEA, 2014a). At the same time, biofuels may provide up to 27% of the world's transportation fuel by 2050, up from the current level of 2% (IEA, 2011). New markets for renewables will depend on technological breakthroughs and smart infrastructures, enabled by significant investments in R&D and infrastructures and new strategic public-private partnerships (IEA, 2014b).

The water-food-energy nexus

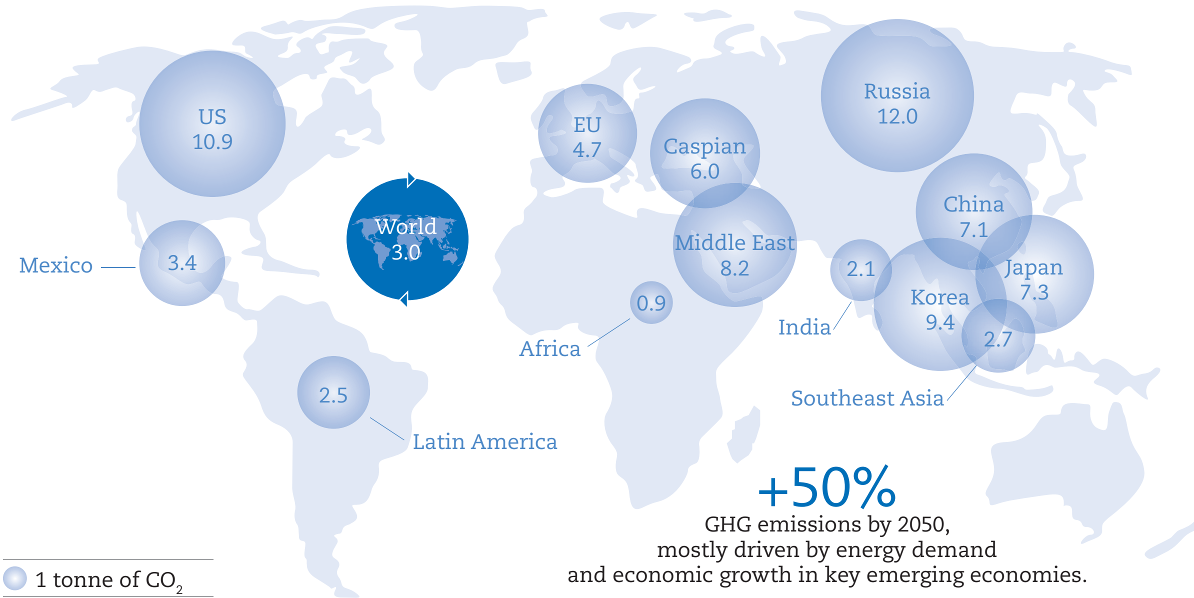
The interconnection of water-food-energy issues and their interdependence make them difficult to address separately. The Internet of Things (IoT), smart apps, sensors, machine-to-machine communication, and the greater connectivity of people and objects offer opportunities to better monitor pressures on the water-food-energy nexus, anticipate critical tensions and balance supply and demand (see Chapter 2). Cities are the places at which these smart innovative approaches could arise and be efficiently deployed (OECD, 2014c).

The nexus among water, food and energy (and environment) is close, complex, and challenging. Policy coherence and a co-ordinated approach among water, agriculture and energy policies, as well as other sectoral policies – particularly transport, industry and construction – will be essential. Smart regulation will be required to regulate natural resources consumption (e.g. water extraction licenses) and put sustainable prices on natural resources and related services as a way to signal scarcity and manage demand. International co-operation on R&D, on resource management and for aligning national policy frameworks will be needed.

Climate change and environment

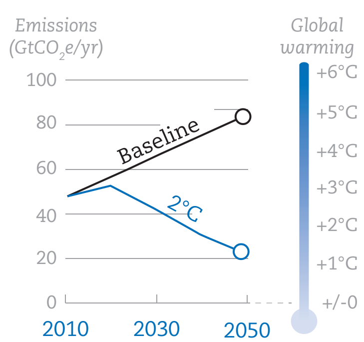
Energy-related CO_2 emissions per capita, 2030

CO_2 emissions account for 75% of global GHG emissions, with most coming from energy production[1]



+50%
GHG emissions by 2050, mostly driven by energy demand and economic growth in key emerging economies.

Global emissions and the 2°C target[2]

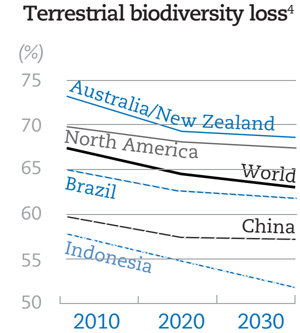


40%-70% reductions in global GHG emissions by 2050 to meet the 2°C Scenario[3].

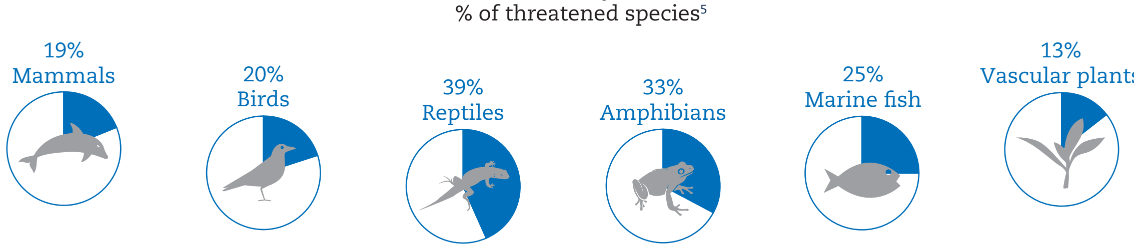
10%
Biodiversity loss by 2050, with highest losses in Asia, Europe and southern Africa[4].

60%
of the world's biocapacity is held by only ten countries that suffer most from heavy land and forest degradation[5].

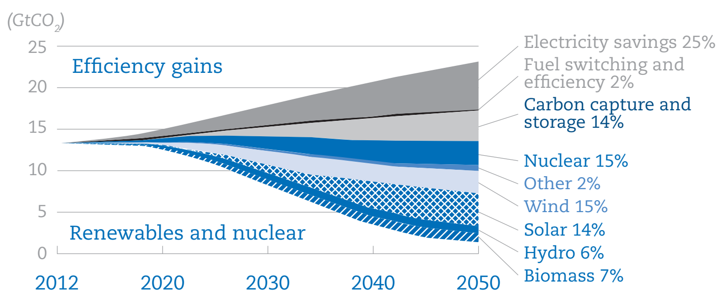
Terrestrial biodiversity loss[4]



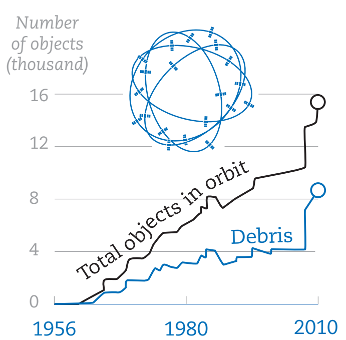
OECD biodiversity is at threat
% of threatened species[5]



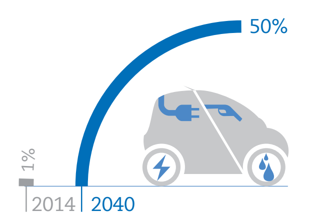
Key technologies to reduce power sector CO_2 emissions[6]



Space junk: danger of collision[7]

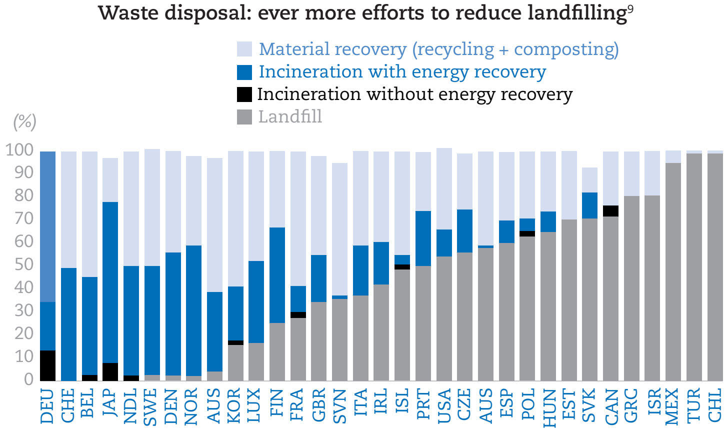


Exploding sales of hybrid vehicles
Total vehicle sales in %[8]



Hybrid cars are expected to become cost-competitive by 2025.

Waste disposal: ever more efforts to reduce landfilling[9]



Over the past two decades, OECD countries have put significant efforts into curbing municipal waste generation.

International co-ordination

- The global nature of climate change and environmental degradation will require greater international co-operation on solutions, including research and innovation.
- Climate change mitigation and adaptation will depend on technology transfer to less advanced countries, which are set to account for the largest increases in GHG emissions over the next few decades due to their rapid development.

Research strategies

- Energy technology innovation will be key in achieving the 2 °C scenario. A comprehensive portfolio of low-carbon technologies, including solutions for decarbonisation, will be needed to achieve policy climate goals.
- Challenges of climate change and ongoing degradation of the natural environment, including loss of biodiversity, could become even more dominant themes in future national research agendas.
- The "circular economy" concept will likely gain momentum and shape future innovation agendas. New technologies, processes, services and business models will be fundamental requirements for a circular economy.

Multi-actor perspective

- While governments are expected to play a leading role in enabling the transition to low carbon societies, the private sector will need to lead innovation efforts in this direction.
- The Internet of Things, smart apps and sensors will enable a closer monitoring of climate change, ecosystems and biodiversity.
- Participatory monitoring and big data will generate large amounts of novel data that could support new research practices and citizen science in support of more sustainable growth.

Sources: 1. IEA (2015b). Energy-related CO_2 emissions per capita by selected region in the INDC Scenario and world average in the 450 Scenario. ; 2. UNEP (2015); 3. UNEP (2014); 4. OECD (2012a). Terrestrial mean species abundance (terrestrial MSA) is a relative indicator describing changes of biodiversity with reference to the original state of the intact or pristine ecosystem (i.e. a completely intact ecosystem has a MSA of 100%).; 5. OECD (2016c). OECD figures are simple average of available country shares. However simple average does not reflect cross-country differences, and some species are more threatened in some countries than in others. Species assessed as Critically Endangered (CR), Endangered (EN), or Vulnerable (VU) are referred to as "threatened" species. Reporting the proportion of threatened species on The IUCN Red List is complicated by the fact that not all species groups have been fully evaluated, and also by the fact that some species have so little information available that they can only be assessed as Data Deficient (DD).; 6. OECD and IEA (2015). The 2°C Scenario (2DS) is the main focus of *Energy Technology Perspectives*. It limits the total remaining cumulative energy-related CO_2 emissions between 2015 and 2100 to 1 000 $GtCO_2$.; 7. NASA (29 September 2016); 8. ExxonMobil (2016); 9. OECD (2015d), OECD (2014d), OECD (2014e).

The world is warming

Global land and ocean surface temperature data show an averaged combined warming of 0.85°C over the period 1880 to 2012. The greatest warming over the past century has occurred at high latitudes, with a large portion of the Arctic having experienced warming of more than 2°C. The last 30 years were likely the warmest of the last 1 400 years in the northern hemisphere (IPCC, 2014). Further global warming over the next few decades is now inevitable.

There is a strong relationship between projected global temperature change and cumulative CO_2 emissions (IPCC, 2014). Anthropogenic greenhouse gas (GHG) emissions are extremely likely to have been the dominant cause of the observed warming since the mid-20th century. Atmospheric concentrations of carbon dioxide (CO_2), methane and nitrous oxide are unprecedented in at least the last 800 000 years. CO_2 emissions account for around 75% of global GHG emissions, with most coming from energy production. Around half of the anthropogenic CO_2 emissions since 1750 have occurred in the last 40 years. Fossil fuel combustion represents two-thirds of global CO_2 emissions (OECD, 2012a) while agriculture is a major emitter of the more powerful greenhouse gases of methane and nitrous oxide.

Mitigating global warming requires much more ambitious strategies to reduce GHG emissions. The IEA's New Policies Scenario is consistent with a long-term temperature rise of 4°C. This ambitious scenario requires significant changes in policy and technologies, but will still lead to dangerous levels of climate change. A more stringent scenario (2DS) that would meet the 2°C target agreed at the Paris climate conference requires a 40%-70% reduction in global GHG emissions by 2050. It will mean increasing the share of low-carbon electricity supply from 30% to more than 80% by this time (IPCC, 2014).

Energy technology innovation will be key in achieving the 2DS. A comprehensive portfolio of low-carbon technologies, including solutions for decarbonisation, could make climate goals achievable (IEA, 2015c). Some solutions will be broadly applicable, while others will target specific sectors. In the power sector, onshore wind and solar PV are ready to be mainstreamed. But high levels of deployment will require further innovation in energy storage and smart grid infrastructure to increase their flexibility to weather variability (IEA, 2015c). Carbon capture and storage (CCS) technologies are projected to play an important role, though require further technical and market development before they can be extensively implemented. Nanotechnology can provide innovative solutions for CCS materials (OECD, 2016b). Biotechnology also offers unique solutions to dependence on oil and petrochemicals. Bio-based batteries, artificial photosynthesis and micro-organisms that produce biofuels are some recent breakthroughs that could support a bio-based revolution in energy production.

There are also expanding markets for low-energy products and components and, in sectors such as industry, transport and buildings, energy efficiency technologies are expected to play a leading role. Nanotechnology can provide innovative solutions to lower energy use in industry and enable the replacement of energy-hungry processes with low-cost processes. In addition, low-energy components or technologies could be instrumental to the development and uptake of other technologies. For example, additive manufacturing can support less material and energy use through sophisticated design and lean production principles. This can be achieved by printing replacement parts that would otherwise be discarded; by reducing weight in a vehicle; or by improving a product's energy efficiency. Such energy savings can be quite large, especially in sectors like aerospace.

As emerging economies are projected to account for most of the increase in GHG emissions over the coming decades, their uptake of innovative low-carbon technologies will be crucial – and could account for almost three-quarters of worldwide CO_2 emissions reductions by 2050 in the 2DS. Rapid economic development in these regions will support technological deployment but international co-operation will be required to ensure technology and knowledge transfer. Furthermore, future technology adoption will require raising domestic skills and organisational capabilities (IEA, 2015c).

Consequences for climate, ecosystems and health are dramatic

A series of severe climatic changes will accompany global warming. Heat waves will likely occur more often and last longer, while extreme precipitation events will become more intense and frequent in many regions. Rainfall will most likely increase in the tropics and higher latitudes, but decrease in drier areas. The oceans will continue to warm and acidify, strongly affecting marine ecosystems. The global mean sea level will continue to rise at an even higher rate than during the last four decades. The Arctic region will continue to warm more rapidly than the global mean, leading to further glacier melt and permafrost thawing. However, while the Atlantic Meridional Overturning Circulation will most likely weaken over the 21st century, an abrupt transition or collapse is not expected (IPCC, 2014).

Climate change will have profound impacts on water and food security at regional and global levels. Extreme and variable rainfall will affect water availability and supply, food security, and agricultural incomes, and will lead to shifts in the production areas of food and non-food crops around the world (IPCC, 2014). The impacts of climate change will likely reduce renewable surface water and groundwater resources in the driest regions, intensifying competition for water among different sectors (IPCC, 2014).

As climate change modifies water-food systems and the quality of air, new diseases could appear or existing ones expand. Global premature deaths from outdoor air pollution are set to double by 2050 (OECD, 2012a). Malaria is the most important infectious disease that is exacerbated by climate change. Currently, more than half of the world's population (3.7 billion) lives in areas at risk. This number is expected to grow to 5.7 billion people by 2050. The bulk of the population living in risk areas (i.e. warm areas which are a suitable habitat for the malaria mosquito) will be in Asia (3.2 billion) and Africa (1.6 billion).

The number of weather-related disasters has increased worldwide over the last three decades, particularly floods, droughts and storms (EMDAT data, cited in OECD, 2012a). Science and technology will play a vital role in monitoring ecosystems and managing natural disasters. National meteorological agencies that are often in charge of early warning systems will increasingly rely on satellite data, in addition to ground-based networks of radars, to maintain continuous observation of global weather, making warning systems more efficient (OECD, 2012c). In particular, the deployment of constellations of nano- and microsatellites could support a continuous monitoring of wider geographic areas, including oceans, and improvements in forecasting (see Chapter 2). Construction and transport industries will draw on innovative materials and technologies to adapt to new extreme environmental conditions.

Global biodiversity is at threat

Changes in temperature and precipitation regimes influence the distribution of species and ecosystems. As temperatures increase, ecosystems and species' ranges tend to shift towards the poles or to higher altitudes (OECD, 2012a). This migration causes some ecosystems to shrink and others to expand. Biodiversity loss is a major environmental challenge. Despite some local successes, biodiversity is on the decline globally and this loss is projected to continue (OECD, 2012a). Around 20% of mammals and birds, almost 40% of reptiles, a third of amphibians, and a quarter of marine fish are already on the list of threatened species (OECD, 2016c). In a baseline scenario, i.e. in the absence of new policy interventions, 10% of biodiversity is likely to be lost by 2050, most of the loss occurring before 2030. The steeping declines are likely to be in the bush and savannah, as well as temperate and tropical forests (OECD, 2012a).

Threat levels are particularly high in countries with high population density and a high concentration of human activities. Pressures on biodiversity can be physical (e.g. habitat alteration and fragmentation), chemical (e.g. toxic contamination, acidification, oil spill, other pollution) or biological (e.g. alteration of species dynamics and structure through the release of exotic species or the commercial use of wildlife resources) (OECD, 2015e). But, to date, the main drivers of global terrestrial biodiversity loss have been land-use change and management, i.e. conversion of natural ecosystems for producing food and bioenergy crops and livestock (OECD, 2012a). Deforestation remains a major concern, although annual deforestation rates are slowing down. Over-exploitation of water resources and changes in the hydromorphology of water systems (eutrophication, acidification) threat aquatic ecosystems.

Yet, the large benefits of biodiversity and ecosystem services provide incentives to investing in conservation and sustainable use. For example, some estimates give pollination services provided by insects at USD 192 billion per year and the global value of coral reefs for fisheries, coastal protection, tourism and biodiversity at USD 30 billion per year. The global loss of forests that provide natural habitats and contribute to carbon sequestration, water regulation and erosion prevention, is estimated at between USD 2 trillion and USD 5 trillion per year (examples cited in OECD, 2012a). In some countries, in Asia and Africa, 80% of the population relies on traditional medicine (including herbal medicine) for primary health care (OECD, 2014f). As extinctions continue the availability of some of these medicines are likely to be reduced and new drug developments may be curtailed.

Most biodiversity-rich areas are located in developing countries. Low-income countries are expected to account for 39% of global terrestrial biodiversity losses, the BRIICS 36% and OECD countries 25% by 2050 (OECD, 2012a). Losses are likely to be high in Japan and Korea, Europe, Southern Africa and Indonesia. Some central European countries already experience extreme biodiversity threat (OECD, 2016c). In addition developing countries tend to bear most of the costs of biodiversity loss as they are often more dependent on natural resources for economic development than developed countries (OECD, 2012a).

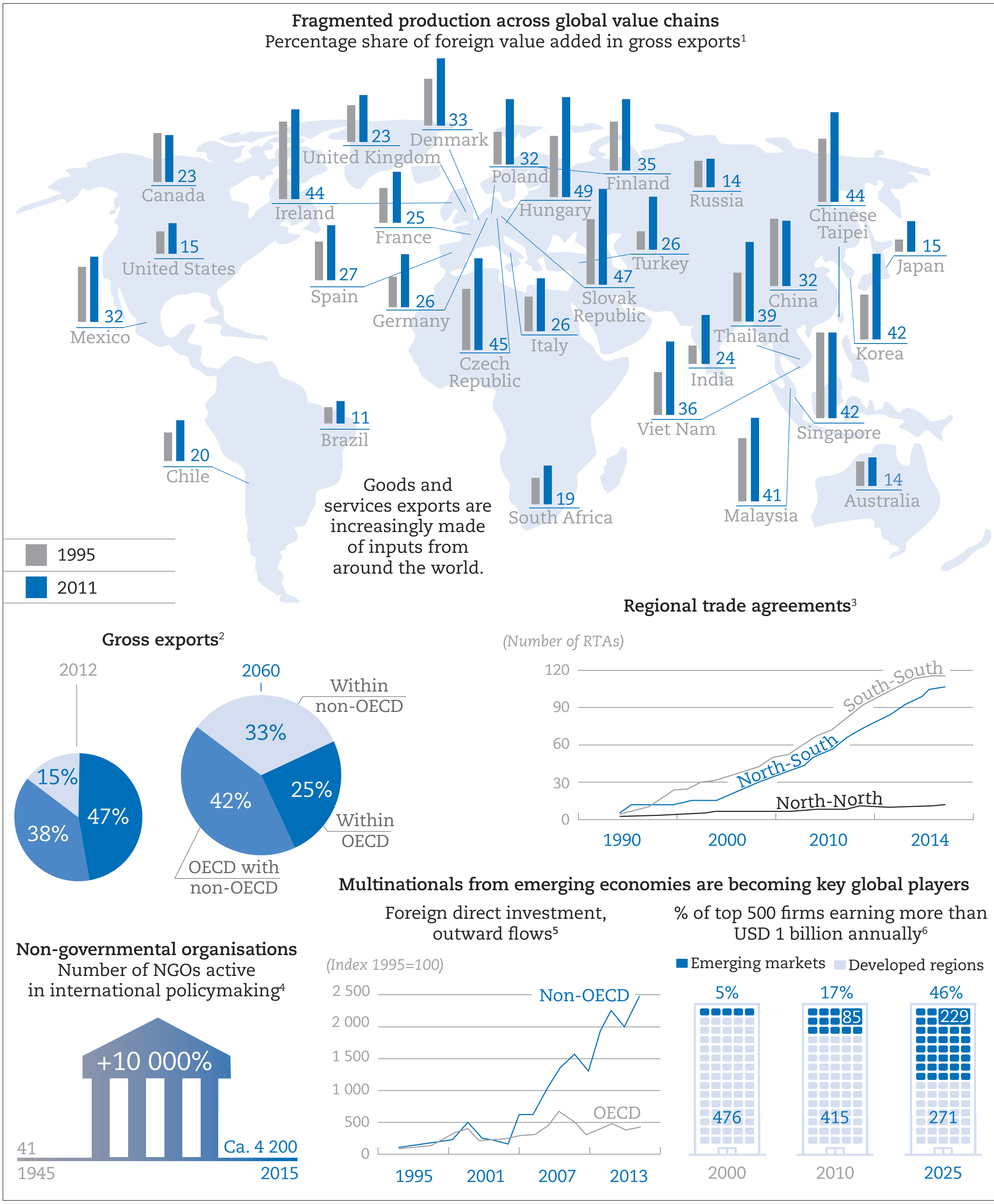
Governments have tried to design networks of protected areas connected by natural corridors with a view to restoring, maintaining and enhancing ecological coherence and the natural adaptive capacity of ecosystems. Where ecosystems span political boundaries, maintaining connectivity may require co-ordination among managers and scientists from neighbouring countries. Local and indigenous communities can also play a critical role in the management of protected areas and as a source of local and traditional knowledge (OECD, 2012a). The IoT, smart apps and sensors could support the functioning of these protected areas and help involve local populations and populations in remote areas in a closer monitoring of ecosystems and biodiversity. Participatory monitoring and big data could generate large amounts of novel data and support new research practices and citizen science.

Waste recycling and the premises of the circular economy

Weak waste management has negative impacts on human health and the environment, e.g. soil and water contamination, air quality, land use and landscape. Over the past two decades, OECD countries have put significant efforts into curbing waste generation and the growth of municipal waste has slowed from 1.24% between 1995 and 2004 to 0% between 2005 and 2014 (OECD, 2015e). Today, a person living in the OECD area generates on average 520 kg of waste per year. Increasing amounts of waste are being fed back into the economy through recycling. Mechanical and biological pre-treatment is increasingly used to enhance recovery rates and incineration efficiency. Government guidelines encourage or require manufacturers to accept responsibility for their products after the point of sale, e.g. the European Union has introduced recycling targets for all its member states. Landfilling of municipal waste has been banned in a few countries. Recycling rates are increasing (by up to 80% in some cases) for materials such as glass, steel, aluminium, paper and plastics (OECD, 2015f).

A perceptible shift is under way towards the "circular economy". OECD countries are stepping up efforts to move to a more resource-efficient economy, and are showing signs of decoupling material consumption from economic growth. The circular economy implies a systemic change, moving to a zero- or at least low-waste, resource-efficient society and involving big changes to our methods of both production and consumption. Looking beyond the potential for materials savings and a smaller footprint on the environment that a move away from the established "take, make and dispose" model could bring, a circular economy would create huge economic opportunities as new services and business models emerge and the relationship between producer and consumer, and between a product and its user, undergoes radical transformation. Repair, re-use, re-distribution and re-manufacture would increase, as would recycling rates; and materials technology would evolve and enable a move from non-renewable materials to the production and use of high levels of renewable materials in finished products (Waste Management World, 2015). This scaling up of the shift to a circular economy promises to deliver substantial macroeconomic as well as corporate benefits. The materials savings potential alone is thought to be over USD 1 trillion annually (WEF, 2014; McKinsey Centre for Business and Environment and The Ellen MacArthur Foundation, 2015).

Globalisation



Crime is increasingly globalised
Value of illicit international trade
(estimates, USD billion, 2015)[7]

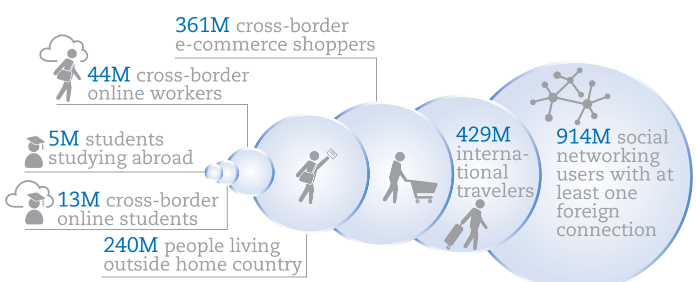
Illicit trade is a
multi-billion-dollar business.

Tax evasion has turned global
Tax revenue losses
(estimates, USD billion, 2015)[8]

USD 100-240 billion could be lost annually due to tax avoidance…

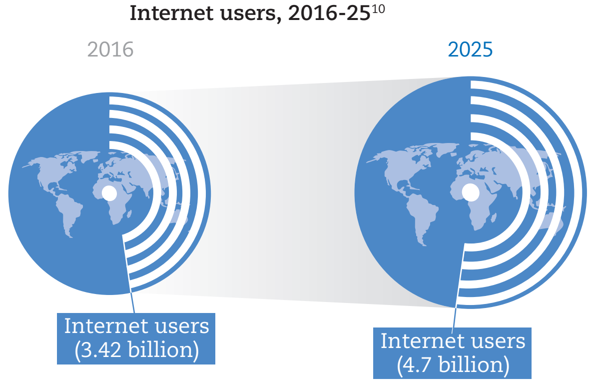
… This is 4% to 10% of global corporate income tax revenues.

Individuals participating in globalisation today[9]



By 2020, some 940 million (M) online shoppers are expected to spend almost USD 1 trillion on cross-border e-commerce transactions.

Internet users, 2016-25[10]



English is the lingua franca of the globalised world with 1 in 4 people using it globally. Non-native speakers account for more than 80% of English online communications[11].

International R&D co-operation

- Globalisation will continue to facilitate the wide diffusion of knowledge, technologies and new business practices and will itself be deepened by this diffusion.
- National STI policy could be framed increasingly in global terms, reflecting the global nature of many problems and issues, and the globalisation of markets and production.
- International agreements and initiatives, such as the Paris Agreement on climate change (COP21) and the UN's Sustainable Development Goals, will further international co-operation in research and direct it towards global grand challenges.

Business R&D

- Business R&D and innovation are increasingly global.
- As important agents of globalisation, multinational enterprises could internationalise their R&D at a faster pace and on a larger scale than before.
- Global value chains could further encourage national industrial specialisation and an increasing concentration of innovation capacities.
- Standards play a crucial role in innovation and are increasingly internationalised since, in a globalised economy, compatibility and interface across borders are ever more important.

Human mobility

- International mobility of highly educated individuals at different stages of their professional careers is a significant driver of knowledge circulation worldwide.
- Countries and institutions are engaged in a global competition for talent to build their own centres of global scientific excellence.
- Digital technologies increasingly help ease the strains of mobility, enabling individuals to maintain regular contact with friends and families for example.

Sources: 1. OECD and WTO (2016); 2. Johansson and Olaberría (2014a); 3. WTO (2013); 4. UN ECOSOC (2016). Figures are cumulative. The cut-off date for these data is 8 January 2015.; 5. OECD (2015f); 6. McKinsey & Company (2016); 7. OECD (2016d); 8. OECD and G20 (2016). BEPS refers to tax avoidance strategies that exploit gaps and mismatches in tax rules to artificially shift profits to low or no-tax locations. Under the inclusive framework, over 100 countries and jurisdictions are collaborating to implement the BEPS measures and tackle BEPS.; 9. Facebook, AliResearch, US Department of Commerce, OECD, World Bank, MGI (2016); 10. Burt, D. (2014); 11. Sharifian, F. (2013).

Globalisation

Globalisation – in the form of international flows of capital, goods, and people – facilitates the spread of knowledge, technologies and new business practices. These dynamics positively affect innovation and long-term economic productivity. Furthermore, technological change, particularly in ICTs and transport, has enabled and even accelerated globalisation. The megatrend of ever more globalisation may continue to exert significant influence over the next 10-15 years, though counter-currents, such as growing protectionism, may be disruptive and give rise to discontinuity.

Trade and global value chains

Since 1995, most countries have experienced significant increases in the share of foreign value added in both exports and final consumption, reflecting the increasing interdependency of the global economy (OECD, 2015g). Global trade integration is expected to continue to grow in the future, albeit at a slightly slower rate than seen during recent decades. Trade in services is expected to continue to expand faster than trade in goods, due partly to the continuing liberalisation of the sector, partly to the increasing share of GDP accounted for by services, and partly to trends in consumption pushed by ageing populations. Trade patterns will reflect shifts in global economic weight, with exports from OECD non-member economies expected to rise from 35% of world exports in 2012 to 56% in 2060 (Braconier, Nicoletti and Westmore, 2014).

The rapid growth of global value chains (GVCs) has been an important driver of economic globalisation during the past decades and has resulted in a growing interconnectedness between countries. GVCs have on average become longer and more complex over time with production spanning a growing number of countries, increasingly also in emerging economies. The increasing international fragmentation of production in GVCs, assisted by digitally-enabled logistics, telecommunications, and business services, have seen more labour-intensive activities typically offshored from OECD countries to economies with low-cost labour. But the extent to which this will continue in the future is uncertain. Wage increases, e.g. in eastern China, and increasing automation are eroding the labour cost advantage of emerging economies, while long and complex GVCs have exposed companies to a growing degree of supply risk in case of adverse shocks. In addition, management, logistical and operational problems, including the protection of IPR, resulted often in significant "hidden" costs (i.e. costs that were not taken into account in the decision to offshore) and have in some cases made offshoring less or not profitable (OECD, 2015h). Taken together, these supply-side factors may motivate some companies in some industries to "re-shore" activities closer to their main markets in OECD countries.

At the same time, emerging economies like China are attempting to switch to higher value-added activities, and shift their positions – both upstream and downstream – in GVCs. Innovation is the key to capacity upgrading. Industrial R&D capacities have developed fast in these regions, and steady increases in R&D intensities point to growing global competition in R&D assets. More broadly, the growing importance of GVCs might result in stronger concentration on a specific set of tasks, i.e. those in which a country's firms have a comparative advantage. Depending on the governance structures of GVCs, this can lead to an increasing concentration of innovation capacities among national actors (OECD, 2015i).

In addition to moves to foster more open multilateral trade over the last few decades, many countries have more recently sought in parallel to establish new bilateral and regional trade agreements (RTAs) to increase trade and spur economic growth. The current proliferation of RTAs in part reflects a demand for deeper integration than has been achieved by existing multilateral agreements. These agreements could see the geography of GVCs accordingly shift towards a more regional organisation.

Multinational enterprises

R&D and innovation activities are increasingly global, thanks to the shifting international organisation of functions within multinational enterprises (MNEs), which are internationalising their R&D at a faster pace and on a larger scale than before (OECD, 2015i). Foreign-controlled affiliates play an important role in domestic R&D in several OECD countries. In 2013, they accounted for more than one-fifth of total business R&D among a majority of countries for which data are available (OECD, 2015g). Patented inventions also often result from collaboration between inventors from different economies. On average, the international co-invention of patents increased by 27% between 2000-03 and 2010-13 (OECD, 2015g).

FDI flows worldwide have tripled since the mid-1990s, growing at a faster pace than international trade in goods and services. Although most flows still take place within the OECD, the landscape has changed dramatically in the past decade. Until 2003, around 95% of FDI outflows originated from OECD countries, but over the past decade their share has fallen below 80% owing to the spectacular rise in overseas investment by emerging economies. Overall, outward flows from BRIICS have more than tripled between 2002-07 and 2008-13. Some of this investment has been directed at acquiring more advanced technologies than those available domestically as part of corporate technology upgrading strategies, a phenomenon that is likely to grow as emerging economies move closer to technological frontiers in certain sectors. As for inward flows, FDI in China and Southeast Asia has risen from an average of about USD 83 billion a year in 1995-2001 to about USD 417 billion a year in 2008-13. China was the largest non-OECD FDI recipient in 2013, with a twofold increase in average annual inflows over 2008-13. Inward FDI may provide recipient countries with access to new technologies and generate employment opportunities and knowledge spillovers for domestic firms (OECD, 2015g).

Standards play an important role in innovation, providing industry-wide consensus on the rules, practices, metrics or conventions used in technology, trade and society at large. Standardisation work is increasingly conducted internationally, since, in a globalised economy, compatibility and interface across borders are increasingly important. Firms that play primary roles in setting international standards gain advantages from doing so, to the extent that the new standards align with their own standards and/or features of their productive base (OECD, 2015i).

Global digital flows

Not only have flows of goods and finance increased over the last two decades, but digital flows of commerce, information, searches, video, communication, and intracompany traffic have surged as well. Cross-border bandwidth has grown 45 times larger since 2005 and is projected to grow by another nine times in the next five years (MGI, 2016). Global digital platforms are helping drive down costs of cross-border communications and transactions, thereby reducing the minimum scale at which businesses can operate globally and enabling small businesses to become "micro-multinationals" (eBay, n.d.). Global digital platforms also help individuals form their own cross-border connections, enabling them to learn, find work, showcase their talent, and build personal networks. Some 900 million people have international connections on social media, and 360 million take part in cross-border e-commerce, figures that are growing rapidly (MGI, 2016).

Globalisation of illicit trade

The liberalisation of trade and relatively low cost of transcontinental supply chains have changed the geographic scope, volume and range of goods traded in illegal markets. The profits of transnational organised crime have been estimated to be as high as USD 870 billion, equivalent to 1.5% of global GDP (UNODC, 2011). The magnitude and gravity of their negative social, economic and even political impacts have also grown (OECD/EUIPO, 2016). For example, international trafficking in narcotics, arms and especially humans have obviously corrosive social effects. Illicit trade in counterfeits undermines the model of investment in research and development, e.g. in pharmaceuticals. Wildlife trafficking destroys biodiversity and can trigger the spread of zoonotic disease. Illicit trade's use of bribery and undue influence also undermines good governance and can threaten political stability (OECD, 2016d).

International illicit networks depend on and benefit from many of the same technologies and innovations that legal private firms exploit to enhance their competitiveness. The Internet is a particularly prominent example, with the migration of criminal activities online increasing the overall digital security threat level. An underground cybercrime economy has emerged, with well-organised transnational groups demonstrating considerable technical innovation skills to commit financial, information and identity theft using increasingly sophisticated technical tools, some of which are automated and deployed on a large scale for maximum impact (OECD, 2015j).

Political globalisation

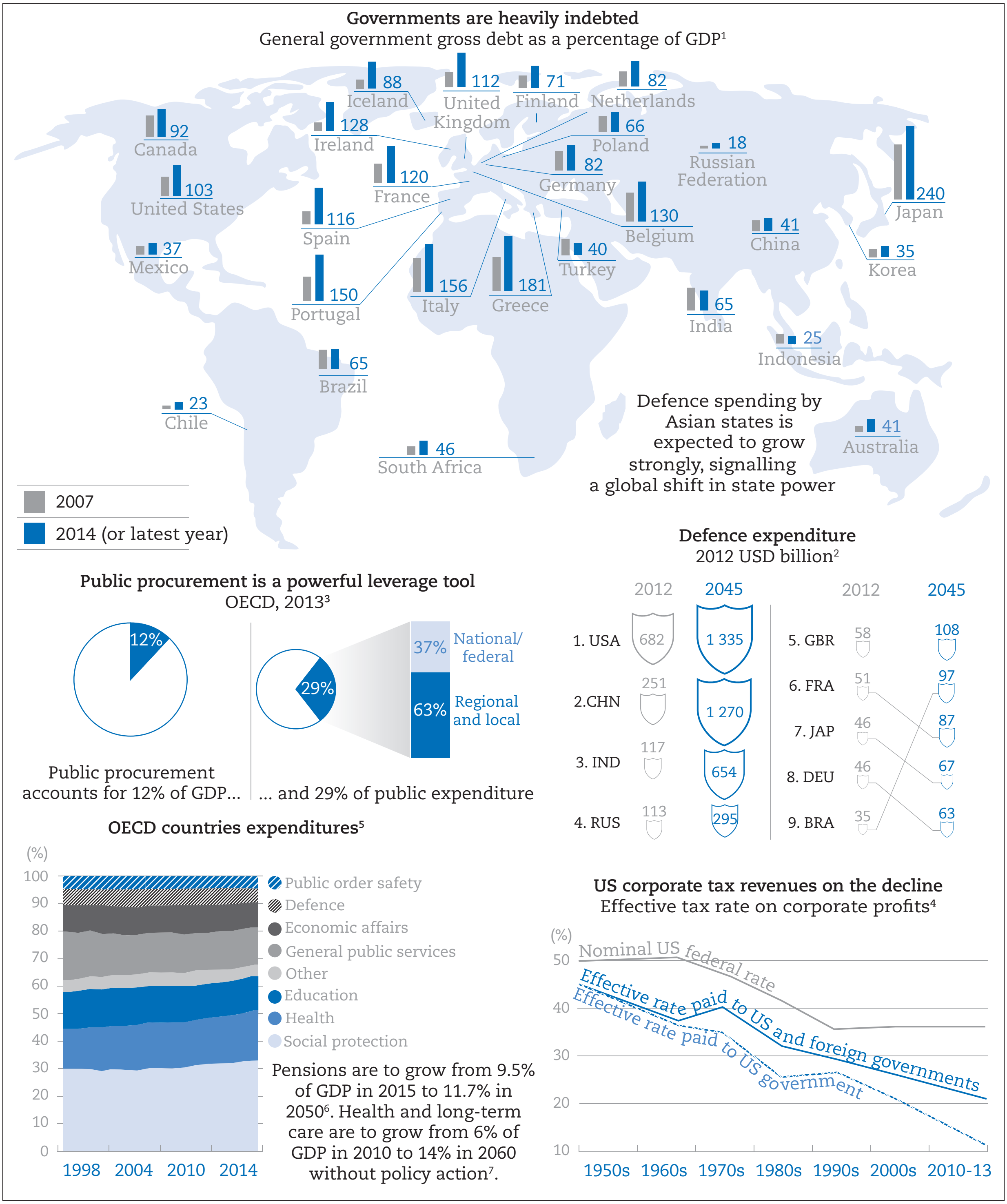
While the State is poised to remain the dominant actor in national and international affairs in the near future, increasing international connectivity between a range of actors, including multinational enterprises, global civil society movements and cities, means the environment for tackling global problems is changing. At the same time, the extraordinary economic development of Asia in recent decades implies a historic shift in economic and geopolitical power that calls into question the legitimacy of many existing post-Second World War multilateral institutions. Lack of representation remains a major concern, particularly among international financial institutions, which has driven some emerging economies to establish parallel national and multilateral mechanisms (e.g. development banks, regional trade blocks, and groupings like BRICS). Taken together, this fragmentation of power could make it more difficult for States to forge international consensus on global and regional issues (OECD, 2015k). On the other hand, a number of recent successes on the global governance front deserve highlighting, particularly the Paris COP21 agreement and the UN's Sustainable Development Goals, both of which have strong STI dimensions.

National STI policy is increasingly framed in global terms, reflecting the global nature of many problems and issues, and the globalisation of markets and production. Cross-border governance is therefore of growing importance for STI, particularly in helping address global "grand challenges" such as climate change and threats to health and resource sufficiency. However, international frameworks in many STI areas are still in their infancy and are affected by several barriers, particularly difficulties in trying to co-ordinate collective funding via national funding regimes. Countries also have concerns about the appropriation of the benefits of pooling public investments in research and innovation, given the emergence of STI as a focus of national industrial policy (OECD, 2015i).

International mobility through tertiary education

International mobility among highly educated individuals at different stages of their personal development and professional careers is a significant driver of knowledge circulation worldwide. A key stage is tertiary-level education, where students that study or spend some time in a foreign tertiary-level institution will build links with other individuals and acquire competences that can be carried over to other places during their working lives (OECD, 2015g). There has been more than a fivefold increase in foreign students since the mid-1970s. The number stood at around 0.8 million worldwide in 1975 and had risen to more than 4 million by 2010. Foreign students are highly concentrated in a few countries, as almost half go to the top five destination countries (the United States, the United Kingdom, Germany, France and Australia). Nevertheless, the fastest growing destination regions are Latin America and the Caribbean, Oceania and Asia, reflecting university internationalisation in a growing set of countries (OECD, 2012b). Looking ahead, the number of students seeking study abroad could double to 8 million by 2025. Average annual growth in demand for international higher education between 2005 and 2025 is expected to exceed 3% in Africa, the Middle East, Asia, Central America and South America (Goddard, 2012). The top sending countries for international students in 2025 are expected to be China, India, Germany, South Korea, Saudi Arabia, Nigeria, Turkey, Pakistan, France and Kazakhstan, and students from China and India are predicted to make up roughly one-third of the total number (British Council, 2013).

Role of governments



OECD countries are increasingly opting to regulate lobbying[8]

1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010 | 2014

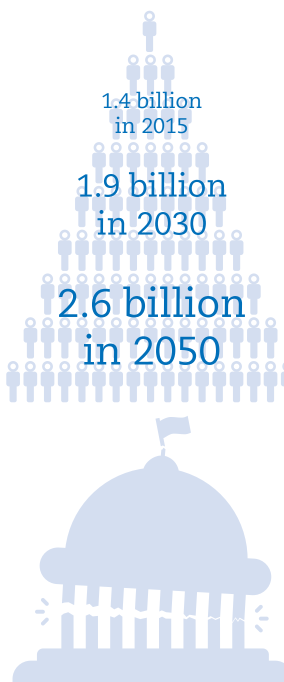
- 1946 United States
- 1951 Germany
- 1983 Australia
- 1989 Canada
- 2005 Poland
- 2006 Hungary
- 2008 Israel
- Mexico
- Slovenia
- 2012 Austria
- 2012 Netherlands
- 2012 Italy
- United Kingdom
- Chile

Only **40%** of OECD citizens trust their governments[9].

Largest corporates to rival governments?
USD billion[10]

Country/company	GDP/profits
Luxembourg	58
Apple	54
Uruguay	53
Costa Rica	51
Croatia	49
Tanzania	45
ICBC	44
Slovenia	43
China Construction Bank	36
Agricultural Bank of China	29
Latvia	27
Bank of China	27
Berkshire Hathaway	24
JPMorgan Chase	24
Estonia	23
Wells Fargo	23
Surgutneftega	20
Toyota Motor	19
Cambodia	18
Gilead Sciences	18
Verizon Communications	18
Novartis	18
Iceland	17
China Mobile	17
Alphabet	17
Samsung Electronics	17

More people will live in fragile states[11]



Rise of megacities: a challenge to nation states?[12]

Megacities may become the epicenter of social, economic and political development, displacing national states in some instances.

Relations with science and innovation

- Governments will continue to play an essential role in guaranteeing scientific autonomy and supporting fundamental science.
- Governments will likely become increasingly proactive in promoting green innovation, using funding for R&D, tax incentives, innovative procurement, standards and regulation.
- The shift to a more multipolar world may increase security uncertainties and possibly spark new arms races, which would likely influence government spending on STI.
- Governments will continue to collect and increasingly make open large amounts of data that are useful for research and innovation.

Government capacity

- While governments will remain the largest investors in public R&D, mounting debt burdens, dwindling tax revenues and rising expenditures on pensions and healthcare could compromise their capacity to fund STI activities at current levels.
- Technological change will present governments with new challenges to manage innovation rents, e.g. through competition policy, and workforce re-skilling, e.g. through education.
- Governments are themselves innovating, conducting experiments and relying increasingly on digital technologies for policy formulation, delivery and evaluation.

Non-state actors

- Cities and regions will become increasingly significant public funders of research and innovation.
- Governments will increasingly partner with businesses, NGOs and philanthropists to support STI, which will influence public research agendas.

Sources: 1. "General government gross debt", in OECD (2015l); 2. ESPAS (2015); 3. OECD (2015l). "Other" includes environment protection, housing etc.).; 4. Zucman, G. (2015); 5. OECD (2016e); 6. "Projections of public pension expenditure as a share of GDP from 2015 to 2050", in OECD (2014g); 7. de la Maisonneuve and Martins (2015); 8. OECD (2014h); 9. OECD (2015l); 10. Forbes (2016); World Bank national accounts data; OECD National Accounts; 11. OECD (2015m); 12. UNDESA (2015b).

The changing economic development roles of government

Historically, many OECD countries implemented highly interventionist industrial policies, often owning the means of production in certain key industries or favouring a few private sector "national champions". These sorts of policies mostly fell out of favour from the 1970s onwards and were replaced by policies that are more horizontal in nature with a focus on improving the framework conditions for all businesses. Such conditions involve enforcement of competition rules, trade openness, the availability of skills (education and vocational training), etc. However, following the recent economic crisis, many OECD countries have shown renewed interest in a more targeted industrial policy. Concerns about a loss of manufacturing capacities, and growing competition from emerging economies, have also contributed to a surge in interest, as has the prospect of a science and technology-driven "new production revolution".

This new approach differs from previous generations of industrial policy. It involves facilitating and co-ordinating roles for government and new ways for government and industry to work together, while also avoiding undue influence from vested interests (Warwick, 2013). Linkages are important for innovation, but do not always operate efficiently, motivating governments to support, among other things, research co-operation, as well as knowledge sharing between firms or between firms and universities. Support to technological development is also "upstream" from the previous "picking winners" focus, with governments supporting general purpose technologies so as not to impede downstream competition or infringe State aid rules in international treaties. Support is also increasingly challenge-focused, as governments seek to redirect technological change from path-dependent trajectories towards more socially and environmentally beneficial technologies and to spur private STI investments along these lines.

Technological change, particularly digitalisation, presents governments with new challenges to manage innovation rents. Policy makers will need to deploy a range of policies that, on the one hand, enable the most innovative firms to invest in frontier innovation and access skilled workers, finance, and markets, while on the other, support the diffusion of innovation throughout the rest of the economy, thus enabling all firms to benefit from these innovations (OECD, 2016f).

Finally, the workings of government have come under the innovation spotlight. For example, given governments collect large amounts of data and increasingly make this openly available, major research and innovation opportunities exist to exploit this using big data analytics. Governments are also increasingly innovating themselves, conducting experiments and relying increasingly on digital technologies for policy formulation, delivery and evaluation.

The role of government in supporting research

State-sponsored public research plays a key role in innovation systems and decision-making processes. It is a source of new knowledge, especially in areas of public interest, such as basic science or fields related to social and environmental challenges, which businesses are not always well equipped or motivated to invest in. Furthermore, governments play a fundamental role in guaranteeing scientific autonomy. They also support 10%-20% of business R&D expenditure in most OECD countries. The standard market failure rationale for this public support is that firms tend to underinvest in R&D on account of its costs and uncertainty, the time required to obtain returns on investment, and the possibility that competitors can capture knowledge spillovers (owing to the non-rival and partly-excludable nature of R&D). All of these rationales for supporting public research and firms' R&D will likely remain sound over the next 10-15 years. The question is whether governments will be able to afford the investments required.

A fiscal crisis of the State?

Fiscal pressures are likely to continue to build up in many countries as demographics evolve unfavourably, and spending pressures stemming from pensions, health, education and infrastructure investment intensify. On average across the OECD, public social expenditure rose from just over 15% of GDP to almost 22% of GDP between 1980 and 2014. Governments are also increasingly indebted, particularly since the financial crisis, and many have recently adopted austerity measures to reduce or even reverse high debt/GDP ratios. At the same time, globalisation has opened up opportunities for multinational enterprises (MNEs) to greatly reduce the taxes they pay. The use of legal arrangements that make profits disappear for tax purposes or allow profits to be artificially shifted to low or no-tax locations result in annual tax revenue losses conservatively estimated at between USD 100 billion and USD 240 billion. This is equivalent to between 4% and 10% of global revenues from corporate income tax (OECD, 2015n). Despite these pressures, governments will remain the largest investors in public R&D, though their capacity to fund STI activities at current levels could be compromised. In this regard, the latest data on general expenditures on R&D in the OECD area show a slight fall in government funding (see Chapter 3), which could be a "weak signal" of future public spending trends.

A crisis of confidence in government?

In the aftermath of the global economic crisis, public trust in governments and institutions has eroded. There is a sense that governments have failed to respond sufficiently during the unfolding of the crisis or to adequately address its aftermath. Technological change has brought about a productive revolution, but also affected employment and generated new risks associated with privacy and cybercrime. Corruption, whether perceived or actual, high unemployment, rising income inequality and concerns that education systems are out of date and fail to provide equal opportunities, all feed a general belief that governments are unable to protect the best interests of their citizens (OECD, 2015k). This crisis of confidence has implications for STI policy, too, as much R&D continues to be performed in the public sector. Furthermore, governments are expected to perform important normative and regulatory roles in governing research and innovation, such as certifying the safety of new products, roles that are difficult to fulfil in a world of uncertainty brought about by rapid and globalised technological change.

Growing instability in the international State system?

A range of trends and developments occurring at global level and covered elsewhere in this chapter – e.g. the growing importance of emerging and developing countries; the shift in centre of economic gravity towards Asia and the concomitant decline in the relative economic weight of North America and Europe; and the rise of GVCs – convey a shift to a more multipolar world. This shift is already generating growing uncertainties in the international system.

Looking back, the last two decades have witnessed a gradual decline in the number (and severity) of internal armed conflicts worldwide – from a peak in 1994 when almost a quarter of the world's countries were embroiled in civil conflict, to less than 15% today. This has been much the result of widespread improvements in factors such as levels of education, economic diversification and more favourable demographic developments (Hegre and Nygard, 2014). The number of interstate conflicts, while fluctuating somewhat, has also been on a declining trajectory (Petterson and Wallensteen, 2015), thanks mainly to a rising body of global norms against such warfare and the deepening economic and financial linkages among countries. Unsurprisingly, when it comes to forecasting the longer-term outlook for armed conflict, views diverge. Hegre and Nygard (2014), for example, forecast that this downward trend will continue, with the share of countries involved in internal armed struggles falling from 15% now to 12% in 2030, and 10% in 2050, and with conflicts concentrated mainly in sub-Saharan Africa and South Asia. Others are somewhat less sanguine. The US National Intelligence Council (NIC, 2012) states that the risks of interstate conflict are on the rise owing to changes in the international system, but does not foresee conflict on the level of a world war involving all major powers. This heightened risk could see governments increase their defence spending. In many countries, a large share of public support for R&D is already provided to firms in the defence industry to develop military equipment and potentially civil applications. Any rise in international tension could see this share increase further.

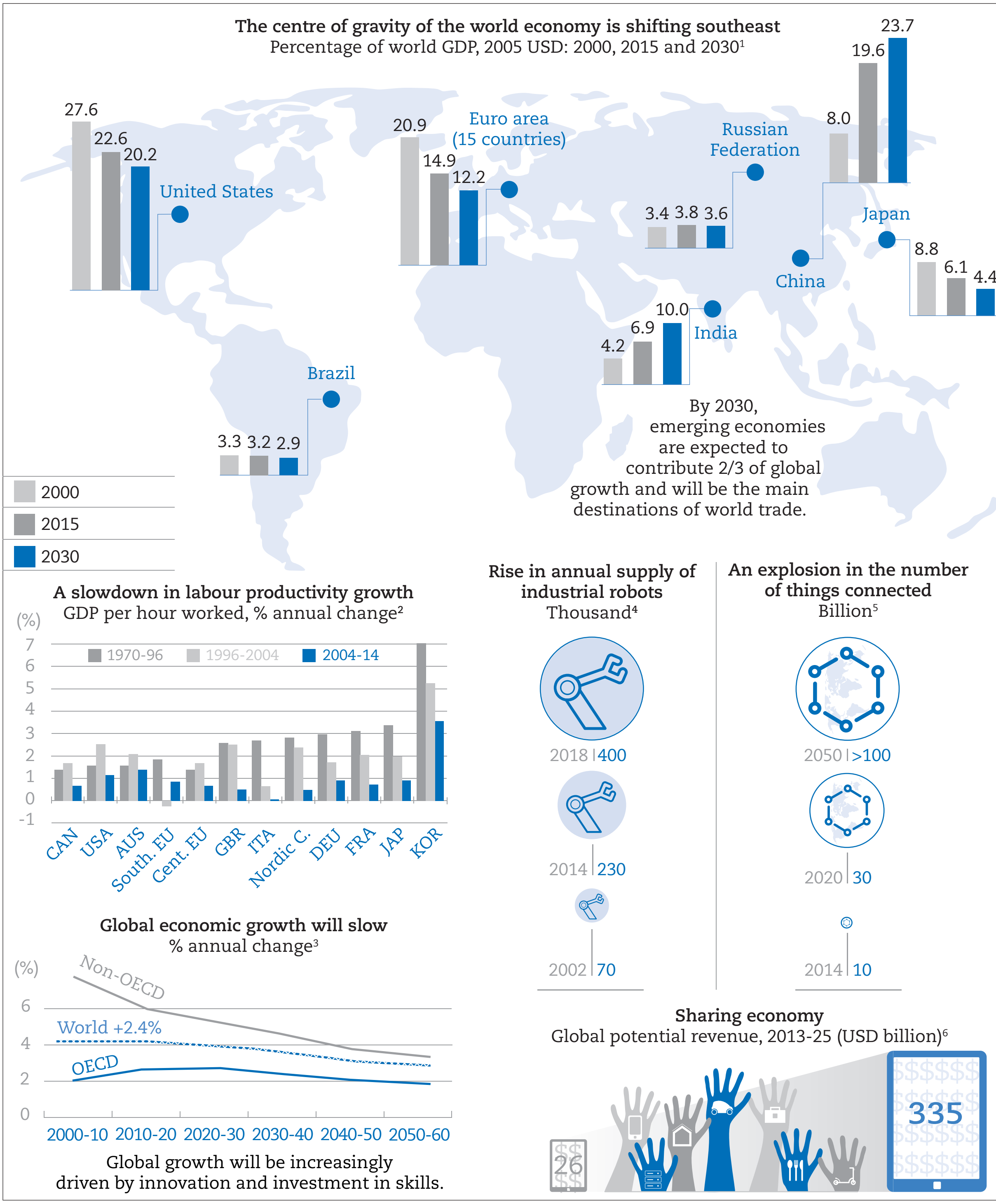
Today, 50 countries are fragile states, marked by either weak or abusive state institutions (OECD, 2015m). They are home to 1.4 billion people, though their population is projected to grow to 1.9 billion in 2030 and 2.6 billion in 2050. Sub-Saharan Africa is by far the most represented region. The weak capacity of fragile states to respond to shocks and stresses means they face heightened risk of experiencing future political, social or humanitarian crisis (OECD, 2015m). Such crises can easily spill over into neighbouring countries and even further afield, with consequences for health, migration, etc. Global responses to some of these crises, particularly those concerning global health threats, are likely to have a major influence on future STI agendas.

Growing significance of non-state actors

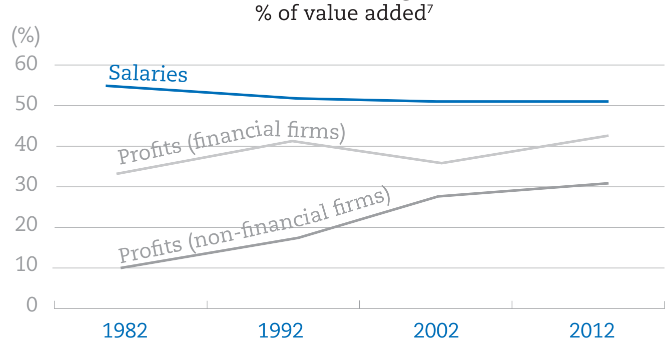
Non-state actors such as multinational businesses, non-governmental organisations, sovereign wealth funds, megacities, academic institutions and foundations endowed with global reach are all expected to play increasingly influential roles in the coming decades. In some cases they may even prove instrumental in the creation of new alliances and coalitions that have wide public support to tackle some of the global challenges facing the planet – poverty, environment, security, etc. (NIC, 2012). In the STI realm, businesses are the main funders of R&D and the locus of most innovation activities. Governments will increasingly partner with businesses, NGOs and philanthropists to support STI, which will influence public research agendas (see Chapter 3).

Cities, and in particular megacities, stand out as one of the increasingly powerful subnational actors. Metropolitan areas are the prime engine of growth. In the OECD area, more than half of economic growth and job creation occurred in the 275 metropolitan areas with over 500 000 inhabitants (OECD, 2013c). The number of megacities of 10 million or more inhabitants has almost tripled over the last 25 years, and they now account for 12% of the world's urban population. Forty or so such cities will exist by 2030. Cities and regions are already supporting research and innovation activities in their jurisdiction and an increasing number have formulated innovation strategies, a trend that is likely to continue.

Economy, jobs and productivity



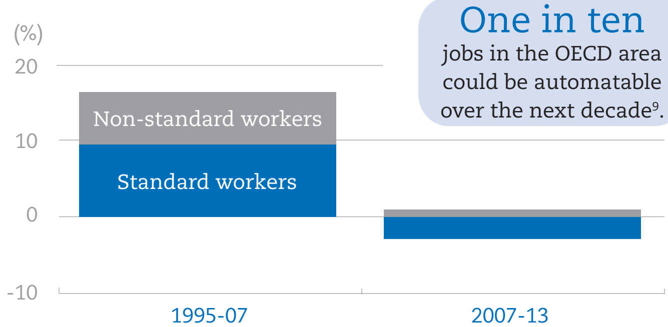
What about wages?
% of value added[7]



Growing precarity of employment
% employment growth, 2007-13, by type of employment[8]

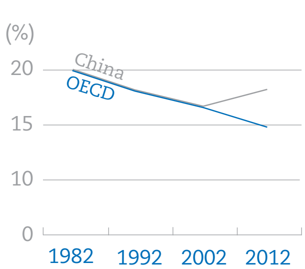
One in ten

jobs in the OECD area could be automatable over the next decade[9].

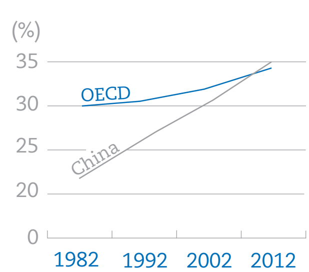


More than half the jobs created since 1995 are non-standard, i.e. part-time, temporary or self-employment arrangements.

Less manufacturing jobs
% total employment[10]



More jobs in R&D-intensive industries
% of manufacturing employment[10]



The persistent decline in manufacturing employment has affected some sectors more than others, with relatively fewer jobs shed in R&D-intensive industries.

Future productivity

- Given population ageing, future income growth will be increasingly driven by innovation and investment in skills.
- Yet, declines in knowledge-based capital accumulation, together with "winner-take-all" business dynamics, could slow the arrival of breakthrough innovations and their diffusion across economies.
- Asian economies are expected to climb up the global value-added ladder. These changes will be accompanied and, in part, driven by big investments in STI.

Digital technologies

- The growing maturity and convergence of digital technologies are likely to have far-reaching impacts on productivity and income distribution.
- A digital platform economy is fast emerging, creating greater opportunity for entrants – including individuals, outsider firms and entrepreneurs – to succeed in new markets.
- Digital technologies will further disrupt all sectors. For example, in financial services, Fintech promises to disrupt the sector through digitally-enabled P2P lending platforms, equity crowdfunding, online payment systems, cryptocurrencies and blockchain.

Future jobs

- Advances in machine learning and artificial intelligence are expected to expand the capabilities of task automation and could lead to a further hollowing out of employment and wages. They will also likely create new jobs that, as yet, have not even been imagined.
- Digital platforms that mediate work could lead to more "non-standard" jobs and contribute to the rise of the so-called "gig economy".

Sources: 1. OECD (2014i); 2. OECD (2016f); 3. OECD (2014j); 4. International Federation of Robotics (2015); 5. Gartner (2013); 6. OECD (2016g); 7. OECD (2016h); 8. Arntz, Gregory and Zierahn (2016); 9. OECD (2015r); 10. OECD (2015g). The loss of manufacturing jobs in the OECD area has affected some industries more than others. Over the past 30 years or so, a steadily increasing share of OECD manufacturing employment has come from R&D-intensive industries, rising from 30% to about 35%. In other words, relatively fewer jobs have been shed in this group of industries (chemicals, machinery and transport equipment) compared to others (e.g. textiles, plastics and basic metals). Changes in global production patterns have seen manufacturing in China become more orientated around R&D-intensive industries, with the share of employment rising from 20% in the early 1980s to about 35% in recent years. However, a high presence of R&D-intensive industries does not necessarily indicate high levels of R&D expenditure, as much R&D can be embodied in imported intermediate goods.

The future of productivity growth

Global growth is estimated to slow from 3.6% in 2010-20 to 2.4% in 2050-60. Given population ageing, income growth will be increasingly driven by innovation and investment in skills (Braconier et al., 2014; Adalet McGowan et al., 2015). However, labour productivity growth has slowed in many OECD countries over the last two decades, which mainly reflects slowing total-factor productivity growth. A pessimistic view holds that this is a permanent phenomenon, on account of a decline in the underlying rate of technological progress. According to this perspective, the types of innovations that took place in the first half of the 20th century (e.g. electrification) are far more significant than anything that has taken place since then (e.g. ICT), or indeed, is likely to transpire in the future (Gordon, 2012; Cowen, 2011). Technological optimists (e.g. Brynjolfsson and McAfee, 2011), on the other hand, argue that the underlying rate of technological progress has not slowed and that the IT revolution will continue to dramatically transform frontier economies (OECD, 2016i).

Recent OECD analysis of productivity trends suggests that the main source of the productivity slowdown is not the slowing of the rate of innovation by the most globally advanced firms, but rather a slowing of the pace at which innovations spread throughout the economy: a breakdown of the so-called "diffusion machine" (Andrews, Criscuolo and Gal, 2015). There are several possible explanations for this concentration: for example, it could be that we are at the start of a new technological trajectory, with developments dominated by a few early adopters. Given technological dissemination follows a sigmoid curve, there is a lag before it diffuses more widely. But another explanation that is attracting increasing attention is "winner-take-all" dynamics, which appear to be particularly prevalent in some industries, such as those involving digital platforms (see below). Since the financial crisis, persistently weak investment in physical capital (machines and equipment, physical infrastructure) has also contributed to a slowdown in labour productivity growth. But perhaps more worryingly, there has also been a slowdown since the early 2000s in knowledge-based capital accumulation, which usually underpins innovations and their subsequent adoption. This decline raises concerns about a structural slowdown in productivity growth and may foreshadow a possible slowdown in the arrival of breakthrough innovations (OECD, 2016i).

Long-term investment plays a key role in promoting innovation-based growth and job creation. Most company investment is carried out with retained earnings, with relatively small recourse to external finance. In recent years, companies have allocated a significant proportion of retained earnings, backed by low-interest rate borrowing, to shareholders in the form of dividends and buybacks. These cash returns have reduced companies' long-term "growth" investments. OECD estimates that companies in advanced economies could increase capital expenditure on average by 60% without any recourse to borrowing, simply by reducing dividends and buybacks (OECD, 2016i). A key policy challenge will therefore be to establish long-term investment incentives that offset tendencies in the financial system to measure profit margins on a short-term basis (WEF, 2011).

The centre of gravity of the world economy is moving east and southwards

The next 50 years will see the centre of gravity of the world economy shift east and south. By 2030, developing countries are expected to contribute two-thirds of global growth and half of global output, and will be the main destinations of world trade. Emerging economies such as China and India are increasingly important markets for firms in many industries. A new middle class is fast emerging that will lead to a rise in consumption of basic consumer products and other product categories. These demand-side factors mean emerging economies are likely to remain favoured locations for production activities, reducing the likelihood of widespread re-shoring to OECD countries (OECD, 2015h). Furthermore, income gains and changing consumption patterns mean that manufacturing exports from China, India and other Asian economies are expected to climb up the global value-added ladder, while significant shifts towards services will see China and other emerging economies gain large shares in services trade at the expense of OECD countries in the long-run (Johansson and Olaberria, 2014b). These changes will be accompanied, and, in part, driven by investments in STI. For example, research spending in China is already second only to the United States (see Chapter 3).

Digital technologies will further disrupt economies

The growing maturity and convergence of digital technologies are likely to have far-reaching impacts on productivity, income distribution, well-being and the environment. By 2030, firms will be predominantly digitalised, enabling product design, manufacturing and delivery processes to be highly integrated and efficient. Additive manufacturing technologies will allow certain products to be tailored to specific user needs, while the IoT, big data analytics, artificial intelligence and machine learning tools will enable smart machines to emerge that will be increasingly adjustable through sensor technologies, cheap computing power and the real-time use of algorithms (OECD, 2015h).

The costs of equipment and computing will continue to fall, while the rise of open source development practices will create further communities of developers, not only in software but also in hardware and “wetware”, e.g. in “do-it-yourself” synthetic biology (see Chapter 2). There will be greater opportunity for entrants – including individuals, outsider firms and entrepreneurs – to succeed in new markets. Pattern-recognition technologies, such as big data and machine learning, will enhance capabilities for assessing user needs and overall demand for innovation. The risks and time-spans in product development and market launch are expected to decrease, spurring additional developments. Innovation-related production costs will fall in key industries, with cloud computing and 3D printing services providing platforms for new firms. Product distribution costs will continue to fall, reducing the cost of launching new products and services (OECD, 2015o). These developments could also provide emerging economies with opportunities to accelerate technological catch-up, possibly allowing them to leapfrog to productivity levels closer to those observed in OECD countries.

In the services sector, digital technologies have helped create new and more efficient businesses, boosted productivity growth, and facilitated international trade in services. Manufacturing in OECD countries increasingly thrives on services inputs for value creation, and the differences between manufacturing and services have become increasingly blurred. A large part of future growth in production is expected to come from so-called “manu-services”, which involve combining advanced manufacturing with a range of different services. The growing and complex interactions between manufacturing and services will call for a more integrated view on manufacturing and services in company strategies, as well as in policy discussions (OECD, 2015h).

The rise of digital platforms

A digital platform economy is fast emerging. By 2015, operators of digital platforms almost fully dominated the top 15 of the world’s largest Internet-based companies ranked by market capitalisation (OECD, 2016j). Platforms are diverse in range and function. For instance, they provide platforms on which applications are built (e.g. Google's Android and Apple's iOS); they support search and social media (e.g. Google and Facebook); they provide services (e.g. Airbnb and Uber); they offer marketplaces (e.g. Amazon and eBay); and they mediate work (e.g. Amazon's Mechanical Turk and UpWork). Platforms lower barriers for small providers to enter markets. Together, they are reorganising a wide variety of markets, work arrangements, and ultimately value creation and capture (Kenney and Zysman, 2016). This implies potentially radical economic and social disruption that will create winners and losers.

Once a platform's networks have reached critical size, network externalities can protect the platform's position and function as barriers to entry for other firms or platforms (OECD, 2016i). These network effects imply that innovations associated with digital platforms are a new version of natural monopolies where one or two firms become dominant and are able to appropriate a generous portion of the entire value created by all the users on the platform (OECD, 2016i; Kenney and Zysman, 2016).

Future jobs

The decreasing cost of computing power and other advances in digital technologies are already disrupting labour markets and making some workers redundant (see Brynjolfsson and McAfee, 2011). Computers have begun displacing labour when it comes to explicit (codifiable) routine tasks that follow precise and well-understood procedures such as clerical work (e.g. accounting) and some physical operations in production lines. For the time being, tasks that are hard to describe as a set of steps and are bounded to particular circumstances remain impervious to automation (Autor, 2015). These tasks are more abstract in nature and often involve problem-solving capabilities, intuition, creativity and persuasion. However, advances in machine learning and artificial intelligence are expected to expand the capabilities of task automation and could lead to more dramatic changes than experienced in the past, and in particular, to a further hollowing out of employment and wages. Recent research conducted for the OECD (Arntz et al., 2016) suggests that around one in ten jobs across the OECD are at high risk of automation. At the same time, these innovations harbour great promise for more robust productivity growth and new jobs that, as yet, have not even been imagined (OECD, 2016i).

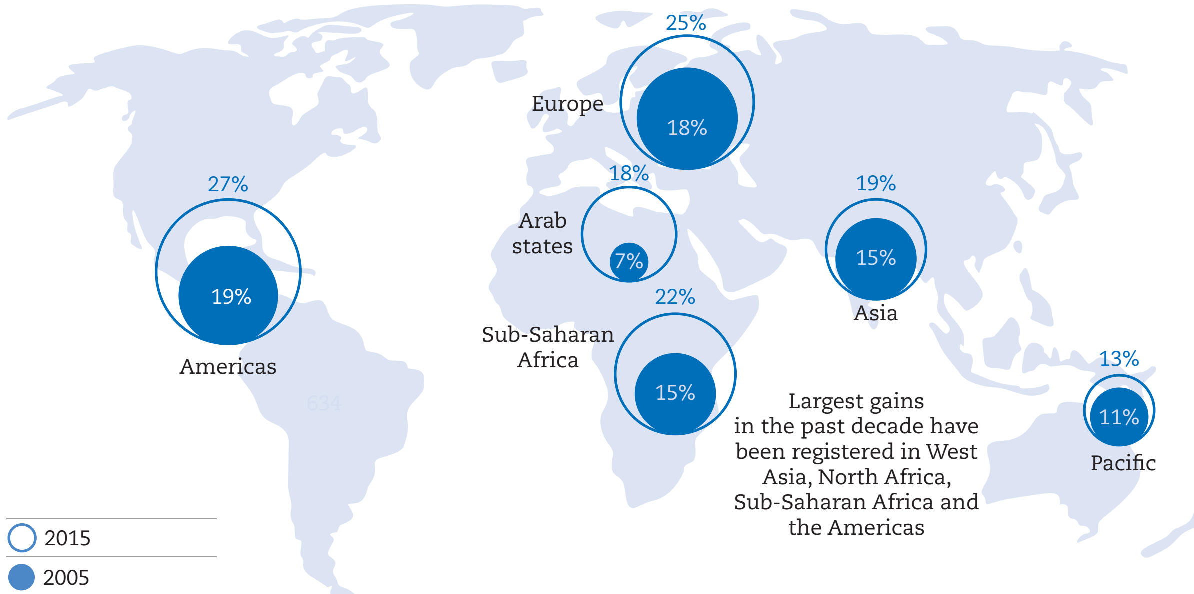
Depending on how quickly economies are able to create new jobs to replace those that have been lost and how wages will evolve, there may still be too few jobs, perhaps on a permanent basis. Greater work-sharing and a reduced working week could help distribute work more evenly, but would need to guarantee a living wage – possibly through some sort of "universal basic income" (Skidelsky, 2013). Work has already become more fragmented and "non-standard", with an increasing number of workers doing lots of different part-time jobs – the rise of the so-called "gig economy". The growth of online platforms that link a vast pool of freelancers, who are physically based in different parts of the world, with companies inviting them to bid to work on a wide variety of tasks, could accelerate this trend. While such platforms offer flexibility to workers and companies, they raise some difficult questions about workplace protections and what a good job will look like in the future (OECD, 2016k). Furthermore, two of the biggest markets for these platforms are India and the Philippines, where lower costs of living allow workers there to undercut their peers in OECD countries. This could trigger a "race to the bottom", driving down real wages and increasing inequality in OECD countries (Fox and O'Connor, 2015).

The future of finance

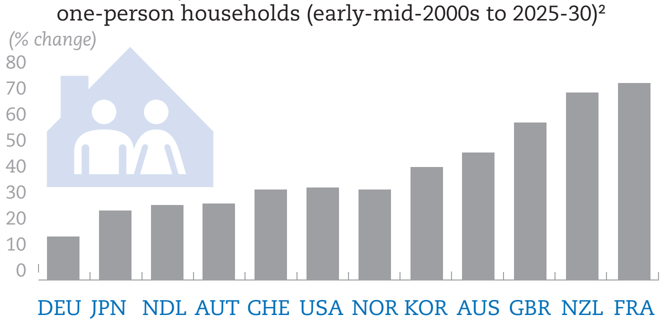
OECD countries have experienced an upwards trend in the value-added share of the financial sector in GDP over the past half-century, which has coincided with the sector's growing influence on the overall economy and society (Mukunda, 2014). The sector's rising profit share is considerably higher compared with the rest of the economy and its high wages have attracted some of the best talent, possibly at the expense of sectors with greater potential for productive innovation (Cournède et al., 2015; Cecchetti and Kharroubi, 2015). While these trends may hold over the next 10-15 years, if not intensify as financial services further develop in emerging economies, "fintech" promises to disrupt the sector considerably. For instance, banks' lending role will be increasingly challenged by digitally-enabled peer-to-peer lending platforms, while equity crowdfunding is also expected to grow (OECD, 2015p). Online payment systems (such as PayPal) and cryptocurrencies (such as Bitcoin) are also forecast to proliferate. Other innovations leveraging the blockchain will lower transaction costs and provide computationally inexpensive methods for securely transferring value. This could disrupt those institutions, like banks, whose raison-d'être lies in the centralised provision of trust behind transactions.

Society

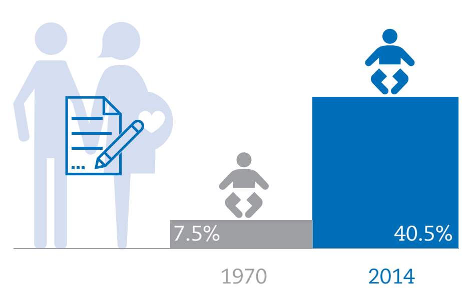
Despite some progress, the gender gap is still prominent
Average proportion of women in parliaments in different regions[1]



Households are getting smaller
Projected increase in the number of one-person households (early-mid-2000s to 2025-30)[2]

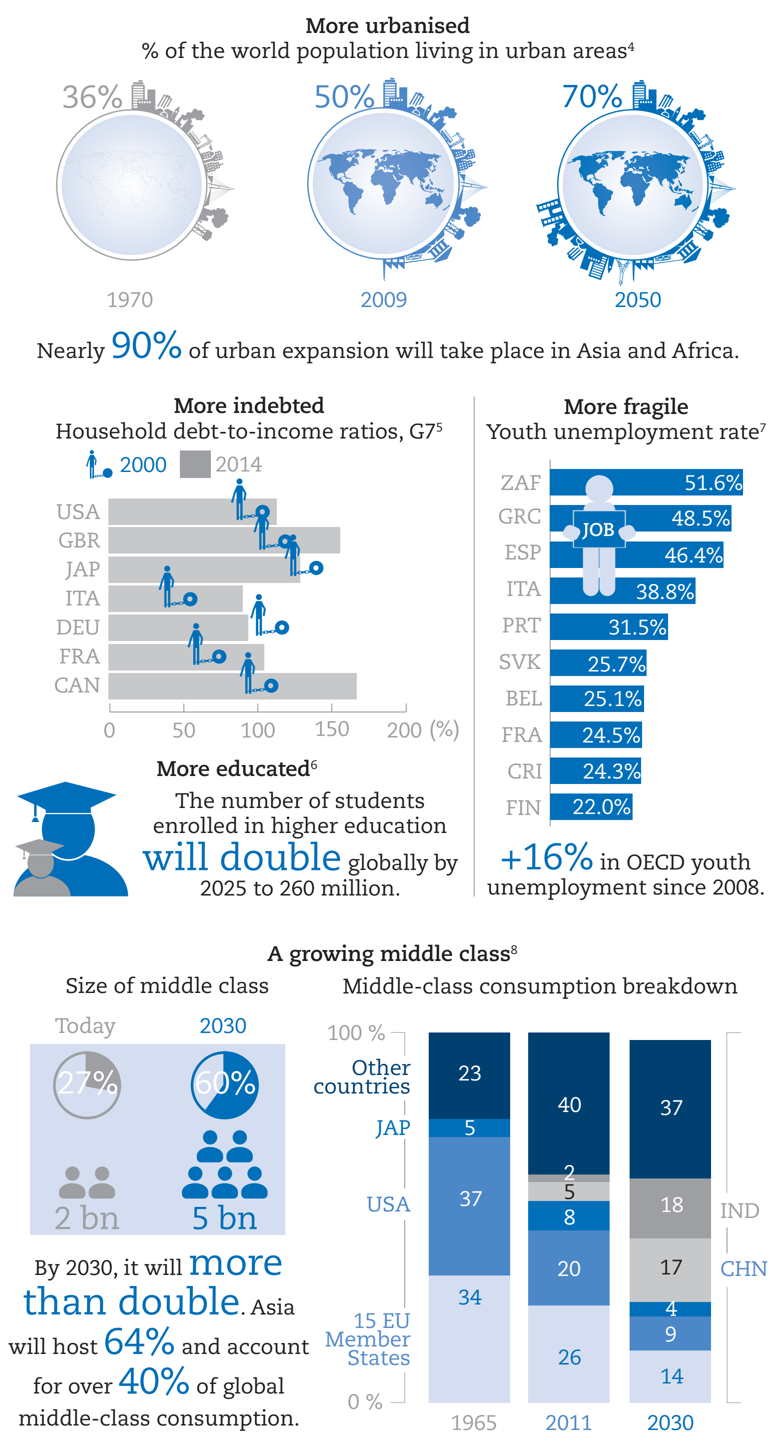


More births outside marriage
% of all births, OECD-27 average[2]



Communication habits by generation[3]

	Silent generation (<1945)	Baby boomers (1945-60)	Generation X (1961-80)	Millennials (1981-95)	Generation Z (>1995)
Aspirations	Purchase of a principal residence	Job security	Work-life balance	Freedom and flexibility	Security and stability
Symbolic product		TV			3D printers, nano-computing...
Attitude towards technology	Disengaged	Early adopters, PCs on the horizon	Computer literate	Digital natives	Dependent on digital technology
Communication channel	Face-to-face	Face-to-face, telephone, email	SMS, email	Social networks, instant messaging	Video calls on devices



Social agendas and STI policy

- Societal challenges, e.g. food security, clean energy, climate action, etc., are increasingly influencing STI policy agendas. This in turn could lead governments to use broader notions of research impacts in their research assessments.

Science and innovation in society

- Digital technologies are transforming societies, altering the ways in which people live, work and communicate. Ubiquitous connectivity will support more flexible working arrangements, though with uncertain consequences for work-life balance.
- New technologies – such as ICTs, synthetic biology, additive manufacturing, nano- and micro-satellites, and advanced energy storage – will empower individuals and social collectives (e.g. NGOs) to conduct their own research and innovation activities.
- A more highly-educated citizenship could become increasingly interested and engaged in the debates around the direction of STI developments, particularly with regards to associated benefits, risks and values.

Urbanisation and consumption

- A growing middle class and increasing consumption in emerging economies will increase demand for innovative consumer goods worldwide.
- In OECD countries and some emerging economies, urban areas will become increasingly "smart", influencing the direction of innovation in sectors such as housing and transportation.
- By contrast, urban development in many developing countries will present health challenges, including the increasing risk of global pandemics. These challenges could have a significant influence on future research agendas.

Sources: 1. IPU (2016); 2. OECD (2016l). The periods over which changes are projected (early-mid-2000s to 2025-30) are as follows: Australia (2006-26), Austria (2007-30), France (2005-30), Germany (2007-25), Japan (2005-30), Korea (2007-30), Netherlands (2009-30), New Zealand (2006-31), Norway (2002-30), Switzerland (2005-30), United Kingdom (2006-31) and United States (2000-25).; 3. Le club des élus numériques (2014); 4. OECD (2012a); 5. OECD and PBO (2016). OECD data for Japan is available only to 2013. The values shown for Japan correspond to 2000 and 2013.; 6. Goddard (2012); 7. OECD (2016h); 8. EEA (2016a). The 15 chosen EU countries are: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom. No Chinese data for 1965.

Families and households

In recent decades families in the OECD area have undergone significant transformation. The extended family has almost disappeared in many countries, and the traditional family consisting of a married couple with children has become much less widespread as divorce rates, cohabitation, couples "living apart together", single parenthood and same-sex partnerships have all increased. With rising migration, cultures and values have become more diverse, more women have taken up work, more young people are spending more time in education and training, and the elderly are living longer and increasingly alone (OECD, 2011). The expectation is that these trends will continue over the coming decades, with significant increases in many OECD countries in: one-person households (reaching 30-40% of all households by 2025-30 in many countries), single-parent households (30-40% of all households with children by 2025-30 in some countries), and couples without children. The increase in childless couple households, divorce rates, remarriages and step-families may weaken family ties and undermine capacity for informal family care, while the growing numbers of single-adult households will put increased pressure on housing (OECD, 2011). From an STI perspective, these household trends will have impacts on consumption and demands for innovation, while the likely gap in elderly care provision will increase demand for assisted living technologies, including telecare and robotics.

Closing gender gaps

There are various signals that the gender gap is closing, given women's growing involvement in politics, rising enrolment rates in higher education and increased participation in the labour market. At the higher education level, gender equality is making significant inroads. In most OECD countries, women already account for at least 50% of tertiary education enrolments. The emergence of such strongly qualified female cohorts has important implications for economic growth, labour markets, family life, patterns of childcare and elderly care. In the developing world, girls' enrolment at all levels of schooling has risen significantly over the last two decades. There is a good deal of optimism that by mid-century, global gender gaps at the primary school level will have largely disappeared, although girls are likely to remain under-educated in many of the world's most intractably poor countries (UK Ministry of Defence, 2014). In the STI field, while there has also been some progress in addressing gender gaps the proportion of female scientists tends to fall as seniority rises (see Chapter 3); there are more male than female entrepreneurs, and the share of women who choose to run a business has not increased substantially in most countries (OECD, 2015q); and most scientific research does not consider sex or gender as variables and treats male as the norm, resulting in different health and safety outcomes for women and men (EC, 2013). These outstanding gaps underutilise women's skills and limit the benefits of today's science.

More connected societies

Digital technologies are transforming societies, altering the ways in which people live, work and communicate. Over the coming decade, the IoT, for example, will see homes, workplaces and the wider environment (e.g. advanced city infrastructures) increasingly interconnected. This ubiquitous connectivity will support more flexible working arrangements, though with uncertain consequences for work-life balance. For the developing world, Internet penetration has been growing quickly, helped considerably by mobile broadband. It is estimated that over the seven-year period from 2014 to 2020, an additional 1.1 billion new individuals will acquire a mobile phone for the first time, or 155 million per year. According to Ericsson (2015), mobile broadband subscriptions will reach 7.7 billion globally by 2020.

Global middle class and consumption

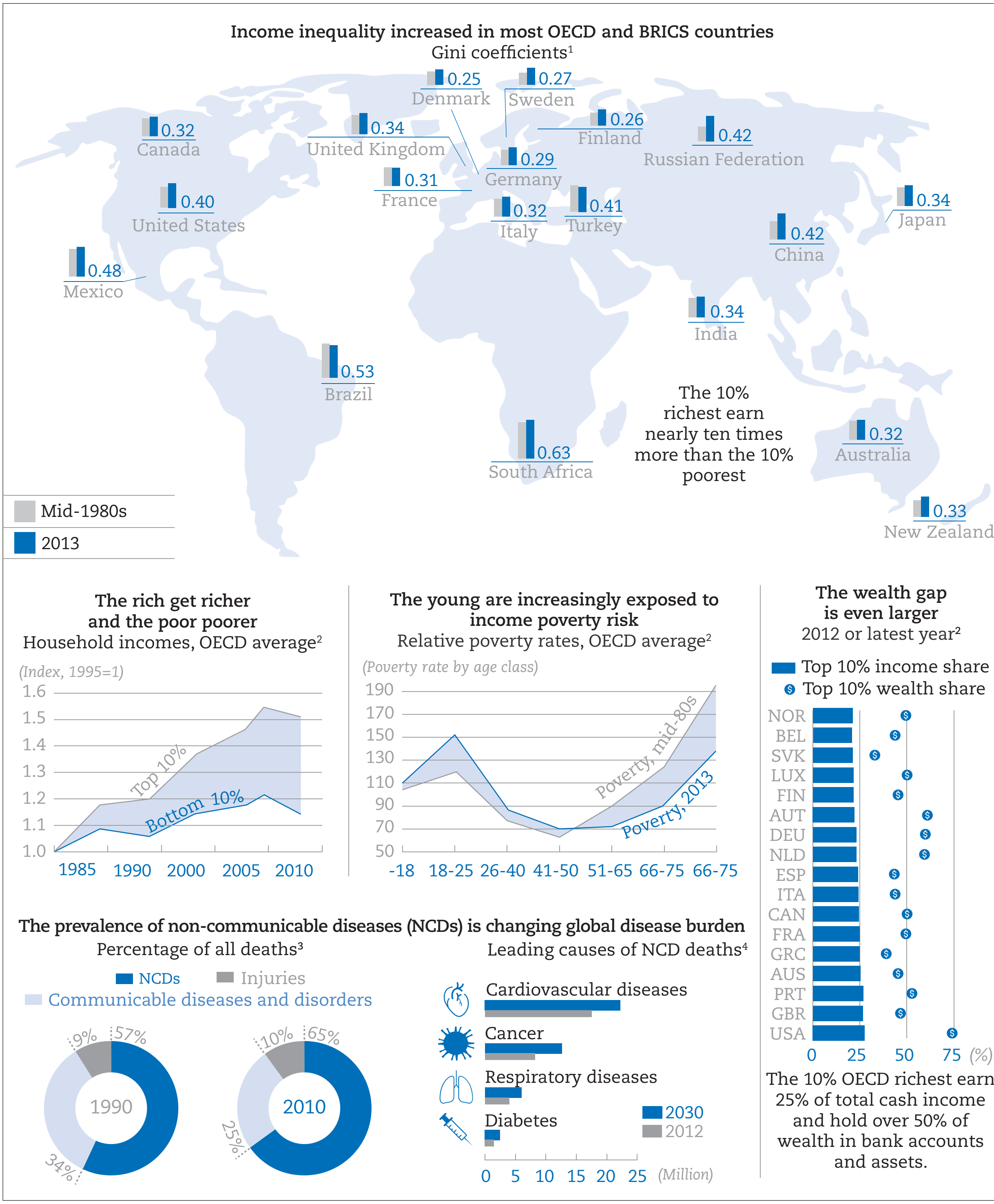
Rising wealth and income in the developing economies of the world is progressing hand in hand with the emergence of a global middle class. By current projections, the global economy's middle class is expected to more than double between 2009 and 2030, from 1.8 billion to almost 5.0 billion, accounting for about 60% of the world population. Some two-thirds of those middle-class citizens are expected to be found in Asia (Gros and Alcidi, 2013). Given the broad range of expenditures that fall within the middle-class definition, some countries have more affluent middle classes than others. Today's middle class in Europe and North America make up just over half of the global total in terms of number of people, but they account for almost two-thirds of total spending by the world's middle class. This is about to change. Asia's share of global middle-class expenditure is expected to climb from around one-quarter today to almost 60% in 2030, bringing about a huge shift from spending on necessities such as food and clothing to choice-based spending on categories such as household appliances and restaurants (Kharas and Gertz, 2010).

Urbanisation

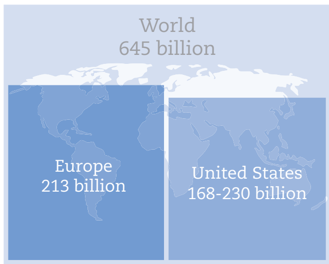
By 2050, the urban population is expected to surpass 6 billion – up from less than 1 billion in 1950 (OECD, 2015s). Almost all urban population growth will occur in cities in developing countries, with nearly 90% occurring in Asia and Africa. Cities make it easier to provide modern energy and water infrastructures to a growing number of people. Building on advances in sensors and their connectivity through high-performance computing, urban areas in more advanced economies will increasingly become "smart cities". Various utility and transport networks and systems will become progressively interconnected, thereby supporting more sustainable use and management of resources (EC, 2014).

At the same time, a growing proportion of low-income groups will become urbanised over the next decades, so that in some regions, urban growth will become virtually synonymous with slum formation. Urban slums suffer from sub-standard housing and inadequate water, sanitation and waste management services, all of which have negative consequences for human health and the environment (OECD, 2012a). Such areas are also more likely prone to conflict and social unrest (UK Ministry of Defence, 2014). Air pollution and unmanaged waste will be major concerns for public health in many urban areas (OECD, 2012a). Climate change will see storm surges and rising sea levels increase over the next decades, which will have major impacts on low-lying coastal cities, especially in Asia, where so much of the world's urban population lives. Extreme weather events will also disrupt complex urban systems (OECD, 2014k), while the proximity of emerging megacities to areas of severe water stress and pollution will likely give rise to new health and environmental problems. Given their seriousness, these challenges are likely to have major impacts on future STI agendas.

Health, inequality and well-being

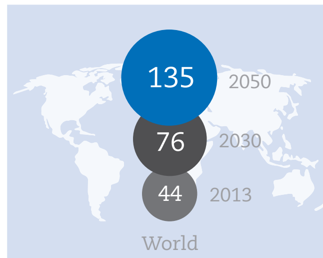


Financial cost of dementia
USD billion, 2013[5]



The global cost of dementia is equivalent to the GDP of Switzerland.

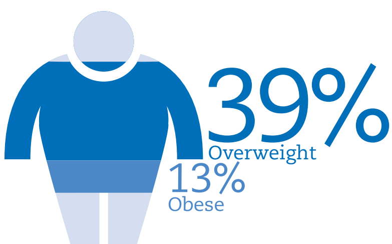
Prevalence of dementia
Million inhabitants[5]



By 2030, dementia cases will rise by +50% in high-income countries and +80% in lower income countries.

Obesity on the rise[6]

Adult obesity, 2014

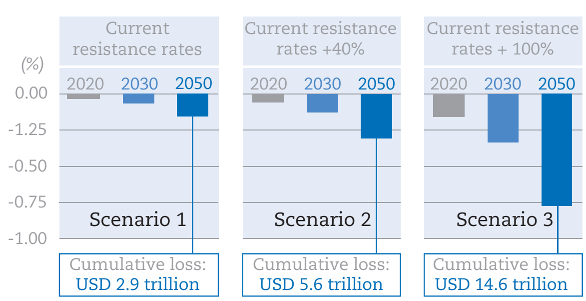


Child obesity, 2014

41 million
children under the age of 5 were overweight or obese in 2014.

Worldwide obesity has **more than doubled** since 1980.

Economic impact of antimicrobial-resistance
GDP loss in OECD countries per year[7]



Today, **700 000** deaths per annum globally are due to antimicrobial resistant micro-organisms.

Innovation and inequality

- Innovation will increase inequality as benefits predominantly accrue to innovators and possibly their customers. For all actors in society to benefit, innovations must diffuse.
- Furthermore, most new technologies require new sets of skills to use. This possibly contributes to unemployment and inequality, and highlights the need for skills training.
- On the other hand, technologies can directly promote social inclusion and economic growth, e.g. digital technologies have opened up access to education, financial services and other knowledge-based services.
- New concepts such as social innovation, frugal innovation, inclusive innovation and social entrepreneurship are leading to new innovative business models and can contribute to a more inclusive approach to innovation.

Health innovation

- Much of the extension of life expectancy and improvements in quality of life over the last century can be attributed to the success of biomedical research and innovation.
- Pharmaceutical research is entering a new era of open science and the use of converging technologies to uncover the genetic and biochemical underpinnings of diseases.
- Digital technologies will massively increase the amounts of medical data available and enhance the power of data analysis in the service of healthcare decision-making.
- New public and private R&D will be essential to deal with the threat of growing antimicrobial resistance.
- Patient groups are increasingly prominent in shaping research and innovation agendas. Furthermore, "do-it-yourself" science groups and maker communities are likely to be increasingly visible in the healthcare field, enabled by low-cost advanced technologies like synthetic biology and additive manufacturing.

Sources: 1. PovcalNet (2016). Data are based on primary household survey data obtained from government statistical agencies and World Bank country departments. The Gini coefficient is based on the comparison of cumulative proportions of the population against cumulative proportions of income they receive, and it ranges between 0 in the case of perfect equality and 1 in the case of perfect inequality. The poverty rate is the ratio of the number of people (in a given age group) whose income falls below the poverty line; taken as half the median household income of the total population. However, two countries with the same poverty rates may differ in terms of the relative income-level of the poor.; 2. OECD (2015r); OECD (2016m); 3. EEA (2016b). DALY refers to Disability Adjusted Life Years, defined by WHO as "the sum of Years of potential life lost due to premature mortality and the years of productive life lost due to disability".; 4. WTO (2015a); 5. OECD (2015t); 6. WTO (2015b). Data are Europe (2008), Ireland (2010), United Kingdom (2014), United States (2010), and World (2010). There are considerable methodological differences between the studies summarised here, so this figure should be treated as illustrative only. In general, estimates include indirect costs, such as the opportunity cost of informal care, but methodologies for estimating these costs vary. All costs are in US dollars, inflated to 2013 in line with consumer prices, and so may not match the numerical values stated in the source papers.; 7. Cecchini, Langer and Slawomirski (2015).

Wealth and income distribution: towards global convergence

Barring major global catastrophes, and despite slowing global growth rates, the world is very likely to be a much richer place by mid-century. World GDP is expected to more than triple by 2060, per capita incomes are also set to rise rapidly, and wealth accumulation is anticipated to continue apace. However, whether this will also be a better world depends very much on how incomes and wealth will be distributed across the globe and within countries. At present, the prosperity gulf between developed and developing economies remains wide, though has been narrowing for several decades. By 2060, disparities in GDP per capita are expected to further narrow across countries; per capita income levels of the currently poorest economies will more than quadruple (in 2005 purchasing power parity terms), whereas they will only double in the richest economies; and China and India are expected to experience more than a sevenfold increase of their income per capita (Johansson et al., 2012). This economic convergence will in most instances coincide with a deepening of STI capabilities in emerging and developing economies. Such capabilities can be acquired in a variety of ways, notably through investments in education and R&D, which will see a growth in universities and other research centres in non-OECD settings. Connections with foreign sources of knowledge, e.g. via trade, FDI, human mobility, and R&D collaboration, are also likely to play a critical role in emerging economies' technological upgrading.

Local divergence in incomes and wealth

Inequalities within countries will pose major political, social and economic risks in the coming years. In the vast majority of advanced countries, the gap between rich and poor has reached its highest level for three decades. Today, the richest 10% of the population in the OECD area earn nearly ten times the income of the poorest 10%, up from seven times in the 1980s, though the ratio varies widely across OECD countries. In Nordic and many Continental European countries, the ratio is significantly lower than the average, but in Italy, Japan, Korea, Portugal and the United Kingdom it is closer to 10 to 1, between 13 and 16 to 1 in Greece, Israel, Turkey and the United States, and as high as between 27 and 30 to 1 in Mexico and Chile (OECD, 2015r). The working-age population, including families with children, has borne the brunt of increased inequality, consistent with rising unemployment in the last years of the period. The widening of the income distribution has been accompanied by a shift in the age profile of income poverty, with young people replacing the elderly as the group most at risk of relative poverty, a trend which began to emerge in the mid-1980s (OECD, 2015r).

The distribution of wealth is considerably more unequal than that of income, and both household wealth and its concentration have increased markedly over the last four decades. Across those OECD countries for which data are available, the top 5% and 1% wealthiest households own 37% and 18% of total household wealth respectively, while the bottom 60% of the distribution owns only 13% of total household wealth (OECD, 2016i).

Inequality undermines education opportunities for the disadvantaged, which in turn reduces social mobility, leading to a slowing of human capital accumulation. Recent analysis (e.g. Piketty and Zucman, 2013; Braconier et al., 2014) suggests that increasing inequality in incomes and wealth will very likely continue for many years to come. Indeed, based on current trends, earnings inequality in an average OECD country could rise by more than 30% by mid-century, bringing OECD countries as a whole to the same level of inequality experienced in the United States (Braconier et al., 2014). In the case of emerging and developing economies, over two-thirds of countries, encompassing 86% of the population of the developing world, will experience growing inequalities. For many, the prospects of long-term help are particularly gloomy: by 2030, some two-thirds of the world's poor could be living in "fragile" states (ESPAS, 2015).

Insofar as technological change and innovation alter how capital and labour are deployed in an economy, they have implications for income distribution. Innovation will increase inequality given that the benefits accrue mainly to innovators and possibly also to their customers. For all actors in society to benefit, innovation diffusion is necessary. Moreover, regarding employment, most new technologies have required higher levels of skill to use than those they displace. This so-called "skill-biased technological change" has been one driver of inequality over recent decades (Paunov, 2013). On the other hand, technologies can directly promote social inclusion and economic growth. For example, digital technologies have opened up access to education through Massive Open Online Courses (MOOCs) and Open Educational Resources (OERs); connected remote populations as well as those with lower incomes to free or very low-cost knowledge and information services through low-cost mobile access; and promoted access to financial services to the "unbanked" through digital payments systems and mobile banking (OECD, 2016*j*). Furthermore, new concepts such as social innovation, frugal innovation, inclusive innovation, and social entrepreneurship are leading to new innovative business models and may contribute to a more inclusive approach to innovation (Paunov, 2013). These concepts blend traditional market-based approaches with solutions that address the long-term needs of societies and the environment, as well as key policy challenges, such as unemployment, poverty and climate change.

Growing levels of education

Access to education and the acquisition of knowledge and skills will be one of the most important keys to improving life chances – not only in the advanced economies, but also and especially in the developing world. The average level of educational attainment is set to rise more quickly in developing countries than in advanced economies, shrinking the gap between the two. The number of students around the globe enrolled in higher education is forecast to more than double to 262 million by 2025. Nearly all of this growth will be in the developing world, with more than half in China and India alone. As a result, by mid-century, it is possible that a majority of the world's young people will have had a university or higher-level education. In almost all OECD countries, the proportion of the population who will be graduates in 2025 is likely to increase, in some cases very significantly (OECD, 2008).

Infectious diseases

Deep dividing lines may persist for some time to come not only in respect to technology, education, income and wealth, but also and especially with regard to health. The healthcare systems of the future will have to face a growing spectrum of challenges, not least from a rapidly changing world panorama of disease. Progress has been made in the battle against some infectious diseases such as tuberculosis (TB), HIV/AIDS and malaria. HIV/AIDS mortality has fallen quite dramatically in recent years, and deaths from TB (95% of which occur in low- and middle-income countries) are declining, albeit very slowly (WHO, 2014a). Approximately half of the world's population is at risk of malaria (with 90% of malaria deaths occurring in Africa). However, between 2000 and 2013, an expansion of malaria interventions helped to reduce malaria incidence by 30% globally, and by 34% in Africa. During the same period, malaria mortality rates decreased by an estimated 47% worldwide and by 54% in

Africa (WHO, 2015). These and other interventions have seen life expectancy rates rise and converge across the world. However, trends are at work in society that suggest future progress in countering infectious diseases may become harder to achieve. Urbanisation is continuing to gather pace in the developing world; climate change is influencing geographic patterns of human and animal infections (e.g. malaria); international tourism is growing; and global migration levels are unlikely to abate.

But perhaps the most worrying trend in fighting infectious diseases is growing antimicrobial resistance. These drugs have been extensively misused in both humans and food-producing animals in ways that favour the selection and spread of resistant bacteria. The bulk of antimicrobials is given to animals. In the United States, for example, antimicrobial use in the livestock sector accounts for about 80% of total annual consumption. Between 2010 and 2030, global consumption of antimicrobials in the livestock sector is projected to increase by about 67% (Cecchini et al., 2015). With such intensive use, antibacterial drugs have become less effective or even ineffective. Furthermore, failure in antimicrobial drug discovery is contributing to the rise of global resistance. The result is an accelerating global health security emergency that is rapidly outpacing available treatment options (WHO, 2014c).

Non-communicable and neurological diseases

While the annual number of deaths due to infectious disease is projected to decline, the total annual number of deaths from non-communicable diseases (NCDs) is expected to increase from 38 million in 2012 to 52 million by 2030. This epidemic of NCDs is being driven by powerful forces such as demographic ageing, rapid unplanned urbanisation, and the globalisation of unhealthy lifestyles. While many chronic conditions develop only slowly, changes in lifestyles and behaviours are occurring rapidly and pervasively. The leading causes of NCD deaths in 2012 were cardiovascular diseases, cancers, respiratory diseases and diabetes. These four major NCDs were responsible for 82% of NCD deaths. Going forward, annual cardiovascular disease mortality is projected to increase from 17.5 million in 2012 to 22.2 million in 2030, and annual cancer deaths from 8.2 million to 12.6 million (WHO, 2014b). The prevalence of diabetes has been increasing globally in recent decades, and WHO projects that it will be the seventh-leading cause of death in 2030. NCDs already disproportionately affect low- and middle-income countries, and current projections indicate that by 2020 the largest increases in NCD mortality will occur in Africa and other low- and middle-income countries (WHO, 2011).

Cases of neurological disease, spurred in particular by rising longevity and the anticipated rapid ageing of societies in the coming decades, are expected to multiply. Alzheimer's Disease International (ADI), for example, estimates that 46.8 million people worldwide are living with dementia in 2015, and that the number will almost double every 20 years, reaching 76 million in 2030 and 135 million in 2050. Fifty-eight percent of all people with dementia live in countries currently classified by the World Bank as low- or middle-income countries. This proportion is estimated to increase to 63% in 2030 and 68% in 2050 (ADI, 2015).

Advances in medical research and technologies

Much of the extension of life expectancy and improvements in quality of living over the last century can be attributed to biomedical research and innovation that have successfully targeted life-threatening diseases and debilitating conditions. Still, the global health challenges for the next decades are immense. But the very scale of those challenges across the developing world and the advanced economies offers vast opportunities for established and novel medical procedures, specialised treatments, new medicines and technological solutions, as well as for the development and implementation of innovative systems of health provision and care co-ordination and management. Pharmaceutical research is entering a new era of open science and use of converging technologies to uncover the genetic and biochemical underpinnings of diseases. Technological advances in DNA sequencing, omics technologies, synthetic biology, and gene editing have given researchers new tools to decipher and treat chronic NCDs (OECD, 2015i). Digital technologies – including the IoT (e.g. medical sensors, the "quantified-self" movement, etc.), big data analytics and artificial intelligence will massively increase the amounts of medical data available and enhance the power of data analysis in the service of decision-making. Robotics and neurotechnologies will also likely find extensive use in the medical field. Each of these digital technologies is discussed in Chapter 2, where many healthcare applications are highlighted. Finally, while still small-scale and marginal, do-it-yourself science groups and maker communities are likely to be increasingly visible in the healthcare field, enabled by low-cost advanced technologies like synthetic biology and additive manufacturing that allow them to research and develop their own therapeutics and medical devices.

Concluding remarks

This chapter has set out the main global megatrends that are expected to have a strong impact on societies and economies over the next 10-15 years. Considering their impacts on STI, some common themes emerge. First, the megatrends will shape future R&D agendas and the scope and scale of future innovation demand. For example, ageing societies, climate change mitigation and adaptation efforts, various health challenges, and growing digitisation are, among other factors, expected to influence the research and innovation activities carried out by firms and the public science system.

Second, the dynamics and impacts of many of these factors are international or even global in scope and call for a more internationalised framing of STI activities and policies. STI activities are already extensively internationalised, of course, e.g. through the activities of multinational enterprises and international scientific co-operation among research universities and public research institutes. Economic development in emerging economies has also seen the distribution of STI activities broaden across the globe and this is set to continue over the coming decades. STI policy, by contrast, remains overwhelmingly national in its framing. While there is often good reason for this, the scale and scope of future "grand challenges" calls for greater international STI policy co-operation, e.g. through joint programming, shared facilities, etc. that targets appropriate technology transfer and research collaboration.

Third, the megatrends suggest STI activities could be confronted with disruptive resource constraints over the next few decades. Many megatrends raise urgent issues that demand public policy responses and these could compete with STI for policy attention and resources. Furthermore, a growing, but ageing global population, together with evolving patterns of mobility and migration, will likely impact future STI labour markets.

The direction of influence is not one-way, of course, and developments in STI will shape the dynamics of megatrends and offer solutions to the challenges they raise. For example, from a shaping perspective, globalisation is enabled by advances in communications and transport technologies; future income growth will be increasingly driven by STI developments; and improved health outcomes and increasing life expectancy are heavily dependent on health technology innovation. These are among some of the beneficial impacts of STI, but there are also possible negatives. For example, STI developments could exacerbate inequalities without sufficient attention to wider diffusion and skills acquisition; and developments in artificial intelligence and robotics raise concerns around future employment opportunities. These and other impacts of STI – bearing in mind that technological change is a major megatrend in its own right – are further discussed in Chapter 2.

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Chapter 2

Future technology trends

Technological change is set to have profound impacts over the next 10-15 years, widely disrupting economies and societies. As the world faces multiple challenges, including ageing, climate change, and natural resource depletion, technology will be called upon to contribute new or better solutions to emerging problems. These socio-ecological demands will shape the future dynamics of technological change, as will developments in science and technology.

This chapter discusses ten key or emerging technologies that are among the most promising and potentially most disruptive and that carry significant risks. The choice of technologies is based on the findings of a few major foresight exercises carried out in recent years. The ten technologies are as follows: the Internet of Things; big data analytics; artificial intelligence; neurotechnologies; nano/microsatellites; nanomaterials; additive manufacturing; advanced energy storage technologies; synthetic biology; and blockchain. The chapter describes each technology in turn, highlighting some of its possible socioeconomic impacts and exploring related policy issues. A final section highlights some common themes across the ten technologies.

Introduction

Technological change is a significant megatrend in its own right, constantly reshaping economies and societies, often in radical ways. The scope of technology – in terms of its form, knowledge bases and application areas – is extremely broad and varied, and the ways it interacts with economies and societies are complex and co-evolutionary. These conditions create significant uncertainty about the future directions and impacts of technological change, but also offer opportunities for firms, industries, governments and citizens to shape technology development and adoption. Various types of technology assessments, including trend analyses, evaluations, forecasts and foresight exercises, can provide helpful inputs in this regard.

Technological forecasting has been widely practiced in the worlds of business, public policy, and R&D management since the 1950s. Its goal is to predict with the greatest accuracy possible technological trajectories and their impacts. Scores of different methods are used. Many of them are quantitative and exploit, for example, patent and bibliometrics data to help identify emerging technologies at a relatively early stage. Others rely on expert judgement, particularly when there is considerable uncertainty about future developments. All approaches have well-documented strengths and weaknesses, making it common practice to combine methods.

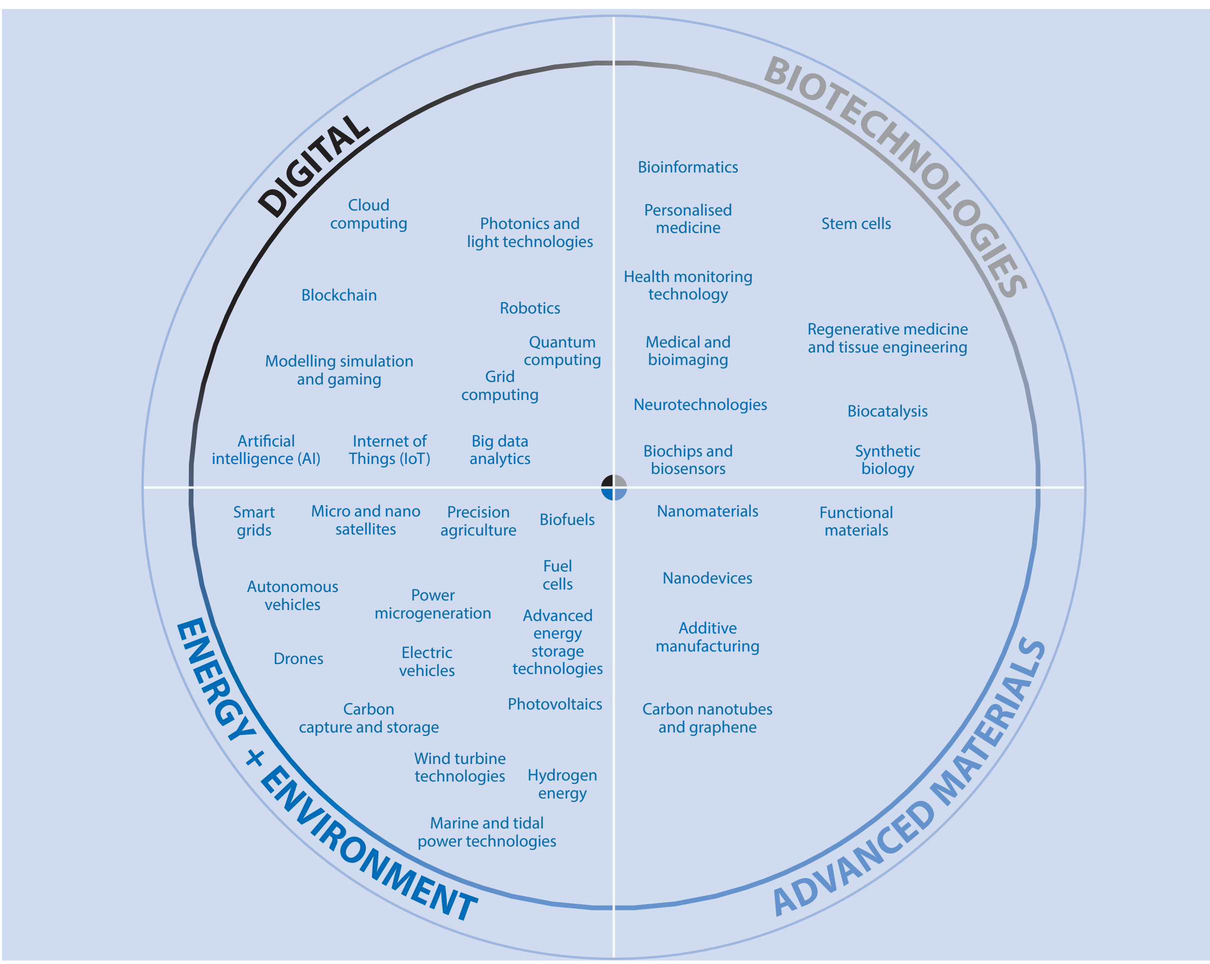
Over the last two decades, technology foresight has emerged as a complementary approach to forecasting. It tends to take a more active stance on the future, eschewing forecasted predictions in favour of multiple futures, often in the form of scenarios, and embracing uncertainty. With an emphasis on co-creating the future – as opposed to trying to predict it – technology foresight exercises invite wide participation, typically involving hundreds, or even thousands, of people from various walks of life to deliberate the future. Still, many exercises are dominated by experts and some form of technological forecasting typically features among the methods employed. Such exercises often identify lists of key or emerging technologies for further investment and policy attention.

Many national governments periodically conduct foresight exercises that seek to identify promising emerging technologies, typically over a 10-20 year time horizon. This chapter examines the results of foresight exercises recently carried out by or for national governments in a handful of OECD countries – Canada, Finland, Germany, and the United Kingdom – and the Russian Federation, where results were available at the time of drafting this report. It also includes the results of an exercise recently conducted by the European Commission. Each exercise is briefly described in Annex 2.A1.

These six exercises have identified well over one hundred key or emerging technologies between them, as shown in the tables in Annex 2.A2. The degree of similarity of results between the exercises is perhaps striking, though it should be borne in mind that this is in part an artefact of the mapping approach used: for the sake of brevity, only top-level labels are shown, beneath which there is more detailed and nationally-specific information that reflects the technological strengths and needs of the country. At the same time, many of these technologies are enabling, "general-purpose" technologies, so it is little surprise that they are widely identified as priorities across many countries.

Some of the most commonly-identified technologies are shown in Figure 2.1 where they have been mapped into four quadrants that represent broad technological areas: biotechnologies, advanced materials, digital technologies and energy and environment. As far as the chart allows, technologies are mapped closer to/further from the "frontiers" of other technologies to reflect their relative proximity/distance. The rest of this chapter covers ten of these technologies (highlighted in Figure 2.1), outlining briefly their main characteristics and development dynamics and promises (essentially their current/possible economic, social and environmental applications), and the main issues their future development/applications may face, including technical, ethical and regulatory issues. The ten technologies are as follows: the **Internet of Things**; **big data analytics; artificial intelligence; neurotechnologies; nano/ microsatellites; nanomaterials; additive manufacturing; advanced energy storage technologies; synthetic biology;** and **blockchain**.[1]

Figure 2.1. **40 key and emerging technologies for the future**



This selection does not infer any sort of priority of the chosen technologies. Rather, it is intended to provide a sample of key or emerging technology areas across a broad cross-section of fields and to demonstrate the potential disruption of technological change over the next 10-15 years. A final section of the chapter highlights several common features exhibited by these technologies and some of the policy implications that follow.

The Internet of Things

The Internet of Things (IoT) promises a hyper-connected, digitally responsive society that will have a profound impact on all sectors of the economy and society. While it has great potential to support human, societal and environmental development, several safeguards need to be put in place to ensure data protection and security.

The Internet of everything

IoT comprises devices and objects whose state can be altered via the Internet, with or without the active involvement of individuals (OECD, 2015a). The term goes beyond devices traditionally connected to the Internet, like laptops and smartphones, by including all kinds of objects and sensors that permeate the public space, the workplace and homes and that gather data and exchange these with one another and with humans. The IoT is really an Internet of everything, since, in addition to connecting things, it also enables digital connections among other elements in the physical world, such as humans, animals, air and water. The networked sensors and actuators in the IoT serve to monitor the health, location and activities of people and animals and the state of production processes and the natural environment, among other applications (OECD, 2016a). The IoT is closely related to big data analytics and cloud computing. While the IoT collects data and takes action based on specific rules, cloud computing offers the capacity for the data to be stored and big data analytics empowers data processing and decision-making. In combination, these technologies can empower intelligent systems and autonomous machines.

The IoT is spreading rapidly

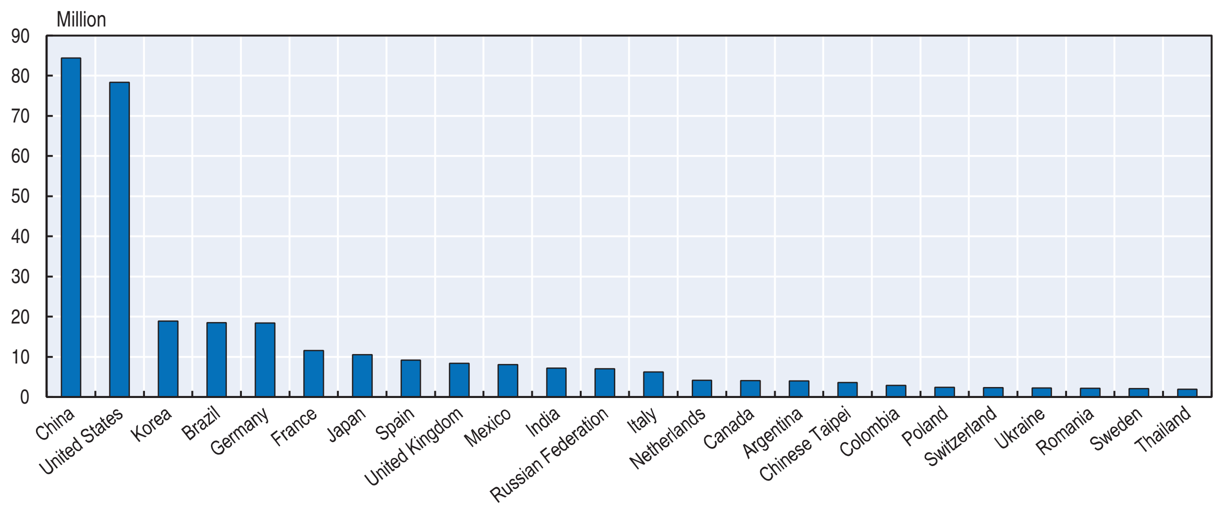
The number of connected devices in and around people's homes in OECD countries will probably increase from 1 billion in 2016 to 14 billion by 2022 (OECD, 2015a). Figure 2.2 shows a country breakdown of 363 million connected devices crawled and surveyed by Shodan, a search engine for Internet-connected devices. By 2030, it is estimated that 8 billion people and maybe 25 billion active "smart" devices will be interconnected and interwoven in one huge information network (OECD, 2015b). Other estimates indicate a number of 50 to 100 billion connected devices in and outside people's homes by 2020 (Evans, 2011; MGI, 2013; Perera et al., 2015). The result is the emergence of a gigantic, powerful "superorganism", in which the Internet represents the "global digital nervous system" (OECD, 2015b).

The IoT will transform societies

The IoT is set to enable a society that is hyper-connected and ultra-digitally responsive. Its economic impact is estimated between USD 2.7 trillion and USD 6.2 trillion annually by 2025 (MGI, 2013). While the IoT has profound implications for all aspects and sectors of the economy, the largest impacts are expected in the healthcare sector, the manufacturing sector, network industries and local government.

Health and healthcare: The IoT provides opportunities to deliver better healthcare and improve people's health by connecting inner and outer bodily sensors to both personal health monitoring devices and professional healthcare systems. In particular, these devices will allow remote monitoring of patients at home and at work (OECD, 2015a). An Internet of bionano things monitoring and managing internal and external health hazards may be emerging (Akyildiz et al., 2015). The treatment of chronically ill patients in particular is expected to become more efficient (MGI, 2013).

Figure 2.2. **Online devices, top 24 countries, 2015**



Source: OECD (2015a), *OECD Digital Economy Outlook 2015, http://dx.doi.org/10.1787/9789264232440-en*, citing Shodan, *www.shodanhq.com.*

StatLink http://dx.doi.org/10.1787/888933433251

Smart manufacturing: The IoT will also affect manufacturing by improving factory operations and managing risk in the supply chain (OECD, 2015a). Existing business processes, such as product logistics, inventory management and the maintenance of machines, will change radically. Waste and loss could be significantly reduced by using sensors and circuit breakers. The IoT offers data and tools to create comprehensive supply-chain intelligence. Combined with advances in robotics, this may lead to fully automated production processes, from user customisation of specifications to final delivery (OECD, 2015c).

Energy systems: IoT-enabled smart grids with smart energy meters allow for two-way communication between energy consumers and the energy grid (OECD, 2015a). Smart grids will help cut utility operating costs and reduce power outages and electricity waste by providing real-time information about the state of the grid (OECD, 2015a). Furthermore, the IoT will allow consumers to have real-time information on energy use and will encourage them to manage their consumption based on smart pricing programmes (already implemented in areas of the United States) that incentivise lower energy use during demand peaks.

Transport systems: The IoT holds great promise for the improvement of transport management and road safety. Sensors attached to vehicles and elements of the road infrastructure may become interconnected, thereby generating information on traffic flows and the technical status of vehicles and of the road infrastructure itself. Already smartphones are actively used by navigation providers to monitor road usage and provide users with real-time traffic updates. Traffic lights and road toll systems may be better adapted to the actual road usage, emergency services can be triggered automatically, and protection against car theft may be enhanced (OECD, 2015a).

Smart cities and urban infrastructures: In addition to smart grids and traffic optimisation, the IoT holds promise for other efficiency gains in the functioning of cities.

Embedded sensors in waste containers and in the water management infrastructure enable the streamlining of garbage collection and may improve water management (MGI, 2013). Furthermore, citizens may use location-based services on their mobile phones for civic participation (e.g. to report damage to roads and other types infrastructure) as well as to give city planners new insights into the usage of public roads (OECD, 2015a).

Smart government: As in the case of manufacturing processes, IoT-enabled real-time monitoring and intelligent systems can benefit the public sector. Smart government combines information, communication and operational technologies to plan and manage operations across the different levels of government to increase efficiency and deliver better public services (OECD, 2016a). The large amounts of data generated by the IoT could be leveraged by policy makers to design responsive and adaptive instruments with real-time monitoring and evaluation.

Further development of the IoT is challenged by high ICT-related costs and emerging skills needs

How fast and how effectively the IoT will evolve over the next 15 years depends to a large extent on the roll-out of fixed and mobile broadband and the decreasing cost of devices (OECD, 2015a). In addition, in order to optimise the potential of the IoT, business and government will have to build capacity to process the large amounts and variety of data that are produced. The large volume of data generated by the IoT is of little value if information cannot be extracted and analysed. To this end, data analytics provide a set of tools and techniques that can be used to extract information from data (OECD, 2015b). This includes data mining (pattern identification from datasets), profiling (the construction of profiles and the classification of entities based on their attributes), business intelligence (periodic reporting of key operation metrics for process management), machine learning (self-improving algorithms that perform certain tasks) and visual analytics (tools and techniques for data visualisation). Skills for data analysis are a key asset for the future, and not just for growth: social inequity is also likely to worsen if the gap continues to widen between those who can and those who cannot keep up with IoT developments (Policy Horizons Canada, 2013).

There are persisting technological uncertainties

Intertwined developments in the areas of big data, the cloud, machine-to-machine communication and sensors underpin the rise of the IoT. The impact of the IoT depends in particular on new and emerging technological developments in big data analytics and artificial intelligence. At the same time, sensors, computers, actuators and other kinds of devices will need to communicate effectively with each other for the IoT to flourish. Yet the favourable context of the IoT has fuelled a number of competing standards in wireless and connectivity solutions, software platforms and applications, raising interoperability issues (OECD, 2016a). Over time, market-driven processes are expected to cause these to converge on a smaller number of effective solutions.

At the core of all concerns is an issue of trust

Security and privacy are considered the most important risks relating to the IoT. Hackers may be able to remotely take over connected objects such as the electricity grid or driverless cars or manipulate IoT-generated data. The reliability of the network is a major issue, since human lives may depend on successful, sometimes real-time transfers of data.

The key issue of consent and perhaps the notion of privacy itself are also challenged by the near-continuous flow of sensitive data that the billions of ubiquitous sensors will produce (OECD, 2015a). Furthermore, artefacts in the IoT can become extensions of the human body and mind. Human autonomy and agency may be shifted or delegated to the IoT, with potential risks for users' privacy and security (IERC, 2015).

Conflicts with existing regulations and regulatory uncertainty may act as bottlenecks when rolling out IoT services in different countries (OECD, 2015a). The international dimension of the IoT adds further complexity, since objects and artefacts could be controlled remotely from abroad, while litigation falls under national legal frameworks.

Big data analytics

Analytics tools and techniques are needed to reap the promises of big data. The socio-economic implications are tremendous, but a major policy challenge will be to balance the need for openness with the threats that an extreme "datafication" of social life could raise for privacy, security, equity and integrity.

Making sense and value of big data

Big data analytics is defined as a set of techniques and tools used to process and interpret large volumes of data that are generated by the increasing digitisation of content, the greater monitoring of human activities and the spread of the IoT (OECD, 2015b). It can be used to infer relationships, establish dependencies, and perform predictions of outcomes and behaviours (Helbing, 2015; Kuusi and Vasamo, 2014). Several types of data analytics allow extracting information from data by contextualising it and examining the way that it is organised and structured (OECD, 2015b). Data mining comprises a set of data management technologies, pre-processing (data cleaning) techniques and analytical methods with the aim of discovering information patterns from datasets. Profiling techniques seek to identify patterns in the attributes of a particular entity (e.g. customers or product orders) and classify them. Business intelligence tools seek to monitor key operational metrics and create standard reports on a regular basis in the interest of informing management decisions. Machine learning encompasses the design, development and use of algorithms that execute a given task while simultaneously learning how to improve its performance. Visual analytics are tools and techniques that allow data to be effectively observed, interpreted and communicated through (often interactive) charts and figures.

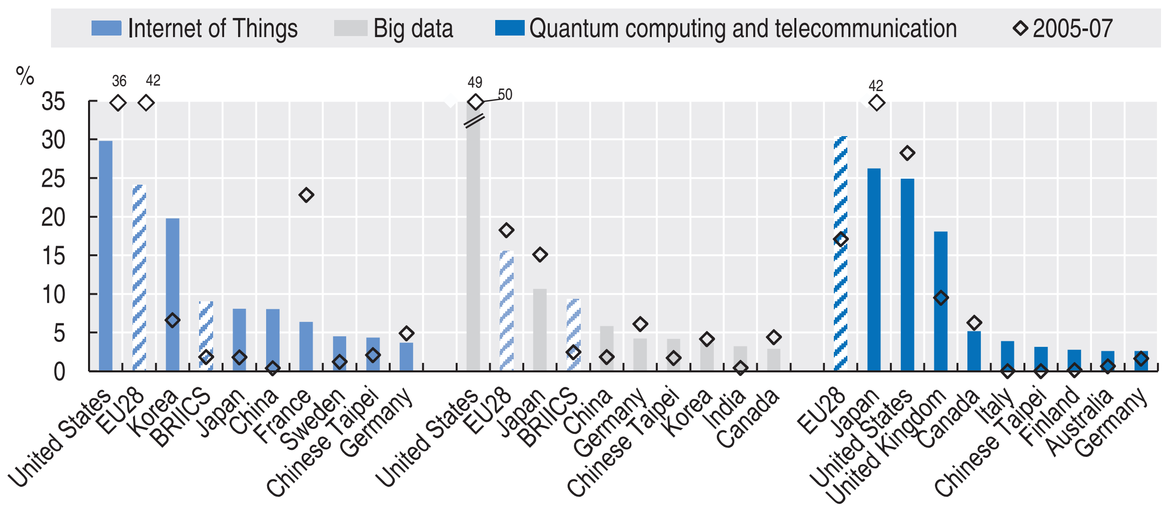
Big data analytics offers opportunities to boost productivity, foster more inclusive growth and contribute to citizens' well-being (OECD, 2015b). Firms, governments and individuals are increasingly able to access unprecedented volumes of data that help inform real-time decision-making by combining a wide range of information from different sources. The IoT and the continuing acceleration of the volume and velocity of accessible and exploitable data will further hasten the development of big data analytics.

Big data will bring tremendous opportunities for businesses and consumers

The exploitation of big data will become a key determinant of innovation and a factor in competitiveness for individual firms (MGI, 2011). On the one hand, it allows firms to closely monitor and optimise their operations, not only by gathering large volumes of data on their production processes or service delivery, but also on how customers approach them and place orders. On the other hand, it provides consumers with more personalised products and services that are specifically tailored to their needs. The abundance of potential market applications is reflected in the growing investment in big data analytics and relevant technologies (the IoT and quantum computing and telecommunication), as shown in Figure 2.3. The number of patent filings for these technologies has grown at double-digit rates in recent years.

Figure 2.3. **Main patenting economies in selected emerging technologies**

Economies' share in IP5 patent families filed at USPTO and EPO, 2005-07 and 2010-12



Source: OECD (2015d), *OECD Science, Technology and Industry Scoreboard 2015*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/888933273495*.

StatLink http://dx.doi.org/10.1787/888933433269

Big data will bring opportunities for the public sector as well

Big data analytics offers significant room for improving public administration efficiency (MGI, 2011). Collecting and analysing large volumes of public sector data can lead to better government policies and public services, thereby contributing to the increased efficiency and productivity of the public sector. For instance, predictive analysis can facilitate the identification of emerging governmental and societal needs (OECD, 2015b). Open data from the public sector can also be commercially exploited by private companies. It also represents a key resource to build public trust by enhancing the openness, transparency, responsiveness and accountability of the public sector (Ubaldi, 2013). Through big data analytics, citizens will be able to take better informed decisions and participate more actively in public affairs.

In particular, research systems and the healthcare sector are set to benefit

Increasing access to public science has the potential to make the entire research system more effective and productive by reducing duplication and the costs of creating, transferring and re-using data; by allowing the same data to generate more research, including in the business sector; and by multiplying opportunities for domestic and global participation in the research process (OECD, 2014a). The rise of open data and open access policies and infrastructures is already making isolated scientific datasets and results part of big data. The number of stakeholders involved in research practices and policy design will continue to increase, making science a citizen endeavour, reinforcing a more entrepreneurial approach to research and encouraging more responsible research policies.

Big data analytics offers the potential of bringing substantive improvement to different dimensions of healthcare, including patient care, health systems management, health research and the monitoring of public health (OECD, 2015b). Sharing health data through electronic health record systems can increase efficient access to healthcare and provide novel insights into innovative health products and services (OECD, 2013a). The diagnosis, treatment and monitoring of patients may become a joint venture between analytical software and physicians. Clinical care may become more preventive in nature, as monitoring and predictive analytics help discover pathologies early on. On top of open research data, the IoT will enable a plethora of health-related data on both sick and healthy people that could serve as valuable research input and bring advances to medicine. Broad data on healthcare utilisation could be put together with deep clinical and biological data, opening new avenues to advance common knowledge, such as on ageing-related diseases, or to support interdisciplinary research, for instance, on the combined effects of cure and care (Anderson and Oderkirk, 2015).

Gaps in IT, skills and legal infrastructures still need to be filled

The rise of big data analytics poses major challenges to skills and employment policies (OECD, 2015b). The demand for data specialist skills will exceed both the current supply of the labour market and the current capacity of education and training systems, requiring rapid adjustments in curricula and the skill sets of teachers and on-the-job workers. Big data is also expected to increase the need for new supercomputing powers, large storage facilities, and a fast, widespread and open Internet (including the IoT), which current IT infrastructures cannot fully support. Legal institutions must also evolve to better promote a seamless flow of data across nations, sectors and organisations. There are growing concerns about how to define and appropriate open access rights, while maintaining publishers' and researchers' incentives to keep publishing and performing research. International co-operation will be essential in that respect.

There is a risk of widening social inequalities

Growing social inequalities will result not only from the job destruction and employment polarisation that will inevitably accompany the structural shift in skills, but also from weaker social mobility and a persisting digital divide. Discrimination enabled by data analytics may result in greater efficiencies, but may also limit an individual's ability to modify path-dependent education and careers trajectories and escape socio-economic lock-ins. In addition, a new digital divide is arising from growing information asymmetries and related power shifts from individuals to organisations, from traditional businesses to data-driven businesses, and from government to data-driven businesses (OECD, 2015b). Social cohesion and economic resilience could be undermined, especially in developing economies. To prevent increases in income inequality, governments will need to help workers adjust to the evolving shifts in the demand for skills by promoting lifelong learning and improving access to high-quality education.

Privacy, security and integrity are also at stake

Big data analytics may incentivise the large-scale collection of personal data that could become accessible in ways that violate individuals' right to privacy. For instance, having patients share sensitive health data may support medical research and enable them to benefit from preferential medical treatment. Yet making medical data accessible to business interests (e.g. insurance companies and employers) raises major issues of privacy and equity. Privacy is also endangered if these data are not well protected and if hacking or misuse could result from breaches in security.

Big data analytics offers a unique possibility to combine personal data with pattern recognition programmes, enabling the generation of new information and knowledge about people (ITF, 2014). However, the same data and same programmes could serve to manipulate people, distort their perception of reality and influence their choices (Glancy, 2012; Helbing, 2015; IERC, 2015; Piniewski, Codagnone and Osimo, 2011). Individual autonomy, free thinking and free will would be challenged, potentially undermining the foundations of modern democratic societies. Policy makers will need to promote the responsible use of personal data to prevent privacy violations, particularly by defining the right set of consumer protection and competition policies, and to expand the oversight capacity of privacy enforcement authorities.

Artificial intelligence

Artificial intelligence (AI) seeks to endow machines with reasoning capabilities that may one day surpass those of human beings. While their full impact remains difficult to appraise, intelligent systems are likely to bring considerable productivity gains and lead to irreversible changes in our societies.

When machines start thinking

AI is defined as the ability of machines and systems to acquire and apply knowledge and to carry out intelligent behaviour. This means performing a broad variety of cognitive tasks, e.g. sensing, processing oral language, reasoning, learning, making decisions and demonstrating an ability to move and manipulate objects accordingly. Intelligent systems use a combination of big data analytics, cloud computing, machine-to-machine communication and the Internet of Things (IoT) to operate and learn (OECD, 2015a). AI is empowering new kinds of software and robots that increasingly act as self-governing agents, operating much more independently from the decisions of their human creators and operators than machines have previously done.

The rise of intelligent machines

Early efforts to develop AI centred on defining compendiums of rules that software could use to perform a task. Such systems would work on narrowly-defined problems but failed when confronted with more complex tasks such as translation and speech recognition (OECD, 2015b). The rise of statistical methods brought key breakthroughs to the field of AI by focusing on data analysis. Instead of aiming to provide exhaustive prescriptive procedures, machine (or statistical) learning aims to make decisions based on probability functions derived from past experiences. This way, a computer can play chess not only by using the set of available legal moves and considering their possible outcomes, but also by referring to past games and calculating how likely it is for a specific move to lead to victory. Through machine learning, software applications can perform certain tasks while simultaneously learning how to improve performance, i.e. by collecting and analysing data on its experience and proposing adjustments to its own functioning that may incrementally improve how the task is performed. As a result, machines develop, tweak and polish their own rules that guide their operation. Advances in the IoT and data analytics have enriched this branch of algorithms with a growing source of data for decision-making. Through advances in computing power and machine learning techniques, it is expected that the cognitive power of machines will surpass that of humans (Helbing, 2015).

AI is not constrained to the digital world; combined with advances in mechanical and electrical engineering, it has also enlarged the capacity for robots to perform cognitive tasks in the physical world. AI will enable robots to adapt to new working environments with no reprogramming (OECD, 2015c). Advanced robots that can adapt to changing working conditions and learn autonomously could generate substantial savings on labour costs and productivity gains. AI could, for instance, lead to better inventory management and resource optimisation. Furthermore, AI holds great promises for safety, by physically replacing humans, reducing work accidents, and enhancing decision-making in hazardous and dangerous situations.

AI may deeply disrupt industry

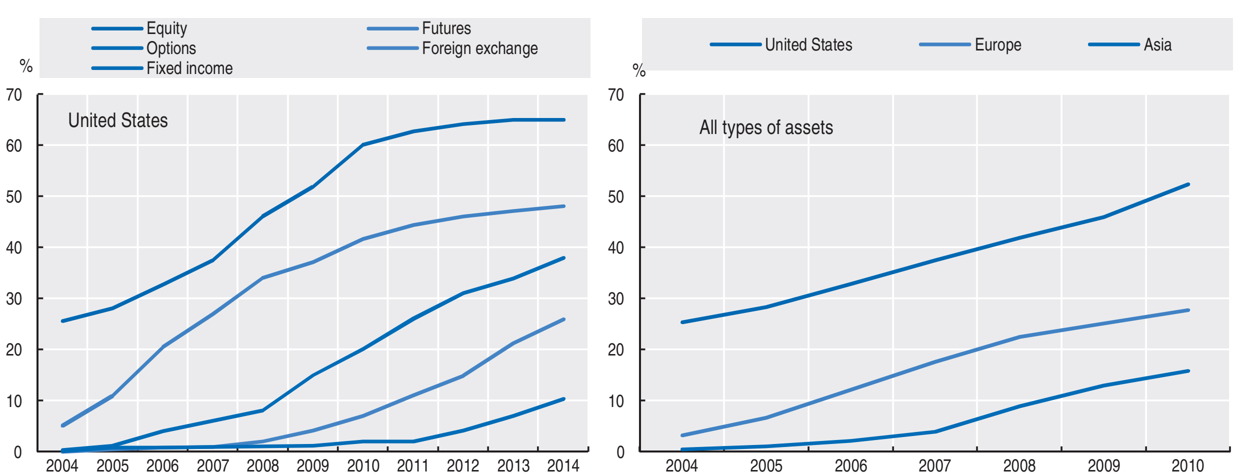
AI-enabled robots will become increasingly central to logistics and manufacturing, displacing human labour in productive processes (OECD, 2015b). AI is expanding the roles of robots, which have been traditionally limited to monotonous tasks requiring speed, precision and dexterity. Sensors are increasingly embedded in production lines, making them smarter and more efficient by adapting processes to changing production requirements and working conditions. Sectors that are likely to experience a new production revolution and radical transformations include agriculture, chemicals, oil and coal, rubber and plastics, shoe and textile, transport, construction, defence, and surveillance and security (López Peláez and Kyriakou, 2008; ITF, 2015; Roland Berger, 2014; ESPAS, 2015; MGI, 2013; UK GOS, 2012).

AI may revolutionise a broad range of services too

AI will be increasingly deployed in a wide range of service industries including entertainment, medicine, marketing and finance. Finance has already been revolutionised by big data analytics and AI as algorithms now conduct more trades autonomously than humans in the United States (Figure 2.4). This trend has been particularly strong in stock exchanges, but is also apparent in the trading of other types of assets such as futures, options and foreign currencies. Machine learning has the potential to advance the role of

Figure 2.4. **Algorithms conduct more and more trades autonomously**

Algorithmic trading as a share of total financial trading, selected countries, 2004-10
and by types of assets in the United States, 2004-14



Source: OECD (2015b), *Data-Driven Innovation: Big Data for Growth and Well-Being*, *http://dx.doi.org/10.1787/9789264229358-en.*

StatLink http://dx.doi.org/10.1787/888933433273

algorithms in trading by allowing them to adjust their strategies over time. Many AI-based products are taking the form of web-based services (OECD, 2015b). For instance, recommendation engines powering Amazon, Netflix and Spotify are based on machine learning technologies. In the health sector, diagnostics are likely to become more accurate and accessible with AI-enabled analysis of medical databases (OECD, 2016a). Surgery robots are already in use, and further automation of health-related tasks is highly probable (López Peláez and Kyriakou, 2008). As its performance improves, especially its anthropomorphist capacity, AI may increasingly perform social tasks. "Social robots" may help address the needs of ageing societies by assisting humans physically and psychologically, artificially acting as companions and diminishing the social isolation of the elderly (IERC, 2015).

AI could augur massive "creative destruction"

Advances in machine learning and artificial intelligence might soon expand the capabilities of task automation. While the degree to which AI displaces labour is still a matter of debate, advances in smart systems will inevitably enable automation of some knowledge work. Automation will no longer depend on a differentiation between manual and intellectual tasks but on the task having some routine features. Middle-income classes may be under particular pressure, as an increasing number of administrative, cognitive and analytical jobs may be performed by data- and AI-empowered applications.

Reaping the benefits of AI depends on several framework conditions being in place

An essential factor for reaping the benefits of AI is the provision of reliable transport, energy and communication networks, including the IoT (OECD, 2015a). AI can make mistakes that result in potentially serious damage (e.g. wrong patient diagnosis). AI decisions may also be subject to misunderstanding, criticism or rejection (e.g. loan refusal). The imperfect nature of AI raises questions about the principles of legal responsibility and how liability should be shared among AI itself, AI constructors, programmers, owners, etc. Laws and legal frameworks will need to be devised and implemented before many of the benefits of AI can be reaped in markets like transportation and health. Another legal dimension of AI concerns the intellectual property rights (IP) to inventions enabled by AI, and how IP rights and revenues should be shared. Legal considerations will have major consequences on insurance markets and IP systems.

Given these projected trends, new skills needs are expected to emerge. Demand for knowledge workers who are able to develop AI or to perform AI-enabled tasks will increase. Creative or tacit knowledge, which is less codifiable, and skills requiring social interaction or physical dexterity, which are less easily automatable, are likely to remain in human hands over the next few decades (López Peláez and Kyriakou, 2008; Brynjolfsson and McAffee, 2015). Today's education systems will need to ensure young people are equipped with the right skills to perform in tomorrow's AI-enhanced environment. Training systems will help smooth the transition and ensure people can cope with and leverage the development of AI technologies.

AI may change humans in unforeseeable ways

The integration of AI into the private sphere will create emotional attachment in humans, particularly in relation to humanoid AI-enabled robots, and alter human social behaviours. Some argue that behavioural differentiation between AI and non-AI machines may justify providing social robots with legal rights and that their protection could serve as a guide to the broader regulation of socially desirable behaviours (Darling, 2012). Others consider that social relationships between humans and robots should be reflected in moral obligation (Coeckelbergh, 2010). More broadly, the use of AI for all human purposes raises several ethical and philosophical issues around human life, including the possible de-humanisation of society. It questions the role humans will play in a new AI-enhanced society and could redefine how people make use of their time, i.e. by rebalancing the time spent on work and leisure.

Neurotechnologies

Emerging neurotechnologies offer great promise in diagnosis and therapy for healthy ageing and general human enhancement. However, some neurotechnologies raise profound ethical, legal, social and cultural issues that require policy attention.

What are neurotechnologies?

Neurotechnology can be defined as any artificial means to interact with the brain and nervous system in order to investigate, access and manipulate the structure and function of neural systems (Giordano, 2012). This encompasses, for example, brain research itself; electronic devices that can repair or substitute brain functions; neuromodulation devices used to treat mental illness; artificial synapses and neuronal networks for brain-computer interfaces; and the development of artificial intelligence.

Neurotechnologies hold great promise for new therapies and human enhancement

Neurotechnologies promise to help better understand the natural processes of the brain, to study and treat neurological disorders and injuries, and to enhance cognitive capabilities so as to enhance human performance. Examples of neurotechnologies in research and application are:

- **Optogenetics:** the engineered, optical control of neurons to observe and control their connection and function (Hoffman et al., 2015). Optogenetic approaches promise to revolutionise neuroscience by using light to manipulate neural activity in genetically or functionally defined neurons with millisecond precision. It offers neuroscientists a powerful tool for investigating the causal links between neural cells, networks and behaviour. Future work will expand brain science into the emotional realm, elucidating new facts about neurodegenerative diseases, behaviour and thought (Kravitz and Bonci, 2013).
- **Neuromodulation technologies:** targeted neuronal stimulation in basic research and brain disorders. Neuromodulation devices are becoming increasingly important in the treatment of nervous system disorders and raise questions related to authenticity and the self, enhancement, use in vulnerable populations (e.g. in children or mentally ill people), involuntary use (e.g. court-ordered or psychiatrist-ordered) and unsupervised use.
- **Brain-computer interfaces:** used to sense and decode neuronal activity patterns by external devices – linking thought commands to external devices. Brain-computer or brain-machine interfaces can enable hands-free device control and user-state monitoring, which can be useful for automobile drivers, pilots, astronauts and others engaged in focus-demanding tasks (Potomac Institute, 2015; Shih, Krusienski and Wolpaw, 2012). More speculatively, brain-computer interfaces could be used to enhance baseline intelligence, allowing multiple brains to co-operate on tasks and enhance performance. They could also be used to develop new senses for human beings, such as the ability to sense magnetic

fields or infrared or radio waves. Technical challenges remain, such as developing fully implantable, untethered, clinically viable neural interfaces with lifetime operation, or increasing the performance of prosthetic device control (Maharbiz, 2015).

- **Nanorobots:** could be defined as systems that are made of assemblies of nanoscale components with individual dimensions ranging between 1 nanometre (nm) and 100 nm (Mavroidis and Ferreira, 2013). Nanorobots can be injected by the millions into the bloodstream and hold great potential in the field of neuroscience, diagnostics and therapy. Future applications could enable actuation, sensing, signalling, information processing, intelligence and swarm behaviour, as well as bypassing the blood-brain barriers. The potential computer-like, IT control of nanorobots and swarm behaviour in future diagnostics and therapies represents a disruptive step in health innovation.

Advances in brain science are key to developing novel neurotechnologies (and vice versa)

Any future computer emulation of brain functions will have its roots in current brain research initiatives. Collaborative research consortia around the globe aim to further advance brain science in order to deliver new paradigms for innovative research and products. Amongst others, the large-scale brain research initiatives listed in Table 2.1 are expected to shed light on long-standing questions in brain science, medicine and philosophy: what are the neural correlates of mind and consciousness; how do large networks of nerve cells process information in healthy brains, and what are the pathological changes in neurodegenerative diseases; how do disparate parts of the brain co-ordinate and work together; and how to build computers in different and more “intelligent ways”?

Table 2.1. **Major initiatives in brain science and technology**

Initiative (Country/ Region)	Goal	Potential future impact
Human Brain Project, “HBP” (Europe)	To achieve a multi-level, integrated understanding of brain structure and function through the development and use of ICT.	Neuromorphic and neurorobotic technologies; supercomputing technologies for brain simulation, robot and autonomous systems control and other data intensive applications; personalised medicine for neurology and psychiatry.
Israel Brain Technologies (Israel)	To promote international collaboration and dialogue; to accelerate local research, industry and innovation.	Mobile platforms to enable real-time interpretation of emotional and cognitive brain activity; treatments and cures for ALS (amyotrophic lateral sclerosis); implanted platform neurotechnology in brain-computer interfaces, epilepsy monitoring and neuromodulation.
Brain Mapping by Integrated Neurotechnologies for Disease Studies, “Brain/MINDS” (Japan)	To map the structure and function of neuronal circuits so as to ultimately understand the complexity of the human brain.	High-resolution, wide-field, deep, fast and long imaging techniques for brain structures and functions; techniques for controlling neural activity; determining causal relationships between the structural/functional damage of neuronal circuits and disease phenotypes and eventually developing innovative therapeutic interventions for these diseases.
Blue Brain Project (Switzerland)	To build a supercomputer-based, digital reconstruction of the rodent brain, and ultimately the human brain.	Neurorobotics and neuromorphic computing applications to better understand the brain and to advance diagnosing and treating brain diseases.
Brain Research through Advancing Innovative Neurotechnologies, “BRAIN Initiative” (United States)	To accelerate the development and application of new technologies that will enable researchers to produce dynamic pictures of the brain that show how individual brain cells and complex neural circuits interact at the speed of thought.	Proof-of-principle cell type-specific targeting of therapeutic manipulations in humans; devices for *in vivo* high-density intracellular recording; hybrid technologies that expand our ability to monitor activity non-invasively in the human brain; links between brain activity and behaviour; data analysis tools to help understand the biological basis of mental processes.

Current brain science projects have enormous potential for solving persistent challenges in medicine, for providing the tools to transform industries, and for opening the door to understanding the brain and mind. However, in spite of the many remarkable advances in neuroscience and the broad scope of future technological applications, basic research has not yet answered one of the fundamental questions for an understanding of how brains work: what is the biological and physical relation between assemblies of neurons and elements of thought?

The consumer and defence industries are expected to increase their investment in brain science as the potential of neurotechnologies grows. Innovation in the field is booming, and patents have been awarded to firms well beyond those in the medical field, such as those working in video games, advertising, automobiles and the defence industries (Sriraman and Fernandez, 2015). In particular, brain-computer interfaces could be widely applied in fields such as entertainment, defence, finance, human computer interaction, education and home automation; the most promising areas are assistive technologies and gaming. Brain-computer interfaces are also being used for monitoring reactions and evaluations in fields such as marketing and ergonomics.

Brain science and neurotechnologies are resource-intensive undertakings

Brain science remains a resource-intensive and economically risky field of research. To a large extent, success in basic research and technology innovation depends on cutting-edge and often high-cost infrastructure, such as computing power and high-resolution imaging technologies. Collaborative partnerships and novel investment models offer interdisciplinary, pragmatic ways to share risks and strengthen commitment in neuroscience and technology. Limited resources have led to the development of more integrative and centralised approaches to research and to the creation of “brain observatories” (Alivisatos et al., 2015). These centres provide the adequate collaborative environment for realising and sharing the potential of novel technologies in brain research. However, large investments and novel mechanisms for sharing risks and benefits require new “rules” on how to govern the collective use and patenting of data and complex neurotechnologies.

Neurotechnologies carry risks

New paradigms and technologies for enhancing humans are likely to develop rapidly. Current innovations in brain science and technology are giving rise to a dizzying array of new approaches to understanding our brains and minds. Invasive neurotechnologies that require neurosurgery bear the risk of potential unintended physiological and functional changes in the brain resulting from implanted electrodes or stem cells, as well as infection and bleeding associated with the surgery itself. Non-invasive neurotechnologies pose fewer risks, although their long-term use may lead to negative consequences on brain structure and functioning (Mak and Wolpaw, 2009; Wolpaw, 2010; Nuffield Council on Bioethics, 2013) and may also be associated with complex unintended effects on mood, cognition and behaviour (Nijboer et al., 2013).

Neurotechnologies raise important societal questions

The potential of neurotechnology to change some central concepts and categories used to observe and understand values, norms and rules related to humans’ moral status raises certain ethical, legal and social considerations. The blurring of the distinction between man and machine makes it more difficult to assess the limits of the human body and raises questions concerning free will and moral responsibility (Schermer, 2009). There are other important questions, too, for instance: who receives the greatest benefits from resource-intensive and often high-cost interventions; how best to balance the risk and ethical responsibilities of brain science and human enhancement applications with therapeutic opportunities; and how to address the inherent tensions between intellectual property rights regimes and a push for greater openness about discoveries and data-sharing.

Given the potentially disruptive nature of novel brain technologies and their applications, stakeholders should aim to assess the ethical, legal and social questions early on in research and development. There is a need to balance the opportunities offered by novel "brain devices" for, e.g. thought-controlled computing, "mind reading" and deep brain stimulation, with the potential impacts on human dignity, privacy and equity. Regulatory agencies are being challenged by the recent shifts in technology paradigms that include, for example, a rise in product complexity and a melding of the natural, medical and social sciences. Here regulatory science is often seen as lagging behind the rapid developments in technologies and practices. In this context, there is a need for policy makers, regulators and the public to better understand the opportunities and challenges of emerging and converging technologies in order to ensure cognitive liberty (i.e. the right to mental self-determination) and to facilitate responsible decision making in, for example, regulatory policy development, public and private funding, and product adoption.

Nano/microsatellites

Increasing use is being made of small and very small satellites with growing capabilities. This will give policy makers an expanding spectrum of sophisticated tools to address "grand" challenges for both civilian and defence purposes.

Ever smaller, cheaper and faster

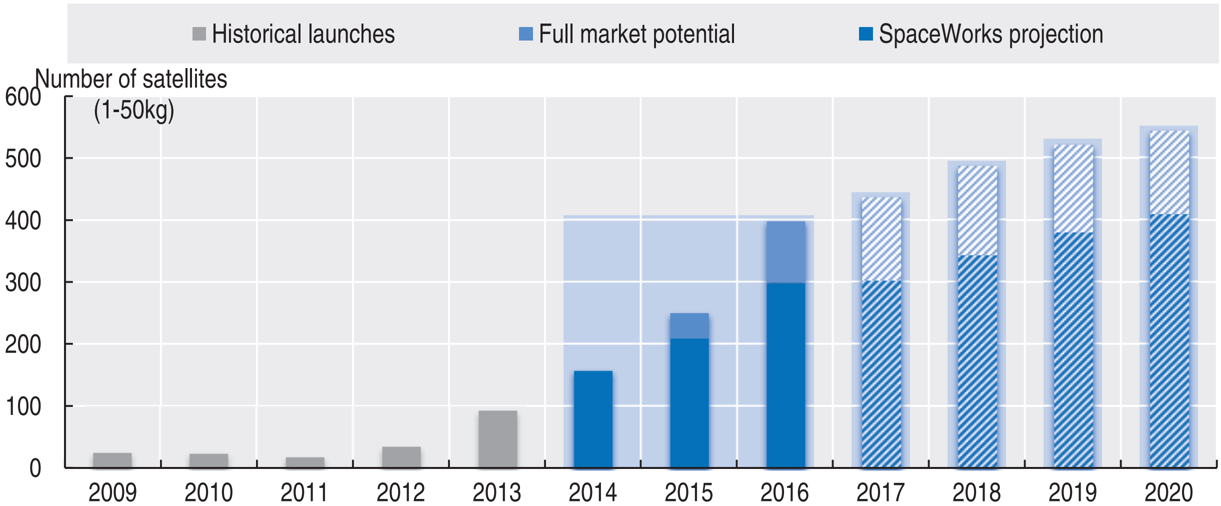
The last few years have witnessed the start of a revolution in the design, manufacture and deployment of satellites. Small satellites, which have become very popular, weigh less than 500 kilogrammes (kg) (a typical communications or meteorological satellite placed in geostationary orbit, at an altitude of around 38 000 kilometres (km), weighs several tonnes, while an environmental satellite such as Jason 2 in low Earth orbit, at an altitude of around 500 km, weighs a little more than 500 kg). Nano- and microsatellites weigh between 1 kg and 50 kg. CubeSats are miniaturised satellites whose original models measured 10 by 10 by 10 centimetres and weighed 1 kg (also known as "1 unit"). Satellite units can be combined to create larger CubeSats.

Small satellites offer vast opportunities in terms of the speed and flexibility of construction. Whereas conventional large satellites may take years if not decades to move from drawing board to operational mission, very small satellites can be built very quickly. By way of illustration, it took Planet Labs just nine days to build two CubeSats in early 2015.

The smaller the satellite, the cheaper it is to build and launch. A nano- or microsatellite can be built for EUR 200 000 to EUR 300 000. Small satellites are becoming much more affordable, as off-the-shelf components are now commonly used to build satellite platforms and support mass production. Most of the electronics and subsystems required to construct a nanosatellite in-house can be bought online (OECD, 2014b). The main cost barrier remains access to space. Small satellites can be launched as secondary payloads for less than EUR 100 000. They can also be deployed from the International Space Station, after having been transported there as cargo.

Since the launch of the first CubeSat in 2002, the number of very small satellites in operation has increased at a remarkable rate. In 2014, 158 nano- and microsatellites were launched, i.e. an increase of 72% compared with the previous year (US FAA, 2015). It is expected that between 2014 and 2020 more than 2 000 nano- and microsatellites will require launching worldwide (SpaceWorks, 2014) (Figure 2.5).

Figure 2.5. **Launch history and projection for nano- and microsatellites, 2009-20**



Note: The Full Market Potential dataset is a combination of publically announced launch intentions, market research and qualitative/ quantitative assessments to account for future activities and programmes. The SpaceWorks Projection dataset reflects SpaceWorks' expert value judgment on the likely market outcome.

Source: SpaceWorks (2014), *www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf.*

StatLink http://dx.doi.org/10.1787/888933433285

Interest in small satellites continues to grow worldwide

The advent of small satellites is ushering in an era of low-cost high-benefit applications in almost every field of human endeavour. Small satellites are finding use across a wide range of applications – from Earth observation and communications to scientific research, technology demonstration and education, as well as defence. A broad range of actors, including research institutions, industry and the military, is increasingly designing whole new classes of missions – navigation, communications or remote sensing – for both civilian and defence purposes.

Creating new commercial ventures in the space economy: The increased use of off-the-shelf components as opposed to more expensive space-qualified products is creating a new world market for space systems and services. Developers are increasingly turning to complex system architectures to get small satellites to interact in constellations. By way of illustration, in 2013, the firm Skybox Imaging launched its first high-resolution imagery satellite as part of a planned constellation of 24 small satellites to provide continuously updated and cheaper satellite imagery. Likewise, Planet Labs launched the Flock 1 constellation with 28 nanosatellites in early 2014. Some experts have drawn analogies with the large mainframe computers of the 1970s that transformed into networks of small computers connected via the Internet.

Pushing knowledge frontiers: CubeSats are very popular in universities as technology demonstrators. They are emerging as low-cost educational satellite platforms and have gradually become the standard for most university satellites. As of spring 2014, almost a hundred universities worldwide were pursuing CubeSat developments (OECD, 2014b). At the educational level, university small satellites can help students much more quickly put into practice their engineering and scientific competences.

Monitoring lands and oceans: Although large satellites in geostationary orbits remain key pillars for telecommunications and meteorological infrastructures, small satellites used in large constellations in lower orbits promise ground-breaking improvements, for example, in Earth observation. Microsatellites provide the capacity for around-the-clock observation. A case in point is the monitoring of the health of oceans and inland waters. Satellite constellations can be used for monitoring illegal fishing and improving awareness of marine domains to combat criminal activities. Similarly on land, constellations could help monitor agricultural crops, improve crop productivity and keep track of deforestation.

Opening space to all: Small satellites have become very attractive in the past five years, due to their lower development costs and shorter production lead times. Small satellites are thus attracting a lot of interest around the world, and many countries are developing them as part of funding their first space programmes. Almost thirty countries have developed CubeSats so far, with the United States launching over half of them, followed by Europe, Japan, Canada, and several South American countries (OECD, 2014b). Over the last decade, the Ukrainian launcher Dnepr has launched 29% of satellites of 11-50 kg, with India's Polar Satellite Launch Vehicle being the second leading launcher.

Further expansion of the small satellites industry faces several challenges

A perennial trade-off between size and functionality: The smaller the satellite, the fewer instruments it can carry and the shorter its life expectancy because of the smaller amount of on-board fuel. Larger satellites still have a major role to play, as they can carry more instruments and have longer lifetimes, in particular in carrying out important commercial and governmental missions. However, recent advances, both in miniaturisation and satellite integration technologies, have dramatically reduced the scale of the trade-off (US NASA, 2014).

Dealing with high business risk: Increasingly, nano- and microsatellites are being launched in large clusters, and a single failure (at launch or on deployment) can lead to substantial losses. The 2014 failed Antares rocket launch led to the loss of over 30 satellites (SpaceWorks, 2015).

The growing environmental threat from debris and collisions: The main environmental concern is that the fast deployment of small satellites will heighten the risk of collision in some already-crowded orbits, creating a cascading effect as more debris generates an ever-greater risk of further collisions. According to international guidelines on space debris, most satellites should either move to a "graveyard" orbit or re-enter the atmosphere when they reach their end-of-life operations. However, by construction, very small satellites do not have the on-board fuel for de-orbit manoeuvres.

What are the STI policy implications?

Governments could support the development of nano- and microsatellites by encouraging their use for educational purposes in universities and research institutions, creating more favourable conditions for specialised start-ups and fostering synergies in satellite-related entrepreneurial clusters.

As the variety of uses of nano- and microsatellites increases, so too will the volume of data generated for private and public purposes. Policy makers should create the right regulatory frameworks and business environments to ensure that this explosion of data can be exploited for the benefit of the many.

Nanomaterials

Nanomaterials display unique optical, magnetic and electrical properties that can be exploited in various fields, from healthcare to energy technologies. However, technical constraints and uncertainties over their toxicity to humans and the environment continue to hinder their widespread application.

Nanomaterials have unique properties

Nanomaterials are defined as material with any external dimension in the nanoscale (10^{-9} metre) or having internal structure or surface structure in the nanoscale that represents a range from approximately 1 nm to 100 nm (ISO, 2012). Nanomaterials can be either natural, incidental or artificially manufactured/engineered. Nanomaterials include carbon-based products; nanostructured metals, alloys and semiconductors; ceramic nanoparticles; polymers; nanocomposites; and sintering and biobased materials (VDI Technologiezentrum GmbH, 2015). Among carbon-based materials, nanotube technologies and graphene are of particular interest for industry and research purposes. Among other materials that currently attract the most attention are nanotitanium dioxide, nanozinc oxide, graphite, aerogels and nanosilver (EC, 2014).

Nanomaterials are expected to have considerable impact on both research and commercial applications in many industry sectors. They represent a breakthrough in controlling matter on a scale where the shape and size of assemblies of individual atoms determines the properties and functionalities of all materials and systems, including those of living organisms. In addition, by exploiting quantum effects, unique optical, magnetic, electrical and other properties emerge at this scale. This is because nanomaterials, in contrast to macroscopic materials, show a high ratio of surface atoms to core atoms. Their behaviour is mainly dominated by surface chemistry. The higher surface proportion increases the surface energy of the particles, causing the melting point to sink and the chemical reactivity to increase.

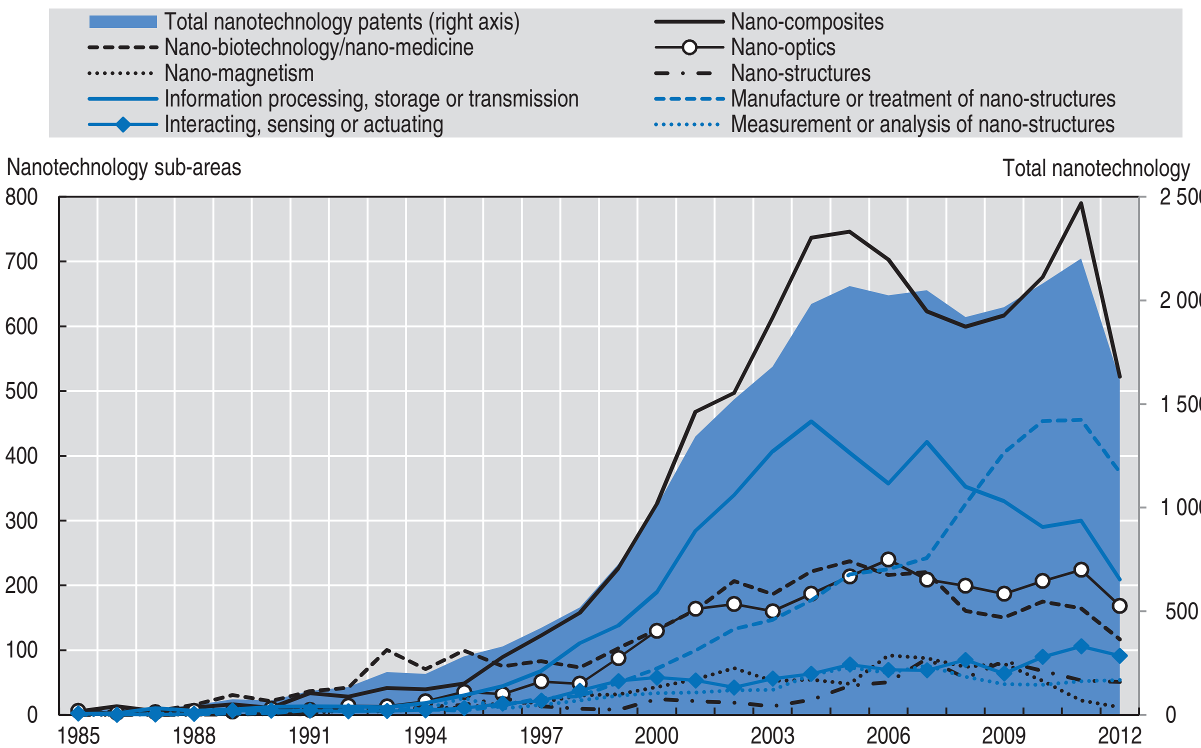
Nanomaterials are expected to have many areas of application

The current value of the market for nanomaterials is around EUR 20 billion (EC, 2014), and the spectrum of commercially viable applications is expected to increase over the next few years. Although marketed in small quantities in absolute figures, commodity applications such as carbon black and amorphous silica have reached a level of maturity and already represent high volumes of the nanomaterials market. Areas of application already encompass medicine, imaging, energy and hydrogen storage, catalysis, lightweight construction and UV protection (VDI Technologiezentrum GmbH, 2015; Tsuzuki, 2009). The areas with the highest application volumes are typically those where nanomaterials have replaced an incumbent material of larger or less controlled particles size. Applications in these areas are driven by the performance enhancements that the control of materials on the nanometre-scale provides, as well as by the resource-efficiency that particle-size reduction entails. The breadth of applications is illustrated by the spread of nanotechnology patents over ten sub-areas (often representing application areas) of the field (Figure 2.6).

One of the most promising areas for the application of advanced nanomaterials (i.e. nanomaterials of complex composition and shape, which have been designed to have specific properties) is in medicine, which currently accounts for the highest share of applied advanced nanoproducts (Vance et al., 2015). Nanomaterials are expected to enhance diagnostics in several ways: for example, increases in the sensitivity of diagnostics chips (lab-on-a-chip) will enable earlier diagnosis of cancer; robust fluorescent markers using nanomaterials are likely to increase the reliability of in-vitro diagnostics (VDI Technologiezentrum GmbH, 2015); and tagged gold nanoparticles will boost the development of molecular imaging and can also be used for rapid screening of cancer drugs that require less specialised equipment than traditional methods (University of Massachusetts Amherst, 2014). Nanomaterials are also expected to enhance medical treatment, e.g. biocompatible nanocellulose could be applied in treating burns.

Figure 2.6. **Nanotechnology patents by sub-area and total, 1985-2012**

Number of patents applications filed under the Patent Cooperation Treaty (PCT)



Note: Data relate to patent applications filed under the Patent Co-operation Treaty (PCT), by priority date, the inventor's residence and fractional counts.

Source: Based on STI Micro-data Lab: Intellectual Property Database, *http://oe.cd/ipstats*, data extracted in July 2016.

StatLink http://dx.doi.org/10.1787/888933433297

Outside of the medical field, nanomaterials will be increasingly used in everyday items. For example, nanofibres have enabled the development of textiles that are water-, wrinkle- and stain-resistant or, if intended, selectively permeable. Combined with e-textiles, they could contribute to the development of smart fabrics/functional textiles (VDI Technologiezentrum GmbH, 2015; EC, 2014), which may also be used in military and emergency response applications to increase human safety. Nanomaterials are also likely to facilitate the development of functional building materials such as self-cleaning concretes. In the energy and environmental area, smart polymeric nanomaterials have expected uses in biodegradable packaging and hydrogels, while silicon nanocrystals are used already in photovoltaic cells (OECD, 2011). Nanomaterials also enable many process innovations. For example, the availability of functional inks has transformed many printing processes, ranging from the creation of printed electronics in high-precision ink-jet processes to the large-scale laminar wet-in-wet printing of layered materials to the high-throughput production of third-generation solar cells in roll-to-roll printing processes. The food packaging industry is already using bespoke infrared light absorbing nanomaterials in PET bottles in order to reduce the energy input required to make the bottles and shorten the curing time during the manufacturing process.

Private sector research on nanomaterials is dominated by multinational enterprises

Industrial research on nanomaterials is dominated by multinational enterprises from a variety of sectors. BASF is one of the leading companies in the fields of chemical nanotechnology, nanostructured materials, nanoparticles and the safety of nanomaterials. For instance, the company is a global leader in research on metallic organic frameworks applied in energy and environmental industries (BASF, 2015). L'Oréal is among the largest nanotechnology patent holders in the United States and has used polymer nanocapsules to deliver active ingredients into deeper layers of the skin (Nanowerk, 2015). Beyond the multinationals, an increasing number of technology start-ups are exploiting nanomaterials in specific niche areas. For example, a promising application area for nanomaterials is waste-water treatment by individuals in less-developed parts of the world. One start-up has developed a cost-effective water filtration membrane based on titanium dioxide nanoparticles that are able to filter dirt and bacteria (Nanowerk, 2014), while another has designed an open-source, 3D-printable water filter prototype that uses activated carbon and nanomembrane technology and that can be integrated into a water bottle cap (Faircap, 2014).

Outstanding technical and environmental concerns restrict the application of nanomaterials

Both the research and development of nanomaterials and their commercialisation have expanded much more slowly than initially anticipated in the 1980s, when nanotechnology was celebrated as the "next industrial revolution". The reasons for the slow progress are two-fold: first, the cost of the R&D instrumentation necessary for advanced nanomaterials research stifles research in many academic laboratories and hampers innovation in small companies. And second, the commercial-scale production of advanced nanomaterials is often delayed, due to an inadequate understanding of physical and chemical processes at the nanometre-scale and to the inability to control the necessary high-throughput production parameters at that scale. These technical restrictions continue to hinder development of cost-effective, large-scale commercial applications of nanomaterials.

There are also questions around unintended hazards (toxic effects) to humans and the environment. While particle size alone is insufficient to account for toxicity (SCENIHR, 2009), the use of nanomaterials in some specific environments may need to be regulated (OECD, 2015e). For example, due to their small size, nanoparticles can permeate cell membranes in the body (via skin absorption, ingestion, inhalation) and travel to places where larger particles cannot physically reach (Suran, 2014). The same risk has to be considered for the use of nanoparticles in agriculture (Das, Sen and Debnath, 2015). Risk assessment is still confronted with a considerable lack of data on exposure of nanomaterials to the environment, requiring further research (EC, 2014; OECD, 2011; Fahlman, 2011). The continuing uncertainty about regulatory requirements is negatively affecting future R&D and the commercialisation of many potentially beneficial applications of nanomaterials.

Additive manufacturing

Progressively adding material to make a product take shape is an unprecedented approach to manufacturing that warrants new business models and implies significant changes to existing industries. However, this technology must overcome several challenges, both technical and regulatory, if it is to permeate industrial processes on a large scale.

A new manufacturing paradigm is emerging

Manufacturing today is primarily subtractive (i.e. products are built by using material and removing unnecessary excess), or formative (i.e. material is forced to take shape using a forming tool). Additive manufacturing (AM) – also commonly known as 3D printing – encompasses different techniques that build products by adding material in layers, often using computer-aided design software (OECD, 2015c; VDI Technologiezentrum GmbH, 2015). Among the most common AM technologies are fused deposition modelling (fused filament fabrication), stereolithography, digital light processing and selective laser sintering.

3D-printing processes are used to build models, patterns or tooling components based on plastics, metals, ceramics and glass. A distinction can be made between three main applications: rapid prototyping is used industrially in R&D for model and prototype production; rapid tooling is applied at later stages of product development; and rapid manufacturing refers to the production of end-use parts using layer-manufacturing techniques directly (Hague and Reeves, 2000; Wohlers Associates, 2014).

AM promises to expand the capacities of production processes

Rooted in manufacturing research in the 1980s, AM was primarily used in the past to create visualisation models of prototypes, which could shorten the product design stage. This is still an important use today, and rapid prototyping is used by engineers, architects, designers and medical professionals, as well as in education and research. More recently, as materials, accuracy and the overall quality of the output have all improved, 3D printing has widened its scope of application. Today, 3D-printed prototypes for fit and assembly are widespread, and they are expected to become even cheaper and faster to produce over the next decade or so (Gibson, Rosen and Stucker, 2015; Bechtold, 2015). Recent technological developments include performance improvements in manufacturing machinery and an expanding range of applied raw materials. Engineers are employing an increasing number of composite materials (such as fibre-reinforced plastics) and functionally graded materials (by varying the microstructure with a specific gradient).

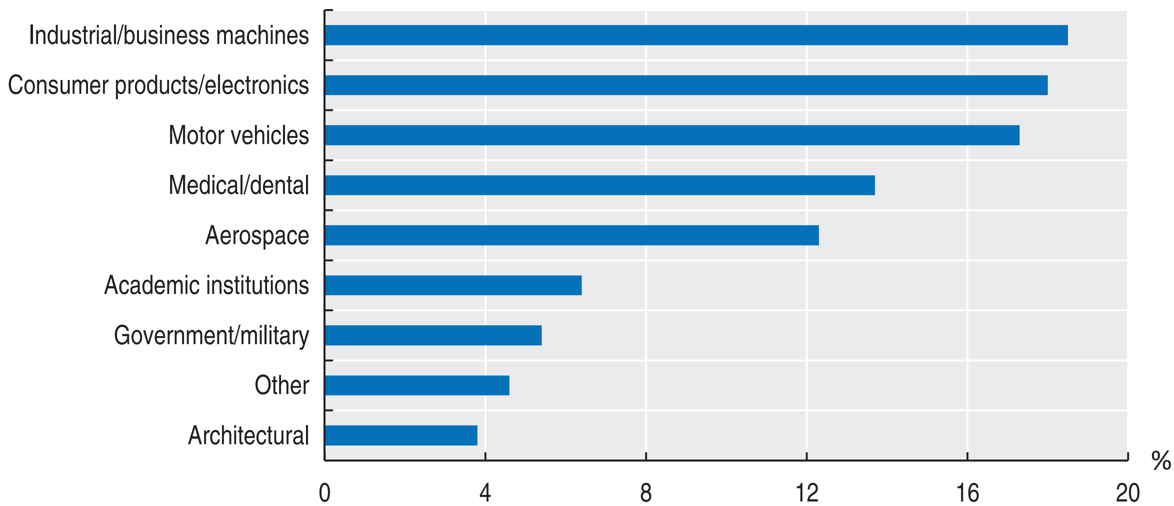
It is estimated that the global AM market will grow at a compound annual rate of around 20% from 2014 to 2020 (MarketsandMarkets, 2014). Wohlers Associates (2014) estimates sales of AM systems and services at USD 21 billion in 2020. As 3D-printing processes continue to mature and grow, they can potentially address many important needs in industrial, consumer and medical markets. In general, AM technologies are profitable where small quantities of highly complex and increasingly customised products are needed (Wohlers Associates, 2014). They allow much room for design flexibility and the personalisation of highly complex samples and components.

Wohlers Associates conducts annual surveys of AM system manufacturers and service providers. In its 2014 edition, 29 industrial AM system manufacturers and 82 service providers worldwide were surveyed, representing more than 100 000 users and customers.

The survey asked each company to indicate which industries they serve and the approximate revenues (as a percentage) that they receive from each – the results are shown in Figure 2.7. The survey also asked the companies what their customers used their printing devices for. The results show that companies use AM technology to produce functional parts more than anything else (Figure 2.8).

Figure 2.7. **Worldwide industrial additive manufacturing revenue per sector**

As a share of total revenue

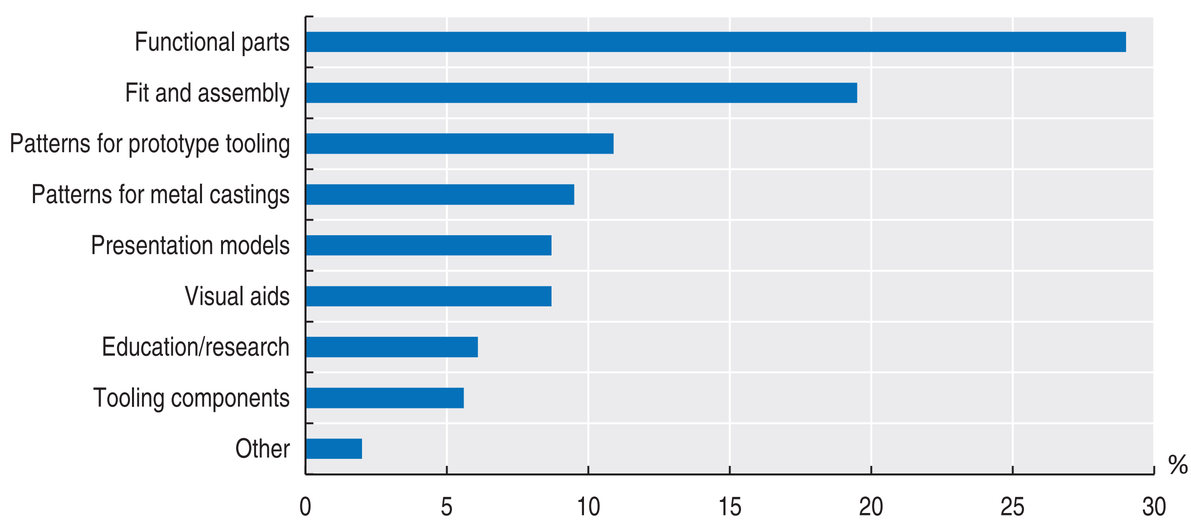


Source: Wohlers Associates (2014), *Wohlers Report 2014: 3D Printing and Additive Manufacturing State of the Industry: Annual Worldwide Progress Report*.

StatLink http://dx.doi.org/10.1787/888933433301

Figure 2.8. **What do companies use additive manufacturing technologies for?**

As a share of total use



Source: Wohlers Associates (2014), *Wohlers Report 2014: 3D Printing and Additive Manufacturing State of the Industry: Annual Worldwide Progress Report*.

StatLink http://dx.doi.org/10.1787/888933433317

AM will lead to innovation in health, medicine and biotechnology

3D-printing technologies are set to bring about new products in health, medicine and biotechnology. Dental applications represent the largest share in the medical field to benefit from 3D-printing technologies. Printed dental prostheses, hip implants and prosthetic hands (bioprinting or bioengineering) as well as prototypes of exoskeletons are already in use. DNA printers and the printing of body parts and organs from the patient's own cells are in the process of development. Not only do bioprinted biological systems resemble humans genetically, but they also respond to external stress as if they are living organs (Kuusi and Vasamo, 2014). Bioengineering experts estimate that animal testing could be replaced by the use of 3D-printed human cells by 2018 (Faulkner-Jones, 2014). In the future, people with particular dietary requirements could print their own fortified or functional food. Bioprinted meat made from living cells could also be a future field of application (VDI Technologiezentrum GmbH, 2015).

AM will also benefit metal processing in a range of industries

Metal processing based on 3D-printing processes, such as selective laser melting and electron beam melting, is common in the automotive, defence and aerospace industries. Many components have already been produced for space applications; their number will continue to grow, as will their complexity. Further research in metal alloys can have long-term impacts on space exploration, as future generations of astronauts may be able to print equipment they need based on material that takes less mass at launch (OECD, 2014b). In energy technologies, AM is increasingly used for the service and maintenance of highly complex replacement parts (VDI Technologiezentrum GmbH, 2015).

Accelerated digitisation and environmental concerns will influence the demand for AM technologies

The digitisation of 3D-printing technologies will allow product design, manufacturing and delivery processes to become more integrated and efficient. As 3D printing will drive digital transportation, and the storage, creation and replication of products, it has the potential to change work patterns and to spark a production revolution. Companies will sell designs instead of physical products. Placing an order will be a matter of uploading the resulting file that will trigger automated manufacture and delivery processes, possibly involving different companies that can easily co-ordinate (OECD, 2015c).

3D printing could also offset the environmental impacts of traditional manufacturing processes and supply chains by lowering the production of waste. Direct product manufacturing using printing technologies can reduce the number of steps required for the production, transportation, assembly and distribution of parts, reducing the amount of material wasted in comparison with subtractive methods (OECD, 2015c). On the other hand, printers using powdered or molten polymers still leave behind certain amounts of raw materials in the print bed that are typically not reused (Olson, 2013). The most commonly used plastic for home-use printing, acrylonitrile butadiene styrene (ABS), is recyclable. Other biobased plastics (such as polylactic acid [PLA]) are biodegradable, without compromising their good thermal, mechanical and processing properties (OECD, 2013b). However, a recent study has shown that the emission rates of ultrafine particles of printers using ABS and PLA are particularly high and could pose health risks (Stephens et al., 2013). Information on the health and environmental effects of newer materials such as fine metal powders, used in selective laser sintering, is still scarce. Likewise, research on the embedded energy of materials, their carbon footprint and the tendency to overprint objects caused by the technology's simplicity and ubiquity will need further attention (Olson, 2013).

The wide adoption of AM still faces several obstacles and risks

The range of materials used in 3D printing is still limited, and their use is subordinate to printing methods and devices. Surface quality and detail are often not sufficient for end-use and require cost-intensive post-processing. Conventional printing devices work slowly, and it is difficult to monitor quality (even though the first print heads with integrated sensors have been developed) during the printing process.

As 3D printing becomes more accessible, legal and regulatory issues around data protection, product liability and intellectual property will come to the fore. Industries, inventors and trademark owners already confront considerable intellectual property infringements in the personal and open source printing sectors (Vogel, 2013). 3D printing could enable decentralised, mainstream piracy, similar to the product piracy that accompanied the digitisation of music, books and movies. The enforcement of owners' rights is costly (litigation expenses, social friction), non-transparent and often arbitrary. Regulators could impose certain restrictions on the technical design of printers in order to inhibit infringing, though this could slow innovation. Imposing taxes on devices or raw materials would affect legitimate uses of 3D printers (Depoorter, 2013). Research is currently underway on watermarking techniques to prevent piracy.

Another obstacle to overcome is the price of the printing devices. In recent years, personal 3D printers have appeared on the electronic consumer market at very affordable prices (below USD 1 000), while at the same time more sophisticated 3D printers (e.g. for metal processing) often sell for more than USD 1 million (EC, 2014; MGI, 2013). Costs are expected to decline rapidly in the coming years as production volumes grow (MGI, 2013). It remains difficult to predict precisely how fast this technology will be deployed, but eventually it will likely permeate the production processes of different types of products in larger numbers (OECD, 2015c).

Advanced energy storage technologies

Energy storage technology can be defined as a system that absorbs energy and stores it for a period of time before releasing it on demand to supply energy or power services. Breakthroughs are needed in this technology to optimise the performance of energy systems and facilitate the integration of renewable energy resources.

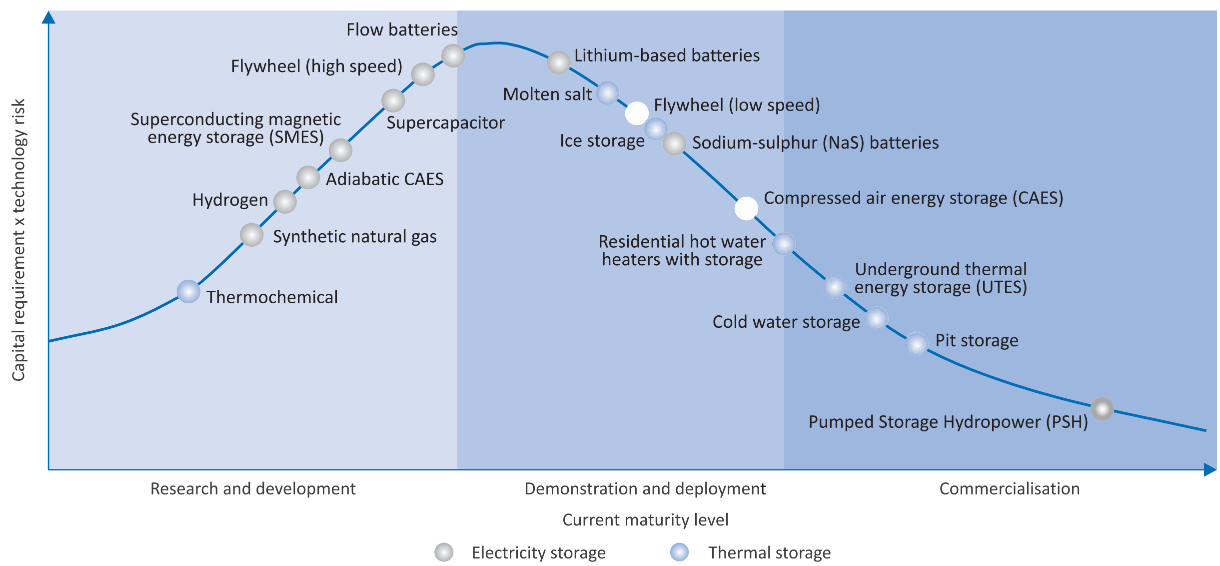
Energy storage technologies are essential to bridge temporal and geographical gaps between energy demand and supply

The availability of renewable energies such as sunlight, wind and tides is intermittent and not always predictable (Carrington, 2016). With renewable energy sources contributing an increasing share of electricity to power grids, investments in storage technologies that allow energy supply to be adjusted to energy demand are increasingly important. Energy storage technologies can be divided into electrical, (electro)-chemical, thermal and mechanical. They can be implemented on small and large scales in either centralised or decentralised ways throughout the energy system. Large-scale grid energy storage devices are used to balance power fluctuations, whereas battery systems are more suited to decentralised balancing, given their limited storage capacity, long charging time and self-discharge (VDI Technologiezentrum GmbH, 2015; MGI, 2013).

Energy storage technologies represent considerable economic potential with far-reaching business opportunities

There has been a sharp increase in the deployment of large-scale batteries and thermal energy storage over the last decade (IEA, 2015). Batteries in particular have experienced major technological acceleration, as reflected in data on patent "bursts" (OECD, 2014a; Dernis, Squicciarini and de Pinho, 2015). A range of different energy storage technologies are still in the early stages of development, including multivalent batteries, high-speed flywheels, lithium-sulphur batteries and superconducting magnetic energy storage systems (Crabtee, 2015; IEA, 2014) (Figure 2.9).

Figure 2.9. **Maturity of energy storage technologies**



Source: IEA (2014), "Energy storage", *IEA Technology Roadmaps, http://dx.doi.org/10.1787/9789264211872-en.*

The economic viability of energy storage will likely depend on the further development of small- and medium-scale battery technologies as well as on large-scale centralised and decentralised grid technologies. Advanced batteries in particular could potentially displace the internal combustion engine in passenger vehicles and support the transition to smart homes and smart offices. In general, new energy storage technology could change where, when and how energy is used.

Small-scale applications – in electric mobility and portable consumer electronics – will be important demand drivers

Electro-chemical energy storage still dominates battery technologies and encompasses lead acid batteries, nickel-based systems, high-temperature redox flow and lithium-ion batteries (around 250 watt-hours per kilogram). Batteries can be used for both short- and medium-term applications, as they benefit from being scalable and efficient (IEA, 2014). The majority of portable consumer electronics devices and passenger hybrid and electric vehicles (EVs) are powered by lithium-ion batteries, which have seen consistent price reductions and performance increases in recent years. In fact, especially big batteries are leading the way: for example, the price of a lithium-ion battery pack in an EV fell by 40% between 2009 and 2013 (MGI, 2013), which saw sales of EVs grow to 665 000 in

2014 compared with virtually none on the road in 2009 (IEA, 2015). Solid-state lithium-ion cells represent a further development of traditional lithium-ion batteries: they replace the liquid electrolyte with a solid material, are more efficient and less dangerous, and are anticipated to be commercially viable in a few years (Motavalli, 2015). To make these technologies more flexible and attractive, car manufacturers have started to sell vehicle-to-home systems, enabling customers to use vehicles to power homes and vice versa. In the future, supercapacitors (high-capacity electrochemical capacitors) that store kinetic energy in pendulum movements and charge without almost any time delay, could also allow cars to charge during normal stops in traffic, e.g. at traffic lights (Kuusi and Vasamo, 2014).

Other new battery systems encompass, for example, the metal-air battery that is at an early level of research. Metal-air batteries typically use lithium or zinc (zinc-air batteries or fuel cells) for the anode, and oxygen, which is drawn in from the environment, as the cathode. This makes the battery lightweight with a long-lasting regenerative cathode. Over the coming decade, energy density could increase to a level that battery-powered vehicles become cost-competitive with vehicles powered by internal combustion engines. Two routes are being pursued to improve energy density: developing electrode materials with higher capacity, and developing cells using higher voltage chemistry (Element Energy, 2012). Marketable products could be available by 2020 (VDI Technologiezentrum GmbH, 2015).

Large-scale applications in grid energy storage will steer demand as well

Power outages cause billions of dollars' worth of damage every year worldwide. Over-generation also remains a major issue (IEA, 2015). Large-scale energy storage systems offer the possibility to balance power fluctuations and to decentralise them. While battery systems are particularly suited for short- and medium-term small-scale, distributed energy applications, their limited storage capacity and self-discharge make them less suitable for load balancing (VDI Technologiezentrum GmbH, 2015). Alternative systems are used for grid energy storage and include hydroelectric energy storage, such as pumped-storage hydroelectricity (PSH), compressed air energy storage (CAES) and hydrogen systems. PSH systems are widely used and account for 97% of grid energy storage worldwide (IEA, 2015). They utilise elevation changes to store off-peak electricity for later use, as do conventional hydropower plants. PSH systems are sophisticated and in many countries represent the only storage technology applied at large scale. Hydrogen and CAES facilities can be used for long-term energy applications and have been deployed by the United States and Germany for several decades. However, these technologies are cost-intensive, have low overall efficiencies and raise safety concerns. Superconducting magnetic energy storage (SMES) and supercapacitors serve as short-term storage applications – in the range of seconds or minutes – by using static electric or magnetic fields. Flywheels store rotational energy through the application of a torque SMES. Supercapacitors and flywheels are usually characterised by high power densities but low energy densities, making them suitable for balancing short-term power fluctuations (IEA, 2014).

Advanced energy storage technologies are expected to reduce greenhouse gas emissions

Energy storage technologies are expected to contribute to meeting the 2°C scenario targets by providing flexibility to the electricity system and reducing wasted thermal energy (IEA, 2015). More energy could be sourced from renewable sources if energy output could be controlled through storage solutions (Elsässer, 2013). At the same time, as renewables are increasingly deployed, the demand for energy storage technologies is also expected to grow (IEA, 2015). Smart storage systems and smart grids may also encourage the production of renewable energy by local co-operative structures (ESPAS, 2015); cost-effective solar, wind and battery technologies are key building blocks for decentralised energy systems (Policy Horizons Canada, 2013). In developing economies, storage systems have the potential to bring reliable power to previously inaccessible remote areas (US Department of Energy, 2014).

Further R&D is imperative to improve the cost efficiency of energy storage

Technology breakthroughs are needed in high-temperature thermal storage systems and scalable battery technologies, as well as in storage systems that optimise the performance of energy systems and facilitate the integration of renewable energies (IEA, 2015). R&D on storage solutions is also underway with a view to realising cost reductions in the technology (IEA, 2014). The high capital costs of storage technologies remain a barrier to wide deployment (IEA, 2015).

As the materials, technologies and deployment applications for storing energy are created, new techniques and protocols must be developed to validate their safety and ensure that the risk of failure and loss is minimised (US Department of Energy, 2014). For instance, the benefits of lithium batteries should be evaluated with regard to the global environmental and health impact of lithium extraction and handling.

Synthetic biology

Synthetic biology is a new field of research in biotechnology that draws on engineering principles to manipulate DNA in organisms. It allows for the design and construction of new biological parts and the re-design of natural biological systems for useful purposes. It is expected to have a wide range of applications in health, agriculture, industry and energy, but it also raises major legal and ethical issues.

Synthetic biology attempts to reshape living systems on the basis of a rational blueprint

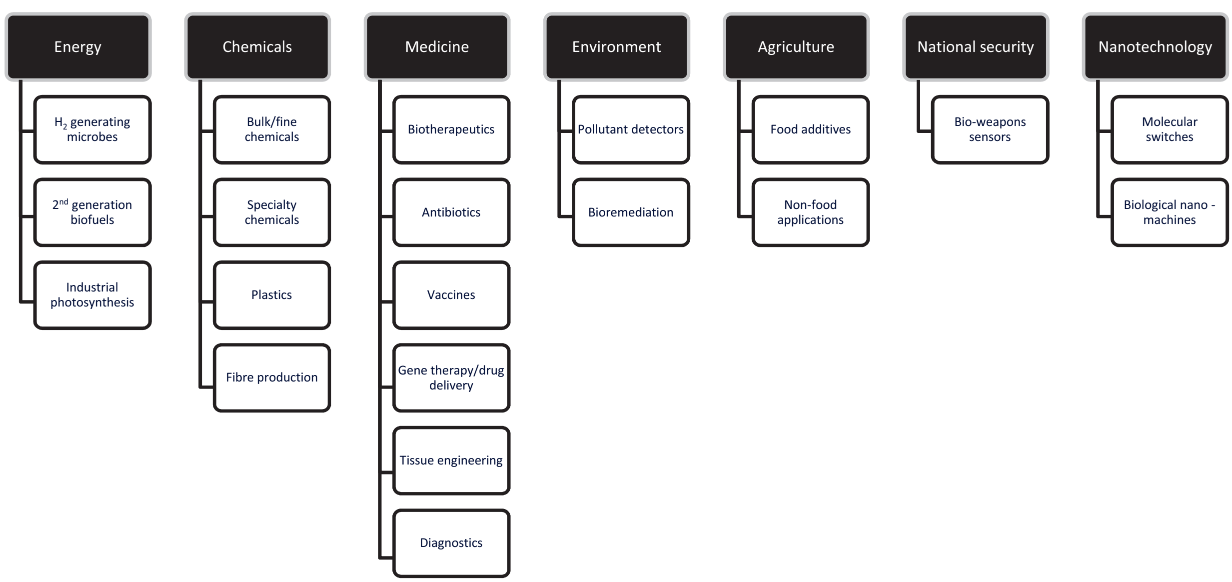
While humans have been involved in genetic manipulation by selective breeding for 10 000 years, it was only in the 1970s that the direct manipulation of DNA in organisms became possible through genetic engineering. Synthetic biology is a recent field of research that has introduced an engineering approach to genetic manipulation. It is defined as the application of science, technology and engineering to facilitate and accelerate the design, manufacture and/or modification of genetic materials in living organisms (EC, 2014). It allows for the design and construction of new biological parts, devices, and systems, and the re-design of existing, natural biological systems for useful purposes (Royal Academy of Engineering, 2009).

While traditional genetic engineering generally uses trial-and-error approaches to produce new biological designs, synthetic biology attempts to reshape living systems on the basis of a rational blueprint (de Lorenzo and Danchin, 2008). To achieve this, synthetic biology utilises engineering principles such as standardisation, modularisation and interoperability. For instance, synthetic biologists create and catalogue functional components called “biobricks” based on DNA sequences that may or may not be found in nature. Biobricks perform certain functions that can be combined to produce innovations in a wide range of sectors, including health, agriculture, industry and energy.

Synthetic biology promises radical innovations across a wide range of business sectors

As a technology platform, synthetic biology has the potential to offer significant socio-economic benefits and to create new businesses and make existing ones more efficient (Figure 2.10). It may be leveraged by several key market sectors, such as energy (e.g. relatively low-cost transport fuels), medicine (e.g. vaccine development), agriculture (e.g. engineered plants) and chemicals. The latter has a wide range of applications through biobased production of new materials, including environmentally friendly bioplastics and cosmetics (e.g. synthetically designed natural fragrances). Within the field of marine biotechnology, many applications are envisaged, but most have not yet even been thought of. A recent example is to modify diatoms to produce biofuels using gene editing (Daboussi et al., 2014). Synthetic biology may also help meet bioeconomy objectives, i.e. the reduction of greenhouse gas emissions and the achievement of food and energy security. As the global population continues to grow and threats to water and soil quality increase, synthetic biology offers far-reaching agricultural applications that promise to increase productivity and efficiency. Examples include not only crops that are resistant to drought and diseases and that increase yields, but also cereals that produce their own fertilisers.

Figure 2.10. **Applications of synthetic biology across sectors**



Source: OECD (2014c), *Emerging Policy Issues in Synthetic Biology*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264208421-en*, based on Collins (2012), "Win-win investments", *www.europarl.europa.eu/stoa/cms/home/events/workshops/synthetic_biology*.

Two emerging developments that could transform synthetic biology

First, gene editing uses the natural immune defences of bacteria to create "molecular scissors" that cut out and replace strands of DNA with great precision (Sample, 2015). This technique is helping scientists further understand the roles of genes in health and how several diseases could be treated by modifying tissues and organs. Patients' immune cells could be reprogrammed to make them attack cancer cells; immune cells could be made resistant to the HIV virus, for instance; and genetic disorders could be stopped from being passed on to offspring.

Second, do-it-yourself (DIY) biology or "biohacking" refers to the work of a growing community of individuals and small organisations that study and practice biology and life science outside of professional settings. The falling costs of equipment, instruments and computing coupled with the rise of open source development practices have fuelled this movement, "democratising" science and giving people access to their own biological data. Since 2003, the cost of gene sequencing has dropped by at least one million-fold (OECD, 2014c). Cost-effectiveness has improved for gene synthesis as well, though at a much slower pace (Carlson, 2014). DIY biology could represent a potential engine of innovation similar to the Silicon Valley, with a large number of individuals discovering and finding applications for biobricks. In the future, innovation in this field could become widespread, with users able to tinker and improve products and services from large firms, as has already occurred in manufacturing sectors (von Hippel, 2005).

The development of synthetic biology faces several obstacles, including biohazard concerns

The development of this technology poses a number of risks for biosafety and biosecurity. Biosafety covers the range of policies and practices designed to protect workers and the environment from unintentional misapplications or the accidental release of hazardous laboratory agents or materials. Biosecurity is usually associated with the control of critical biological materials and information so as to prevent unauthorised possession, misuse or intentional release (OECD, 2014c).

The risks posed by synthetic biology are difficult to assess given the unbounded amount of emergent properties of products and genetically engineered systems (SCHER, SCENIHR and SCCS, 2015). This difficulty is exacerbated by open source practices in synthetic biology. Compared to many other types of science, experimentation in the field faces greater uncertainty of risk, given the self-replicating and transmissible nature of organisms (Wolinsky, 2009). As for biosecurity, DIY biology could be directed towards illegal activities, some of which could threaten public safety (e.g. biological weapons). For gene editing, although much additional expertise would be needed to produce infectious agents, authorities need to ensure sufficient oversight and review.

Synthetic biology raises ethical issues

While gene therapy (i.e. altering the body's ordinary tissues) is an accepted medical technique, this is not the case for modifications that would alter a person's reproduction cells. This type of genome editing (referred to as germline editing) could, in principle, alter the nature of the human species. Representatives from the National Academies of Science of the United States, the United Kingdom and the People's Republic of China gathered recently to agree on a moratorium on permanent alterations to the human genome (Wade, 2015). The group called on scientists around the world to abstain from germline editing research until the risks are better assessed and a broad societal consensus about the appropriateness of these techniques is reached.

There are also substantial technical and legal uncertainties

The future of synthetic biology depends on reliable, accurate and inexpensive DNA synthesis. While the cost of DNA sequencing is now negligible, the cost of writing genetic code needs to tumble by similar orders of magnitude. The technical difficulties involved in reaching parity with sequencing are considerable and create high financial risks for the typically small, high-technology companies working to develop synthetic biology. Major hurdles must also be overcome in bioinformatics and software infrastructure, though the relevant software will likely be available to a mass audience long before DNA synthesis. This can be good for synthetic biology, but it increases the need for biosecurity vigilance, as sequence designs could be easily sent to other countries for manufacture without appropriate controls. At the same time, the large number of regulations that need to be followed to legally produce transgenic organisms (particularly to prevent harm in humans and their escape from controlled environments) is likely to restrict applications (OECD, 2014c; Travis, 2015).

Blockchain

Blockchain is a database that allows the transfer of value within computer networks. This technology is expected to disrupt several markets by ensuring trustworthy transactions without the necessity of a third party. The proliferation of this technology is, however, threatened by technical issues that remain to be resolved.

What is blockchain technology?

Internet applications such as web browsers and email programs use protocols that define how software on connected devices can communicate with each other. Whereas the purpose of most traditional protocols is information exchange, blockchain enables protocols for value exchange. This new technology facilitates a shared understanding of value attached to specific data and thus allows transactions to be carried out. In itself, blockchain is a distributed database that acts as an open, shared and trusted public ledger that nobody can tamper with and that everyone can inspect. Protocols built on blockchain (e.g. bitcoin) specify how participants in a network can maintain and update the ledger using cryptography and through a general consensus. The combination of transparency, strict rules and constant oversight that can potentially characterise a blockchain-based network provides sufficient conditions for its users to trust the transactions conducted on it, without the necessity of a central institution. As such, the technology offers the potential for lower transaction costs by removing the necessity of trustworthy intermediaries to conduct sufficiently secure value transfers. It could disrupt markets and public institutions whose business model or *raison-d'être* lies in the provision of trust behind transactions.

Blockchain technology could disrupt many sectors

Blockchain technology was originally conceived for bitcoins, a digital currency that is not regulated nor backed by any central bank. Instead, the technology aims to be trustworthy by itself (i.e. it makes a trusted third party unnecessary) by preventing double-spending and constantly keeping track of currency ownership and transactions (OECD, 2015f). The supply of bitcoins is limited and regulated by a mathematical algorithm that defines the rate at which currency will be created. The procedure for updating the ledger rewards users who devote computing resources to encrypt transactions (called miners) with new bitcoins that enter the network's monetary base. Once a set of transactions has been encrypted, the entire network (including non-miners) verifies its validity by a 51% majority consensus. As in regular currency trade, bitcoin exchange rates with traditional currencies are determined through a double-auction system. This set-up incentivises scrutiny and thus secures the network: if bitcoin is increasingly adopted and its value increases relative to other currencies, there will be additional incentive to devote computational power for rewards.

While the experience of bitcoin is already forcing a rethink of currencies, the expected impacts of the underlying blockchain technology go beyond digital money. This technology could destabilise incumbents in asset management businesses, but also government authorities, and could transform the way many services are provided. Potential applications can be clustered into three categories:

Financial transactions

The financial applications of blockchain technology go beyond bitcoin and digital money. For example, the technology provides opportunities for cross-border remittance payments, which often represent high transaction costs in proportion to the remittance amount. Equity crowdfunding provides another opportunity, as it often involves large amounts of administrative efforts relative to the size of individual investments (Collins and Baeck, 2015). A blockchain may be "unpermissioned" as in bitcoin, i.e. open to everyone to contribute data and collectively own the ledger; it may also be "permissioned" so that only one or many users in the network can add records and verify the contents of the ledger (UK GOS, 2016). Permissioned ledgers offer a wide range of applications in the private sector. Clearing houses (e.g. the New York Stock Exchange and Nasdaq), banks (e.g. Goldman Sachs), credit card companies (e.g. Master Card) and insurance companies (e.g. New York Life Insurance Company) have already invested around USD 1 billion in start-ups using blockchain technologies (Pagliery, 2015; de Filippi, 2015). By replacing the banking infrastructure necessary for cross-border payments, securities trading and regulatory compliance, distributed ledger technology could cut global banking services by USD 20 billion in annual costs (Santander Innoventures, Wyman and Anthemis, 2015).

Record and verification systems

Blockchain technology can also be used for creating and maintaining trustworthy registries. The distributed ledger provides a robust, transparent and easily accessible historical record. It can be used for storing any kind of data, including asset ownership. Possible uses include the registration and proof of ownership of land titles and pensions, and the verification of the authenticity and origin of works of art, luxury goods (e.g. diamonds) and expensive drugs (*The Economist*, 2015; Thomson, 2015). Within this category of applications, blockchains are permissioned to rely on a central institution for updating and storing the ledger. Already Honduras has plans to build a land title registration system using blockchain (Chavez-Dreyfuss, 2015), which could radically change the way notary offices manage real estate. The shared blockchain ledger could also bring significant improvements to resource allocation in the public sector by consolidating accounting, increasing transparency and facilitating auditing to prevent corruption and boost efficiencies. This technology could further ensure the integrity of other government records and services, including tax collection, the delivery of benefits and the issuance of passports. A shared ledger within the different levels of government could ensure that transactions are consistent and error-free. Also, given that key public and private institutions in emerging countries are less developed and trusted for financial markets to flourish and for public services to be efficient, blockchain could offer a "fast track" for the development of financial services and public registry keeping.

Smart contracts

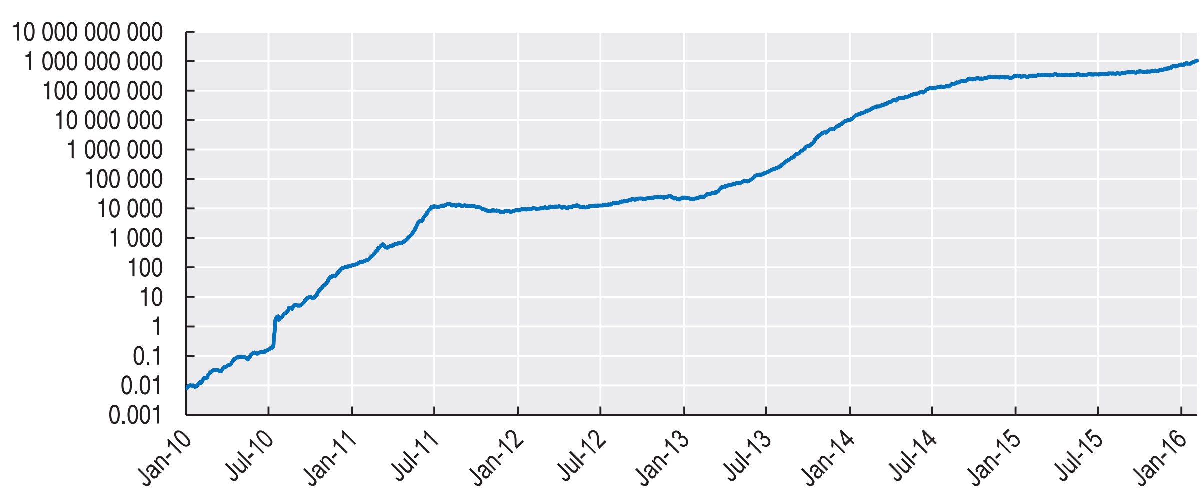
Blockchain technology offers the opportunity to append additional data to value transactions. These data could specify that certain rules must be met before the transfer takes place. In this way, a transaction works as an invoice that would be cleared automatically upon the fulfilment of certain conditions. Such “smart contracts” based on blockchain are also referred to as programmable money (Bheemaiah, 2015). The conditions specified in the transfer as programming code could be used to express the provision of services such as the cloud storage of data (e.g. Dropbox), marketplaces (e.g. eBay), and platforms for the sharing economy, such as Uber and AirBnB (de Filippi, 2015). Microsoft is setting up a joint venture in this field to power its services for renting computer servers (Pagliery, 2015). Smart contracts could also power media delivery platforms, preventing piracy and ensuring that musicians and filmmakers obtain royalties for the distribution of digital content (Nash, 2016).

Several technological uncertainties remain

A critical uncertainty for “institution-less” (unpermissioned) applications is that their security depends greatly on the number of users. This means applications have to scale up sufficiently before becoming trustworthy. Moreover, the standard mathematical algorithm that ensures a tamper-resistant ledger (currently employed by Bitcoin) becomes more computationally intensive as the network becomes more scrutinised. Figure 2.11 shows how the total computing power of the Bitcoin network has increased at exponential rates since 2010. As more miners enter the network, the mathematical algorithm makes the encrypting process more difficult in order to maintain the rate at which bitcoins are created. While this setup incentivises scrutiny, it also translates into vast amounts of electricity required to process and verify transactions conducted within the network, which is now estimated to be comparable to the electricity usage of Ireland (UK GOS, 2016). Less computationally-intensive alternatives for reaching a secure consensus are currently being developed and tested. An additional uncertainty specific to smart contracts lies in the extent to which complex services can be sufficiently programmed into rules. In order for such networks to completely run by themselves (i.e. without a firm backing the service), instructions embedded in transfers should provide an exhaustive definition of the service. While this is likely possible for many routine services (e.g. computing), it is questionable

Figure 2.11. **Total computing power of the Bitcoin network**

Hashes calculated per second, logarithmic scale



Note: Amount expressed in hashes. A hash is a computation that expresses data in a smaller yet representative form. As more miners enter the Bitcoin network, the algorithm makes the encryption problem harder (i.e. requiring more hashes to be calculated) to keep additions to the blockchain (and the minting of Bitcoin rewards) fixed at around 10 minutes.

Source: Based on Blockchain Luxembourg S.a.r.l. (2016), Bitcoin Hash Rate, *https://blockchain.info/charts/hash-rate* (accessed 4 February 2016).

StatLink http://dx.doi.org/10.1787/888933433340

whether this could be achieved with more complicated applications, such as marketplaces and the sharing economy of Uber and AirBnB. These often require dispute resolution mechanisms that are difficult to codify and delimit.

The resolution of technological uncertainties could enable unlawful activities

The pseudo-anonymity of transactions raises several concerns around the technology's potential exploitation for illegal activities. While all transfers conducted through blockchain are permanently recorded and immutable, it contains information only relative to agents' Internet identity, which may not necessarily lead to their real identity. Some users of virtual currencies have already been involved in improper use and illegal activities, including money laundering and the transfer of value for illegal goods. More effective methods of identification could lead to more effective law enforcement in digital currencies compared with the use of cash (OECD, 2015f). However, smart contract applications could also allow the creation and operation of illegal markets that operate without a responsible firm or institution subject to regulatory compliance.

Concluding remarks

While the key and emerging technologies above are wide-ranging in their origins and potential applications, they appear to exhibit some common features that have direct implications for policy:

- The key and emerging technologies covered in this chapter are expected to have wide impacts across several fields of application, many of which cannot be anticipated. These impacts will be shaped by a range of non-technological factors, some of which are highlighted in Chapter 1's megatrends, and include ageing societies, climate change, economic and political developments, and changes in social preferences. Technology co-evolves with society, which makes much technological change – particularly of the more disruptive kind – unpredictable. This uncertainty calls for an open and flexible policy perspective that supports, as far as resources allow, a diversity of technology developments and applications. Diversity not only spreads risks and opportunities but also builds absorptive capacities to exploit research and technologies developed elsewhere. At the same time, regular rounds of anticipatory intelligence gathering (e.g. on "weak signals"), followed by rounds of "sense-making" among policy makers and other innovation system actors, can improve governments' capacity to adjust policy as events unfold and can help foster wider system agility.
- Key technologies are often dependent on other "enabling" technologies for their future development and exploitation. Perhaps the most pervasive enabling technology today is information and communications technology (ICT). Four of the key and emerging technologies covered in this chapter – the Internet of Things, big data analytics, artificial intelligence and blockchain – are or will likely become in the near-future pervasive enabling ICTs. Furthermore, developments in the other six key technologies covered here are to a large extent underpinned by advances in ICTs, together with advances in other technologies. Technology convergence and combination are therefore significant features of technology development and can be aided by cross-disciplinary institutional spaces – for example, for carrying out R&D work and for providing skills training. While many OECD countries increasingly support such spaces, more needs to be done to overcome long-established mono-disciplinary institutional and organisational arrangements for funding and performing R&D that inhibit cross-disciplinary initiatives.

- Public sector research has played pivotal roles in developing key and emerging technologies. Public sector research provides new knowledge of phenomena underpinning emerging technologies and often contributes to prototype and demonstrator development. Just as importantly, public sector research nurtures many of the skills needed for further developing and exploiting emerging technologies. Sufficient investment in public research is therefore important to realise the benefits of these technologies for future growth and well-being.
- Enabled by advances in ICTs and sharp falls in the costs of laboratory equipment and agents, communities and citizens play increasingly prominent roles in developing and exploiting some key and emerging technologies, such as blockchain, synthetic biology and additive manufacturing. The opening up of research, innovation and entrepreneurship in this way is broadly welcome, and some OECD countries are putting in place policy frameworks to support it. At the same time, citizen involvement raises various regulatory issues, for instance, around health and safety protection (this is particularly acute in Synthetic biology where a strong DIY science tradition is fast developing) and intellectual property rights (this features prominently in discussions of additive manufacturing). In fact, governments need to regularly adapt existing or draft new regulations to govern the development and applications of many emerging technologies, irrespective of citizen involvement. Given the fast pace of technological change, this is clearly a challenge, but many governments could improve their anticipatory intelligence on future regulatory issues, which would leave them better prepared to act more quickly and decisively.
- Emerging technologies carry several risks and uncertainties, and many raise important ethical issues, too. This calls for an inclusive, anticipatory governance of technological change that includes assessment of benefits and costs and an active shaping of future development and exploitation pathways. Such governance arrangements remain under-developed in most OECD countries, though this may change in the next few years with the growing policy interest in "responsible research and innovation" (RRI). Governance arrangements that incorporate RRI elements will need to consider a variety of perspectives in assessing future emerging technology pathways. More broad-based assessments would likely benefit from greater reference to the social sciences and humanities than is common in existing assessment arrangements.
- Research and innovation efforts around key and emerging technologies are increasingly distributed across the world and typically benefit from international co-operation. This means that governing emerging technologies and their use, for example, through regulation and agreements, is increasingly a matter for international co-ordination. Organisations like the OECD can provide useful fora for countries to co-operate and co-ordinate in this regard.
- At the same time, as the mapping of foresight exercises shows (see Annex 2.A2), technological development is intensely competitive, with countries investing large amounts in research and innovation in similar technology fields. Competition focuses not only on technical solutions, but also on business models, platforms and standards, particularly at the firm level, where "first-mover advantage" can make the difference between success and failure. Governments wanting to support new industries around emerging technologies will need to look beyond the R&D function to appreciate the wider firm-level and industry dynamics that will likely contribute to their success.

Many of these issues are picked up in Chapter 3 where they are further elaborated.

Note

1. Blockchain technology was not among the emerging technologies identified by the mapped foresight exercises. It has emerged strongly in 2015 as a potentially disruptive general purpose technology and is included here on that basis.

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ANNEX 2.A1

Foresight exercises mapped in this Chapter

Canada – Metascan 3: Emerging technologies: A foresight study exploring how emerging technologies will shape the economy and society and the challenges and opportunities they will create (2013)

The Canadian foresight exercise was carried out by Policy Horizons Canada on behalf of the Government of Canada. The report was published in 2013 and builds upon previous Metascan exercises from 2011 (Exploring four global forces shaping our future) and 2012 (Building resilience in the transition to a digital economy and a networked society). The exercise was a collaborative effort of experts from government, the private sector, civil society and academia. Its aim was to anticipate emerging policy challenges and opportunities, explore new ideas and experiment with methods and technologies to support and inform policy makers. It examined how various emerging technologies divided into four sectors (digital technologies, biotechnologies, nanotechnologies and neuroscience technologies) could impact and drive disruptive social and economic change in Canada within a 10 to 15 years' time horizon. Its main findings raised several socio-economic challenges for Canada, including: emerging technologies will increase productivity but with fewer workers; all sectors will be under pressure to adopt new technologies; competitive advantages will shift causing new inequalities; and how to build a national "innovation culture".

European Union – Preparing the Commission for future opportunities: Foresight network fiches 2030 (2014)

This exercise was carried out by the European Commission's (EC) network of foresight experts, initiated in 2013 by the Chief Scientific Adviser and the Director General of the Bureau of European Policy Advisers. Its main objective was to enable reflection on future science and technology topics that would help the EC's services and directorates to improve their policy planning processes. The exercise was developed with support from various internal and external experts and was based on the outcomes of six workshops covering topics such as future of society, resource access, production and consumption, communication, and health. It had a time horizon of 15 years. The exercise highlighted several upcoming challenges and opportunities, including the third industrial revolution, blurring boundaries between healthcare and human augmentation, and the coupling of energy and environmental policy.

Finland – 100 Opportunities for Finland and the World: Radical Technology Inquirer (RTI) for anticipation/ evaluation of technological breakthroughs (2014)

The exercise was commissioned by the Committee for the Future under the aegis of the Finnish Parliament. It discussed 100 emerging technologies in the context of 20 different value-producing networks, defined as clusters of demand and areas of change that have been created by global megatrends. Additionally, a four-level priority model based on 25 indicators was created to help score radical technologies with regard to their anticipated promises and potential to satisfy citizens' needs. The exercise used systematic study of open data sources on the Internet, evaluations of experts and open crowdsourcing of opinions. No overall time horizon was set, though most of the mapped technologies are projected to 2020 or 2030.

Germany – Science and Technology Perspectives 2030 (Forschungs- und Technologieperspektiven: Ergebnisband 2 zur Suchphase von BMBF-Foresight Zyklus II) (2015)

This exercise – which is the latest in a long line of national foresight exercises conducted in Germany – was carried out by VDI (Verband Deutscher Ingenieure) Technologiezentrum GmbH and FhG-ISI (Fraunhofer-Institut für System- und Innovationsforschung) under the aegis of the Federal Ministry of Education and Research (BMBF). It took a three-step approach: first, it identified societal trends and challenges to 2030 (Ergebnisband 1). This was followed by identifying research and technology perspectives with high application potential (Ergebnisband 2). Finally, new challenges at the interface of society and technology were identified (Ergebnisband 3). The mapping in this chapter is based on the results of the second step (Ergebnisband 2). The overall intention behind the exercise was to provide guidelines for future societal and technological challenges and to facilitate resilient policy development. The results were meant to serve as a basis for discussion within the BMBF as well as for the private sector with a time horizon to 2030.

United Kingdom – Technology and Innovation Futures: UK Growth Opportunities for the 2020s – 2012 Refresh (2012)

The exercise was carried out by the Government Office for Science to examine the disruptive economic potential of future technological developments and new emerging trends on a time horizon of 20 years. It was a "refresh" of an earlier exercise conducted in 2010 and identified 53 technologies likely to be important for expanding the United Kingdom's future competitive advantages. Several interviews and workshops were undertaken with representatives from industry, research, international institutions and social enterprises and a survey was carried out to elicit views on emerging technologies. Potential new opportunities were grouped as follows: biotechnological and pharmaceutical sector; materials and nanotechnology; digital and networks; and energy and low-carbon technologies. The exercise supported the UK Government's prioritisation of particular emerging technologies.

Russian Federation – Russia 2030: Science and Technology Foresight (2014)

The exercise was carried out by the Ministry of Education and Science in co-operation with the National Research University Higher School of Economics. Its objective was to identify Russia's most promising areas of science and technology capable of assuming a pivotal role in solving social and economic issues while realising the country's advantages. It gathered expertise from various Russian organisations, including universities, companies, technological platforms, and leading research centres. The exercise examined global challenges as well as opportunities and threats linked to them on a 15-year time horizon. Future innovation markets, emerging technologies, products and research areas were divided into seven priority fields: ICT; biotechnology; medicine and health care; new materials and nanotechnologies; environmental management; transport and space systems; energy efficiency and energy saving.

ANNEX 2.A2

Foresight studies mapping by main technology area

Table A2.1. **Foresight Studies mapping – biotechnologies**

CAN	DEU	EU	FIN	GBR	RUS
	Epigenetics, epigenomics, proteomics		Artificial cell	Genomics, proteomics and epigenetics	Comparative genomics and proteomics techniques, creation of human genome databases
Sequencing patient DNA and personalised medicine	Routine and complete DNA sequencing, RNA technologies, metabolomics	DNA fingerprinting and personal genomes	Routine and complete DNA sequencing	Nucleic acids	Full-genome DNA sequencing, analysis of human proteome, transcriptional and epigenetic profiles
Synthetic biology	Synthetic biology, cell-free bioproduction systems, metabolic and forward engineering	Synthetic biology	Genetically modified organisms, artificial memory devices (DNA memory)	Synthetic biology	Synthetic biology, metabolic engineering, bioengineering, biosynthetic processes to produce biologically active compounds
	Biomolecular computers				
Bioinformatics					
	Production of synthetic membrane proteins, companion diagnostics	Personalised medicine		Stratified and tailored medicine	Molecular diagnostics, promising drug candidates
			(Stem) cell cultivation	Stem cells	Biomedical cellular technologies, human cells cultivation
	Slowing ageing processes		Longer life time and slower ageing processes		
Tissue engineering		Regenerative medicine and tissue engineering, prosthetics and body implants	Regenerative medicine and tissue engineering	Regenerative medicine and tissue engineering	Human tissue and organ regeneration techniques, tissue equivalents and artificial human organs, immunological technology
	Lab-on-a-chip technologies		Biochips and biosensors	Lab-on-a-chip	On-chip technologies
	Combination of molecular diagnosis and imaging applications		Small portable magnetic resonance imaging scanner	Medical and bioimaging	Metamaterials and software to process and transfer high-resolution images
		Human enhancement		Performance-enhancing pharmaceuticals	
Health monitoring beyond the clinical setting	E-Health, mobile diagnostic applications, "quantified self"		Continuously monitored personal health, self-care based on personalised healthcare	E-Health	

Table A2.1. **Foresight studies mapping – biotechnologies** *(cont.)*

CAN	DEU	EU	FIN	GBR	RUS
Neuroscience technologies, neurostimulation				Modelling human behaviour	Interfaces for neuronal photostimulation
	Bionics, organic electronics, high-tech prostheses, computer-aided surgery, connection between artificial body parts and nerve cells		Biobots, robotic legs, exoskeleton, robotic surgery, sensitive robot-fingers and hands		
Brain-computer interface	Brain-computer interface, brain mapping	Brain-inspired technologies	Brain implants	Brain-computer interface	
					Artificial life systems, including artificial cell elements and chimeric cells
				Sensor technologies	High-sensitivity sensors for physical and physiological parameters
	Nutrigenomics, functional food, food fortifying, nutraceuticals and medical foods	Innovative food	Local or functional food, in-vitro meat, meat-like plant proteins		Functional therapeutic food products, biologically active additives, food protein technologies
Agricultural biofactories, genetically modified crops		Precision agriculture		Agricultural technologies	Biofactories, bioresource centres and biocollections, forestry biotechnologies
Sustainable resource management and harvesting (forest and fish resources)		Fisheries/ aquaculture			Aquabioculture
Bioproduction of raw materials	New biocatalysts		Drugs based on genetically modified organisms, drugs that prevent dementia	Industrial biotechnology	Industrial enzymes and biocatalysts

Table A2.2. **Foresight studies mapping – Advanced materials**

CAN	DEU	EU	FIN	GBR	RUS
Nanodevices and nanosensors, nanotechnology for energy	Nanotechnologies	Nanoelectronics	Nanorobots (nanobots) in health promotion, nanoradio	Nanotechnologies	
Nanomaterials		Nanomaterials	Nanomaterials	Nanomaterials	Nanostructured materials with form memory effects and "self-healing" materials, biocompatible nanomaterials
	Graphene could replace Indium	Graphene and related new technologies	Carbon nanotube yarn or thread	Carbon nanotubes and graphene	Electronic elements based on graphene, fullerene, carbon nanotubes, quantum dots
				Intelligent polymers (plastic electronics)	New-generation polymers (e.g. optoelectronics), monomers for biodegradable polymers, superconducting materials
			Functional materials	Smart (multifunctional) and biometric materials	Hybrid materials, biomimetic materials and medical materials

Table A2.2. **Foresight studies mapping – Advanced materials** *(cont.)*

CAN	DEU	EU	FIN	GBR	RUS
	Heat resistant ceramic materials to increase energy efficiency				Nanostructured composite and ceramic materials and coatings with special thermal properties
	Lightweight construction, fibre-composite materials		New building materials	Building and construction materials	Construction, functional materials and coatings, new types of light and high-strength materials
Construction of 3D-printed homes	Rapid prototyping and rapid manufacturing (3D printing), bioprinting	3D printing	3D printing and bioprinting	3D printing and personal fabrication	Additive technologies
	Flexible touchscreens		Augmented reality, haptic screens		

Table A2.3. **Foresight studies mapping – Digital technologies**

CAN	DEU	EU	FIN	GBR	RUS
	Quantum information technology, multi-core processors (CPUs), in-memory databases	High-performance computing	Processors that take quantum phenomena into account, new data storage technologies	Supercomputing	Predictive supercomputer-modelling systems
	Cloud computing, grid computing	Cloud computing	Cloud computing, grid computing	Cloud computing	Cloud solutions, grid algorithms and software for distributed solutions
	E-learning	Future education and learning	Schools in the cloud		
				Next generation networks	Emergence of single management environments, high-speed data transfer
The Internet of “moving” Things	Intelligent networks, ubiquitous sensor systems, Internet of Things (industry 4.0)	Internet of Things	Internet for robots	Intelligent sensor networks and ubiquitous computing	Internet of Things, machine-to-machine interaction technologies (M2M)
	Clothes with embedded electronic devices and sensors (“wearables”)		Spray-on textiles, robo-tailoring	Intelligent clothing, smart interactive textiles	
			Microfinance and crowd funding, time banks, electronic money		
	“Games for Health”		Gamification		
	Big data	Big data	Open data and big data		Data processing and analysis
		Models and data in decision making		Searching and decision making	
	Visual analytics, predictive analytics, simulation of material properties		Simulation and mapping of brain, predictive analytics based on self-organising data	Simulation and modelling	Predictive modelling, computer modelling of materials and processes
	Photonics, lithography systems, optical measuring systems, quantum optics, photonic micro- and nanomaterials	Photonics and light technologies	Cheap Lidar, high-performance lasers	Photonics	Nanostructured materials with special optical properties, lasers and organic light-emitting diodes based on nanoscale heterostructures

Table A2.3. **Foresight studies mapping – Digital technologies** *(cont.)*

CAN	DEU	EU	FIN	GBR	RUS
The end of privacy	New cryptography and biometric methods, privacy-enhancing technologies, digital forensics	Cyber-security	Capturing and content searching of personal life	Secure communication, surveillance	Information security
			Pattern recognition and pattern search services	Biometrics	
Artificial Intelligence			Artificial Intelligence		Algorithms and software for machine learning, digital devices with replication and/ or self-healing properties
Robotics for traditional and for undersea resource acquisition or on the farm	Service engineering			Service and swarm robotics	Robot assistants freely travelling and interacting with people, nano- and microrobotics systems

Table A2.4. **Foresight studies mapping – Energy and environment**

CAN	DEU	EU	FIN	GBR	RUS
	Smart grids, overlay-grids, super-grids	Future smart cities		Smart grids	Smart networks, long-distance transfer technologies for electric energy and fuel, new-generation power electronics
Decentralised energy systems	Microenergy harvesting			Microgeneration	New-generation microprocessor devices for use in power engineering
	Electrochemical storage and conversion technologies		Rapidly charging light batteries, supercapacitors	Advanced batteries	Electrical and thermal energy storage
			Wireless power transfer		
Electric and hybrid vehicles	Electric mobility, power-to-liquid technologies for the mobility sector	Post-carbon society, carbon dioxide reuse	Self-driving car	Intelligent low-carbon road vehicles	
Autonomous and semi-autonomous vehicles	Connected mobility, car-to-car-communication, car-to-X-communication, smart mobility	Advanced autonomous systems, future mobility	Automation of passenger vehicle traffic, vactrains, magnetic or superconductor-based levitation		Smart transport and new control systems, systems to increase the environmental neutrality and energy-efficiency of vehicles
	Unconventional flying concepts	Drones	Minisatellites, quadcopters, drones, on-demand personal aviation		Micro-, nano-, and pico-satellites
	Fuel cells			Fuel cells	Fuel cells
		"Hydrogen Society"	Inexpensive storage of hydrogen in nanostructures	Hydrogen	Hydrogen production and safe storage, hydrogen for power generation
		Recycling technologies		Recycling technologies	Recycling technologies
	Energy efficiency measures				Low energy consumption buildings, novel light sources and smart lighting systems
		Carbon dioxide capture and storage		Carbon capture and storage, metal organic frameworks	

Table A2.4. **Foresight studies mapping – Energy and environment** *(cont.)*

CAN	DEU	EU	FIN	GBR	RUS
			Small nuclear reactors	Nuclear fission	Closed nuclear fuel cycle, low- and medium-power nuclear reactors
				Nuclear fusion	
Bioenergy	Biofuels, biorefineries, biocatalysts, biomass, biogas, bioethanol and biohydrogen		The production of biofuels using enzymes, bacteria or algae	Bioenergy and "negative emissions"	Technologies for energy biomass production and biomass processing
High-efficiency solar cells	Photovoltaics, solar thermal power generation		Efficient and light solar panels, artificial leaf and synthetic fuel, solar heat	Solar energy technologies	Solar energy technologies
				Marine and tidal power	New hydroelectricity technologies
Wind energy technologies	Wind energy technologies		Flying wind power and other new ways to produce wind energy	Wind energy technologies	Wind energy technologies
			Piezoelectric energy sources, harvesting of kinetic energy		
			Long-term storage of heat		High-performance natural gas heat and power units
					Deep processing of oil and gas condensate, associated petroleum gas
					Monitoring the state of environment, long-term weather forecasts, remote monitoring systems

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Chapter 3

The future of science systems

This chapter focuses on public research systems and the potential shifts that they are likely to experience over the next 10-15 years. While public research systems have their own specific trend dynamics – for example, with regard to research funding, where and how research is performed and reported, and researcher career paths – they are also affected by wider changes in economies and societies. This chapter explores what these changes might mean for public sector research, raising eight main questions about its future: What resources will be dedicated to public research? Who will fund public research? What public research will be performed and for what purpose? Who will perform public research? How will public research be performed? What will public research careers look like? What outputs and impacts will be expected of public research? And what will public research policy and governance look like?

Introduction

Public research plays a key role in innovation systems, providing new knowledge and know-how that can enhance the development of new technologies for societal or economic purposes and that businesses are not always well equipped or incentivised to invest in (see the policy profile "Public research missions and orientation"). Many of today's innovations would not have been possible without the scientific and technological developments enabled by public research. Well-known contemporary examples include recombinant DNA technologies, the GPS global positioning system, MP3 technology for data storage, and voice recognition technology such as Apple's Siri.

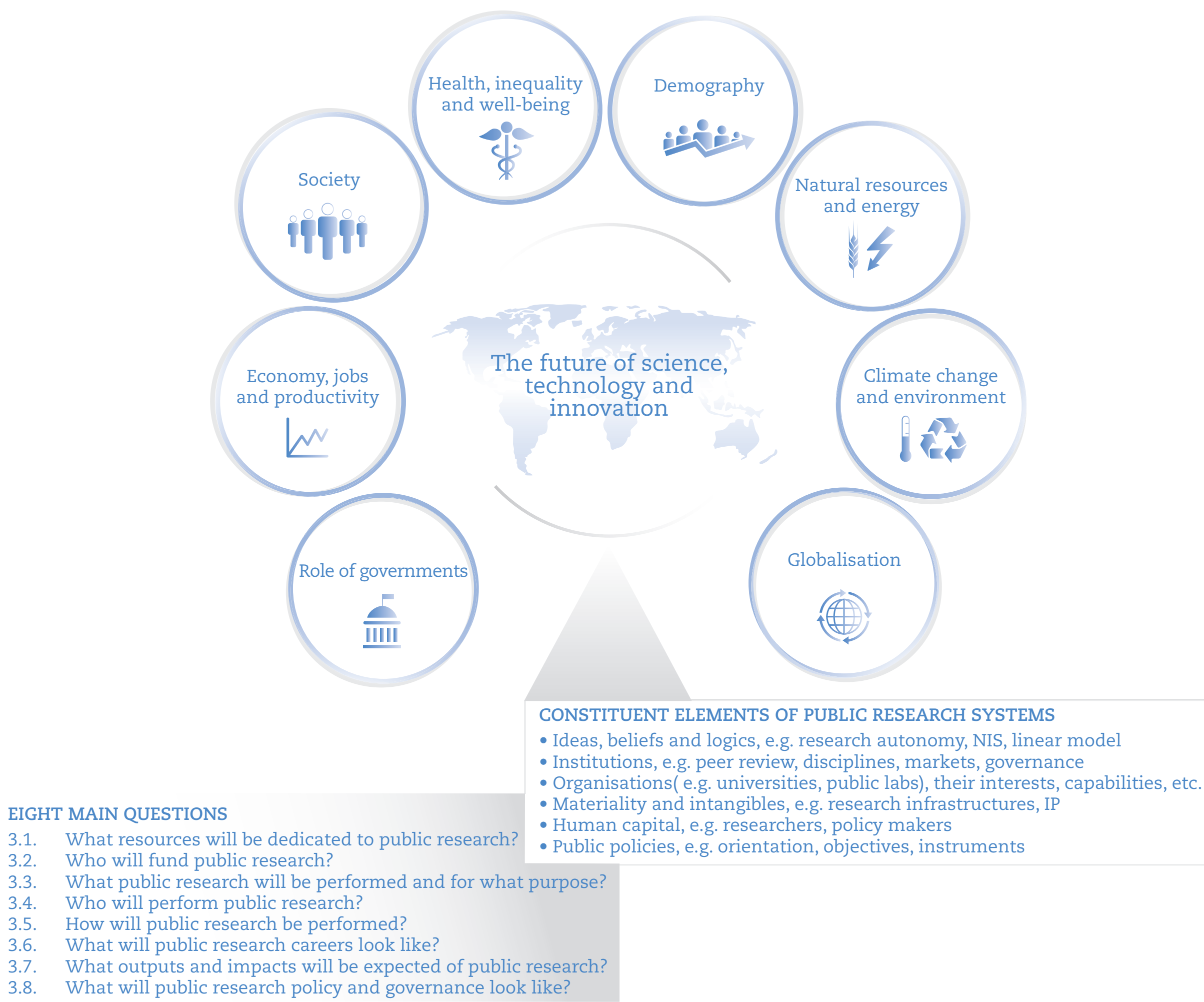
Universities and public research institutes (PRIs) often undertake longer-term and higher-risk research. Although they account for less than 30% of total OECD research and development (R&D) expenditure, universities and PRIs perform more than three-quarters of total basic research. They also undertake a considerable amount of applied research and experimental development that has more immediate potential for translation into tangible societal benefits. As the main funders and shapers of public research, governments have the potential to influence global and national science systems, well beyond the administrative and institutional borders of the public sector.

Public research systems are shaped by many of the megatrends and technology trends discussed in the previous chapters. For example, environmental and health challenges will substantially shape future research agendas, while technological change, particularly growing digitalisation, will affect the way research is performed. At the same time, public research systems have their own specific trend dynamics, for example, with regard to research funding, where and how research is performed and reported, and researcher career paths. While these research-specific trends are clearly influenced by wider megatrends and technology trends, their dynamics are also shaped by long-standing institutional and organisational arrangements that characterise public research systems. They are also shaped by historically accumulated resources, including tangible and intangible assets and human capital. Taken together, these arrangements and accumulated resources provide a lens through which public research trend dynamics can be viewed.

Some of the issues covered in the chapter are still emerging, but most are long-established trends that may change quantitatively and/or qualitatively over the next 10-15 years. These include the ongoing expansion of public research across the world; the broadening variety of public and private funders of public research; and growing digitalisation and internationalisation of research, which are set to make science more open and raise expectations about the contributions of public research to economies and societies. All these issues are highly interconnected: sometimes trends are mutually reinforcing, but often they are in tension, leading to conflict and controversy and opening up the possibility for trend breaks and disruptions. This creates uncertainty about the future of many aspects of public research systems.

This chapter provides a high-level overview of the main trends and issues that are likely to shape public research systems over the next 10-15 years. It builds on some basic trend analysis carried out in the *STI Outlook 2014* (OECD, 2014a), and extrapolates this further into the future, drawing in part on the megatrends set out in Chapter 1 and the technology trends presented in Chapter 2. It is based on desk research, a series of internal and external expert workshops as well as interviews with international experts and academics on the future of science systems. The chapter is structured around eight main questions concerning public research resources and funders, research performance and impacts, research careers, and research policy and governance, as shown in Figure 3.1.

Figure 3.1. **Outline and main issues of Chapter 3**

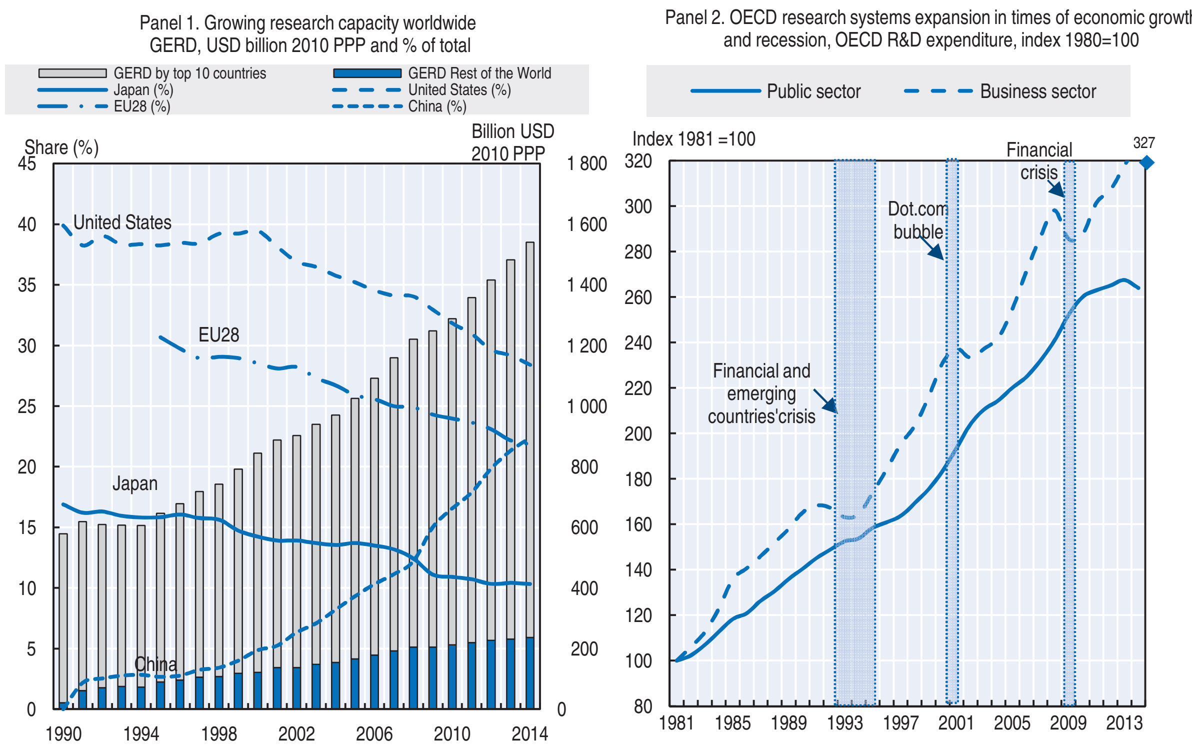


3.1. What resources will be dedicated to public research?

Global R&D capacity has doubled in the last 15 years[1] (Figure 3.2, Panel 1), a remarkable expansion driven by two important factors. First, business expenditure accounts for a growing share of global R&D as firms' expenditure on R&D has increased faster than public R&D expenditure during times of economic growth (Figure 3.2, Panel 2). Although firms will continue to rely on intangible investment and innovation to compete in global markets, the expansion of business R&D expenditure may slow or even halt. Weak recent economic performance, coupled with investment strategies that favour short-term shareholder value, may diminish firms' ability and willingness to undertake risky projects and to invest in research activities (see Chapter 4).There has actually been a slowdown in business investment in intangible assets in many OECD countries that could, in the longer run, disrupt knowledge accumulation and jeopardise the future capacity of firms to innovate.

Figure 3.2. **Business and public investment have expanded global research capacity**

Long-term shifts in gross domestic R&D expenditure (GERD)



Sources: Based on OECD (2016a), *Main Science and Technology Indicators (MSTI) Database, www.oecd.org/sti/msti*; Eurostat (2016), *R&D Indicators Databases*, *http://ec.europa.eu/eurostat/web/science-technology-innovation/data/main-tables*; UIS (2016), S&T Indicators, *www.uis.unesco.org/Pages/default.aspx*. Data extracted from IPP.Stat (2016) on 22 July 2016, *www.innovationpolicyplatform.org/content/statistics-ipp*.

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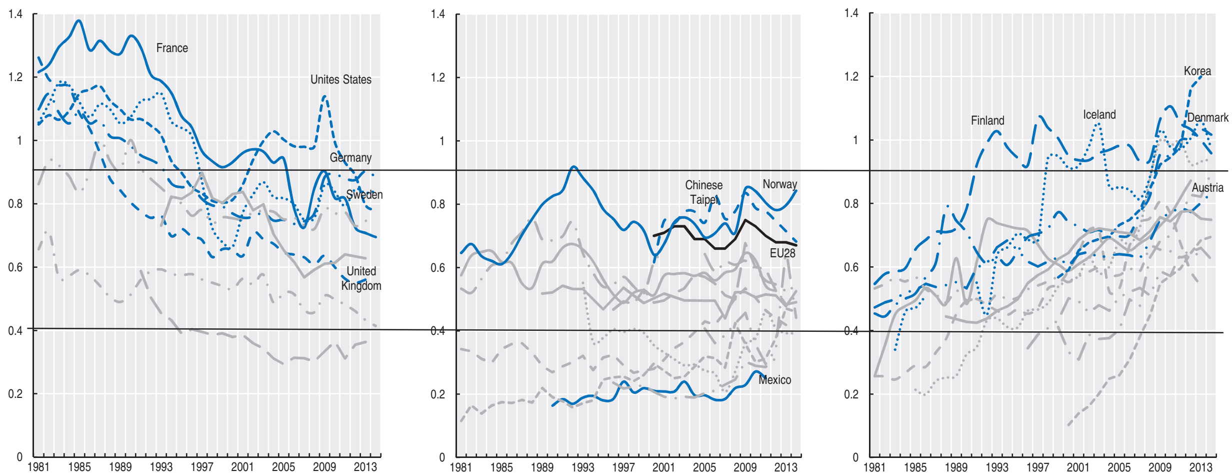
Second, several emerging economies, such as the People's Republic of China, have increased their R&D spending in past decades. OECD countries account for just a small portion of the increase in R&D capacity worldwide and their share of global gross expenditure on R&D (GERD) is in decline (Figure 3.2, Panel 1), a trend that is likely to continue given the growing weight of emerging economies in the world economy. At the same time, several emerging economies are showing signs of economic slowdown, which may reduce their capacity to increase R&D spending at the rates seen in recent years.

The challenges of ageing populations and slower economic growth will place considerable pressure on public spending in many OECD countries over the next 10-15 years: the competition for resources from other sectors, such as health and pensions, could even see declines in public investment in R&D. Indeed, the most recent data show the share of public R&D budgets in GDP declining in many OECD countries as governments pursue post-crisis austerity policies (Figure 3.3). On the other hand, R&D investment could be framed as a tool to keep increases in other public spending in check, e.g. by enabling more rapid innovation in areas like healthy ageing, which would have cost-savings.

Figure 3.3. **Public R&D budgets are likely to plateau around current ratios**

Government budget appropriations and outlays for R&D, as a % of GDP



Note: Panel 1 (decreasing budgets) includes Australia, France, Germany, Israel, the Netherlands, Poland, Sweden, the United Kingdom and the United States; Panel 2 (stable or slowly increasing budgets) includes Argentina, Canada, Greece, Hungary, Ireland, Italy, Mexico, Norway, New Zealand, the Slovak Republic, Slovenia, Chinese Taipei and the EU28; Panel 3 (fast increasing budgets) includes Austria, Belgium, the Czech Republic, Denmark, Estonia, Finland, Iceland, Japan, Korea, Luxembourg, Portugal and Spain.

Source: Based on OECD (2016b), *OECD R&D Statistics (RDS) Database*, April 2016, *www.oecd.org/sti/rds*.

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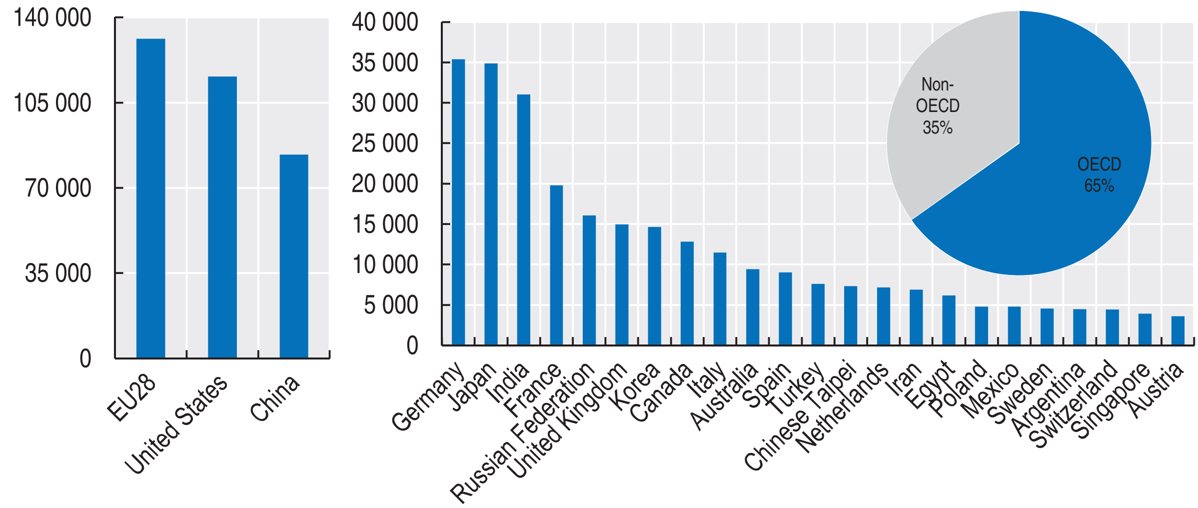
Long-term trends in government budget appropriations or outlays for research and development (GBAORD) show a convergence across countries in the intensity of public budgets allocated to R&D, measured as a percentage of GDP (Figure 3.3). Public R&D budgets oscillate between 0.40% and 0.90% of GDP which signals that public dedicated efforts to R&D may have reached their maximal intensity. The extremes include, at the bottom end, some lower-income Central European and Latin American countries, and at the top end, Korea, some Nordic countries (Denmark, Iceland and Finland) and Germany. Future increases in public R&D budgets might therefore be mainly driven by GDP growth, a growth that is expected to slow at a global level (see Chapter 1).

This points to the possibility of a more prominent role for emerging economies if they continue to enjoy high rates of economic growth in the future, which is far from certain. Already, scientific endeavour is no longer a preserve of high-income countries, with more than one-third of the world's public research concentrated in non-OECD economies (Figure 3.4). For example, China, with the second-largest science base in the world, spent around twice as much on public R&D as Japan in 2014. Similarly, India, the Russian Federation, Chinese Taipei, the Islamic Republic of Iran and Argentina maintain some of the largest public science systems in the world. A more multipolar global research landscape is therefore likely to emerge, with Asia in particular set to play an increasingly prominent role. Nevertheless, a few countries are likely to dominate: five economies (the United States, China, Japan, Germany and India) accounted for 59% of global public R&D in 2014, while 25 OECD countries and non-OECD economies accounted for 90% of the total. This dominance by a few in part reflects their large size. In the longer term, economies that are set to expand their populations and GDP markedly, for example, in Africa, could become more important global R&D players.

Figure 3.4. **Global public research is performed in a few OECD countries and partner economies**

Public R&D expenditure, USD million PPP, and world's share in %, 2014 or latest year available



Notes: Public R&D expenditure includes higher education R&D expenditure (HERD) and government R&D expenditure (GOVERD). The world total is estimated with countries for which data are available. Brazil is not included.

Source: Based on OECD (2016b), *OECD R&D Statistics (RDS) Database*, April, *www.oecd.org/sti/rds*. Data extracted from IPP.Stat (2016) on 26 July 2016, *www.innovationpolicyplatform.org/content/statistics-ipp*.

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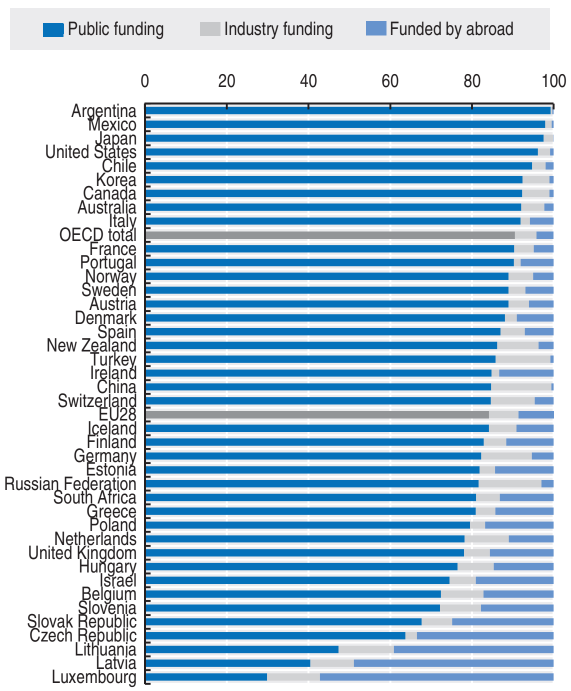
3.2. Who will fund public research?

Any spending squeeze by national governments in OECD countries will pose many challenges for public research, since governments account on average for 90% of total higher education and government R&D expenditure (Figure 3.5). The dominance of government spending in public research is particularly striking in the largest public R&D performers, Japan (98%) and the United States (96%), which tends to skew the OECD average upwards. A similar situation exists in some emerging economies, for example, in Argentina (99%), Mexico (98%) and Chile (95%). Public research is slightly less dependent on funding from national governments in the European Union (83%), reflecting lower shares in the Netherlands (72%), Belgium (71%) and the United Kingdom (70%). In European countries, funding from the European Commission, which is also public funding, is important as well. This is particularly true for the southern and eastern European countries, which receive substantial support for R&D through the EU Structural and Cohesion Funds as part of EU regional policy to reduce intra-European disparities in income, wealth and opportunities (EC/OECD, forthcoming).

Despite fiscal pressures, national governments will remain the main funders of public research in the foreseeable future, but businesses may increase their financial contribution, both reflecting shortfalls in government funding on the one hand, and industry's interest in accessing complementary knowledge and sharing risk on the other. Universities are more likely to capture business funding, following long-term patterns in industry funding of universities and public labs' research (Figure 3.6). Public-private partnerships will remain strategic policy instruments and will help mobilise new sources of funding. Benefits include more immediate socio-economic impacts and increased flow of personnel and ideas between the two sectors. While increased business involvement may reinforce a desirable market perspective in academic research, it can also lead to growing short-termism and greater focus on incremental rather than fundamental, breakthrough research (see the policy profile "Strategic public-private partnerships in science, technology and innovation"). It may also affect other practices, e.g. in placing some restrictions on open data sharing (see below).

Figure 3.5. **Public research funding is concentrated in governments' hands**

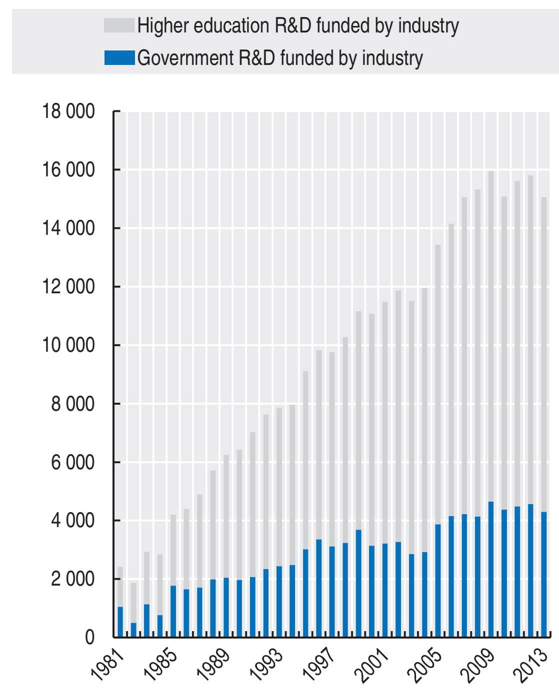
Public R&D expenditure, major funders, share in total, 2014 or latest year available



StatLink http://dx.doi.org/10.1787/888933433387

Figure 3.6. **Industry funding of public research: universities take the lion's share**

Shift in R&D funding, OECD, USD million PPP at constant prices



StatLink http://dx.doi.org/10.1787/888933433392

Notes: Public R&D expenditure includes higher education R&D expenditure (HERD) and government R&D expenditure (GOVERD). The world total is estimated with countries for which data are available.

Source: Based on OECD (2016b), *OECD R&D Statistics (RDS) Database*, April, *www.oecd.org/sti/rds*; Data extracted from IPP.Stat on 25 July 2016, *www.innovationpolicyplatform.org/content/statistics-ipp*.

Charities, foundations and philanthropists have become increasingly prominent funders of university research in recent years, a trend that may well continue. Such funding is especially prominent in the health domain – for example, the Wellcome Trust, based in the United Kingdom, funds a wide range of medical research, the French Association for Myopathy (Association française contre la myopathie) funds research on rare diseases, and the Gates Foundation provides a large share of global research funding related to tropical diseases (see the policy profile "Public research missions and orientation").

While hardly a new phenomenon, science philanthropy – involving often large donations from wealthy individuals – is a fast-growing source of funding for public research (OECD, 2014a). Science philanthropy is typically concentrated in specific fundamental and translational research areas, as well as in institutions at the scientific frontier, and is estimated to provide almost 30% of annual research funds in leading US universities (Murray, 2012). This raises questions about the future of research for the public good: while private donations are widely welcomed, they can be oriented by personal interests and may be dissociated from public goals, thus diverting research towards peripheral fields (Broad, 2014). But, on the other hand, philanthropy often acts as a catalyst for attracting other funders, including the public sector, to support large-scale projects and centres that might otherwise remain unfunded on account of their high costs.

3.3. What public research will be performed and why?

The various megatrends presented in Chapter 1 will heavily influence future research and innovation agendas. Many urgent challenges call for new technological breakthroughs and large-scale institutional and organisational changes that will in part depend on new research. Some examples include: achieving more sustainable growth; the needs of ageing societies; environmental pressures, notably climate change; the depletion of natural resources; threats to energy, water and food security; and, various health issues.

There has already been a general shift in research policy agendas towards environmental and societal challenges, and the "greening" of national research policies has been prominent in many OECD countries since the late 2000s (OECD, 2010; OECD, 2012a). Country responses to the latest science, technology and innovation (STI) policy survey show that achieving sustainable growth or addressing societal challenges are among the top STI policy priorities in a growing number of OECD countries and emerging economies (see Chapter 4). This reorientation is reflected in public budgets for R&D, which have shifted in past decades towards environmental and health-related objectives (though not for energy). National GBAORD has increased faster on environment- and health-related issues than on other civil purposes (Figure 3.7).

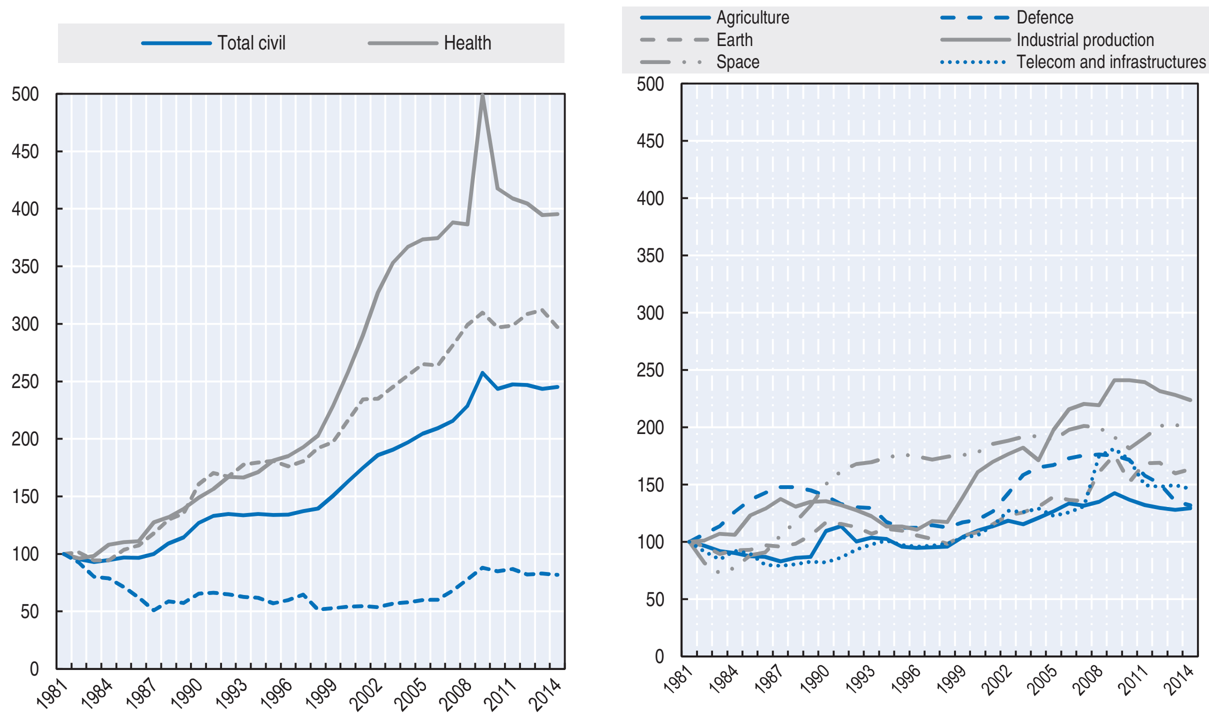
At the international level, the European Union's Horizon 2020 framework programme also focuses on a series of societal challenges, including health, demographic change, food security, sustainability, clean energy, green transport, climate action, and inclusive and secure societies, while the UN-initiated Sustainable Development Goals and the COP21 climate agenda both articulate roles for science and innovation in reaching their targets (see Box 3.1). However, many challenges are ill-structured "wicked problems", involve much uncertainty, and cannot be solved through science and technology alone. It will be important for future policy making to articulate the appropriate roles of science in the socio-technical transitions necessary to deal with these challenges and to adjust policy expectations accordingly.

The breakdown of public R&D budgets by socio-economic objective reveals certain specialisation patterns (Figure 3.8, Panel 1). For instance, the United States has a clear policy orientation towards health R&D (including medical science), which absorbs 24% of its public R&D allocation in 2016. The United Kingdom (22%), Luxembourg (18%), and Canada (17%), devote around a fifth of their R&D budgets to health issues.[2] Mexico (19%), Japan (11%) and Korea (9%) have prioritised energy R&D. While these specialisation patterns will certainly change over the next 15 years, significant shifts take time in the absence of major shocks, since sunk costs in research infrastructures and specialist research workforces imply a substantial degree of lock-in around current research fields.

The focus on societal challenges is unlikely to displace the long-standing emphasis on public science's expected contributions to national economic competitiveness. These concerns will still frame countries' research policy agendas, which will more than ever seek to better link public research with business needs and to attract and retain increasingly mobile knowledge assets, talent and S&T investments.

Figure 3.7. **Growing societal concerns are changing balances in public R&D budgets**

GBAORD, OECD, Index 1981 = 100, 1981-2014



Notes: R&D budgets for the control and care of the environment include research on controlling pollution and developing monitoring facilities to measure, eliminate and prevent pollution. Energy R&D budgets include R&D on the production, storage, transport, distribution and rational use of all forms of energy, but exclude prospecting and propulsion R&D. R&D budgets dedicated to health may underestimate total government funding of health-related R&D. Efforts to account for the funding of medical sciences via non-oriented research and general university funds help provide a more complete picture.

2009 Health data includes the one-time incremental R&D funding legislated in the American Recovery and Reinvestment Act of 2009.

Source: Based on OECD (2016b), *OECD R&D Statistics (RDS) Database*, April, *www.oecd.org/sti/rds*. Data extracted from IPP.Stat (2016) on 25 July 2016, *www.innovationpolicyplatform.org/content/statistics-ipp*.

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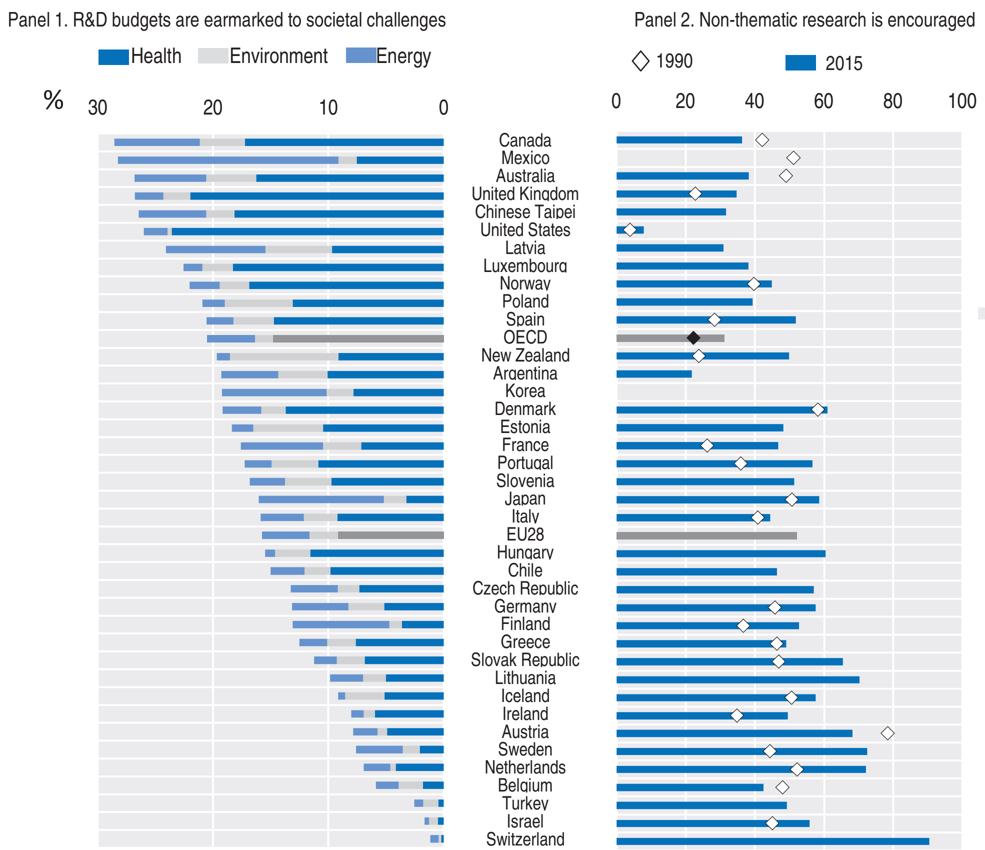
Box 3.1. **The Sustainable Development Goals and STI**

In September 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, which identifies 17 Sustainable Development Goals, with a view to stimulating action over the next 15 years in all economic, social and environment areas of critical importance for sustainable development. The 2030 Agenda targets scientific research and calls for an increase in the number of R&D workers per 1 million people and a substantial increase in public and private R&D. It sets research priority areas in agriculture, health (e.g. vaccines and medicines for communicable and non-communicable diseases), clean energy (e.g. renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology) and marine health (e.g. ocean health and marine biodiversity).

Defence and security issues could also reassert themselves as priorities in national research agendas over the next 10-15 years if incidence of terrorism, risks of armed conflict – or perceived threats – rise. While militaries have for many years been among the biggest investors in scientific research, the proportion of government R&D expenditure devoted to defence in most OECD countries has fallen substantially since the end of the Cold War and is currently at historical lows. This could change if the international system becomes increasingly unstable, as some megatrends suggest (see Chapter 1). At the same time, the defence R&D budgets of emerging powers have grown markedly over the same period, and the People's Republic of China is believed to have the second-largest defence R&D budget in the world after the United States.

Figure 3.8. **Economies are setting R&D budgetary priorities to better address grand challenges**

Share in total GBAORD (%), 2016 or latest year available



Notes: In Panel 1, R&D budgets for the control and care of the environment include research on controlling pollution and developing monitoring facilities to measure, eliminate and prevent pollution. Energy R&D budgets include R&D on the production, storage, transport, distribution and rational use of all forms of energy, but exclude prospecting and propulsion R&D. R&D budgets dedicated to health may underestimate total government funding of health-related R&D. Efforts to account for the funding of medical sciences via non-oriented research and general university funds (GUFs) help provide a more complete picture.

In Panel 2, non-thematic research shares are proxies that include all GBAORD allocated for the general advancement of knowledge, including GUFs. Institutional grants (GUF) could however be distributed according to national research priorities set at national level. The United States is not included in the chart, since US data on GUFs are not available.

Source: Based on OECD (2016b), *OECD R&D Statistics (RDS) Database*, April, *www.oecd.org/sti/rds*. Data extracted from IPP.Stat on 25 July 2016, *www.innovationpolicyplatform.org/content/statistics-ipp*.

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Despite the emphasis on societal, economic and security challenges, the share of public R&D budgets allocated to non-thematic research (i.e. aimed at more general advancement of knowledge) will remain substantial. In 2015, such research accounted for more than two-thirds of the total public allocation in Austria, Austria, the Netherlands, Sweden, Lithuania, and Switzerland (2015 or latest data), and since the early 1990s this share has increased in most countries for which data are available (Figure 3.8, Panel 2). National US data also confirm an erosion of mission-oriented research (Sarewitz, 2012). Over the past 15 years, US mission-oriented agencies that seek principally to serve public goals rather than to advance science have experienced marginal budgetary growth, in some cases not even keeping up with inflation. During this same period, government funding for research almost doubled, and the National Institutes of Health (NIH)[3] and the National Science Foundation (NSF) captured three-quarters of increased federal spending for science.

The reasons for this shift in public research orientation are complicated and vary from country to country. Frequent important drivers include, however, a shift towards relatively autonomous universities as the main performers of public research and a strong policy emphasis on raising research excellence (as currently narrowly defined, i.e. essentially in terms of citations of articles published in leading journals). Broader notions of research excellence that place greater emphasis on the relevance of research for societal challenges could take hold over the next 15 years and could lead to more research spending being channelled along thematic, mission-oriented lines. It is also likely that universities will play enhanced roles in performing mission-oriented research, particularly as they form ever-closer relationships with PRIs and businesses (see below).

Developments in science and technology will also create new opportunities and challenges that will have a significant impact on research agendas over the coming decade. For instance, the potential of big data, neurotechnologies, artificial intelligence, and synthetic biology and their impact on research policies are discussed in more detail in Chapter 2. Making strategic choices on future priorities across very different fields will also be a challenge for research performers and funders alike. New research fields will emerge from the convergence of technologies (encompassing information and communication technologies [ICTs], nanotechnology, biotechnology and the cognitive sciences).

Many of the most significant breakthroughs in science and technology have come at the interfaces between disciplines. One example is synthetic biology where the overarching idea is to apply an engineering approach to biological systems, looking at such systems as living mechanical machines and building devices from standardised biological building blocks (Boyle and Silver, 2009). Synthetic biology applies principles, methods and practices from mathematics, engineering and computer science. It may have applications in manufacturing, the environment, agriculture and medicine (OECD, 2014b). Another example is neuroscience, where a variety of scientific disciplines overlap, from medicine, chemistry and genetics, to linguistics, cognitive science and psychology, to computer science, engineering and mathematics. Applications range from medicine itself (e.g. electronic implants that can repair or substitute brain functions), to brain-stimulation technology, to man-machine communication and interface technologies (e.g. neuro-prostheses).

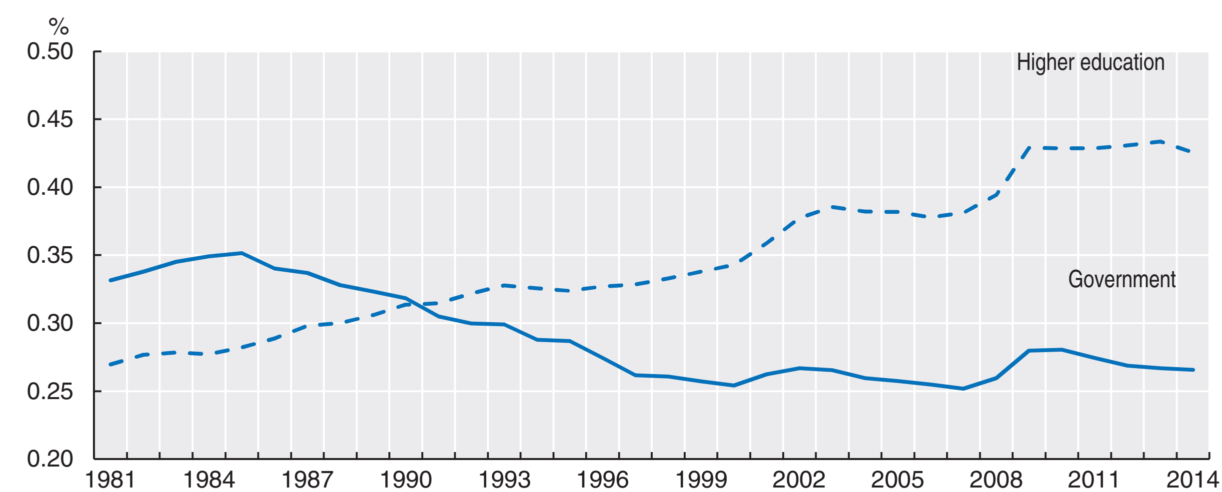
Complex global societal challenges inherently require research that combines traditionally distant academic fields, including the physical sciences and social sciences and humanities. Still, universities, peer review panels, funding agencies and scientific journals remain overwhelmingly organised along disciplinary lines that are not well set-up to accommodate cross-disciplinary activities. Research funders have paid increasing attention to breaking down disciplinary barriers in recent years, and this is set to continue, partially in response to the grand societal challenges but also in an effort to promote the development of disruptive technologies. In the future, this trend towards increasing inter-disciplinarity and trans-disciplinarity could be reflected both in the choice of strategic research priorities and in a re-structuring or bringing together of different research agencies and actors.

3.4. Who will perform public research?

There has been a global shift in national public research systems towards academic excellence and a concentration of resources in world-class research organisations, the vast majority of which are universities. The university model that links teaching and research more closely and involves students upstream in research activities has spread widely, and universities have taken the place of PRIs as the main performers of public research. The share of higher education expenditure on R&D (HERD) in total public research has increased steadily over recent decades in the OECD area, as the share of government expenditure on R&D (GOVERD) has declined (Figure 3.9). Still, universities and public research institutes are very heterogeneous. For example, in most countries, only a small percentage of universities carry out the majority of the research. Such universities often have a considerable degree of autonomy in how they balance and implement their missions, which is influenced by both their size and relative wealth, factors that vary enormously even within individual countries. So while such universities are a critical part of public research systems, governments typically have only limited direct control over them (see the policy profile "Public research missions and orientation").

Figure 3.9. **Public research has shifted towards universities**

R&D expenditure as a % of GDP, total OECD, 1981-2014



Sources: Based on OECD (2014a), *OECD Science, Technology and Industry Outlook 2014*, *http://dx.doi.org/10.1787/sti_outlook-2014-en*; OECD (2016a), *Main Science and Technology Indicators (MSTI) Database*, June, *www.oecd.org/sti/msti.htm*. Data extracted from IPP.Stat (2016) on 25 July 2016, *www.innovationpolicyplatform.org/content/statistics-ipp*.

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As for the public research institute sector, this typically includes a range of research performers, from those performing fundamental research using expensive large research infrastructures to others providing technical services to small and medium-sized enterprises. Those PRIs that focus on more applied research and that are closer to end-market needs have suffered particularly heavy funding cuts, and their existence in the public sector continues to be contested. A major challenge for such institutes has been their difficulty in accounting for the wide range of activities they perform, many of which are not readily amenable to audit and assessment using classical indicators. Many institutes also have large research infrastructures and ageing workforces that are expensive to maintain and that were developed for a different era when government and national industrial champions were major customers for their research. Over the next 15 years, as universities further ramp up their "third mission" and commercialisation activities and increasingly co-operate with the business sector, the overlap between the missions and tasks of PRIs and of universities is likely to grow, with the potential to increase both the competition and co-operation between them. In many OECD countries, public research institutes and universities are increasingly strongly linked through joint projects, PhD training, co-publication, joint appointments, joint research centres and, in some cases, co-location. A few countries, such as Denmark, have even taken the step of merging public research institutes with universities. Such linkages and mergers can be expected to grow in the face of further convergence in organisational missions and public spending constraints.

The move towards more open science (see below) and the advance of digital technologies could also promote citizen science initiatives and enhance public understanding of science (OECD, 2015a). The amount of R&D that is performed in non-public and non-business settings, i.e. by citizens and organised groups, while still quite small and marginal, is expected to increase markedly. Traditionally, such distributed activities are led by established scientists who use volunteer citizens to collect, organise and interpret data cheaply. For example, Galaxy Zoo uses volunteers to identify and classify vast numbers of astronomical images. The involvement of citizens in scientific efforts may also help to develop a culture of scientific awareness. Indeed, schools are increasingly considered an important target for the introduction and promotion of citizen science in some countries, and teachers are increasingly acknowledged for the role they play in facilitating the deployment of experiments and for transmitting socio-scientific values to the young audience.

More recently, "do-it-yourself science" has emerged, where citizens and organised groups conduct their own experiments and even maintain their own facilities or share publicly-accessible facilities. This remains a fringe activity at the moment but could grow significantly over the next decade. Do-it-yourself science could interface with public and private R&D in a variety of ways – as collaborators and user communities, but also as competitors and even opponents on some issues. Indeed, such activities fall outside the governance regimes of mainstream science, raising concerns over research quality and safety.

3.5. How will public research be performed?

Scientific research is itself highly dependent on technological developments and increasingly expensive research infrastructures. This situation has long been the case in physics, but now also applies to other research areas, including the social sciences and humanities. These outlays include large international infrastructures but also smaller-scale technology platforms, libraries and information archives, all of which need to be continuously updated and / or renewed. Large research infrastructures play a growing role in a range of scientific fields and allow many new discoveries. These facilities are dedicated not only to basic scientific research but also to providing direct scientific support for the resolution of major societal and environmental challenges. Strengthening public research infrastructures was among the top STI policy priorities in a majority of countries covered by the 2016 EC-OECD STI Policy questionnaire. For example, the United States is proposing a 10% increase in its 2016 budget for public research infrastructure, while Europe is expanding the number of jointly-funded European Research Infrastructure Consortia (see the policy profile "Financing public research"). Many large research infrastructure investments will also be made in East Asia over the next 15 years, reflecting the region's growing research profile.

Taken together, large research infrastructure investments could herald a new era of "big science", driven by the scale of global challenges, increasing internationalisation, and evolving needs in scientific fields for more large-scale equipment and experiments. Such investments are politically attractive, but costly, and risk crowding out successful but less visible public R&D activities. Such potential trade-offs are particularly acute given future budgetary constraints. Governments will face difficult choices between funding "big science" or single investigator driven projects as well as between funding expensive research infrastructures or research personnel. Furthermore, a considerable and increasing proportion of scientific investment is going to developing and sustaining distributed infrastructures and e-infrastructures, including support for operating costs and skilled personnel, and this will be an increasingly important policy concern (see the policy profile "Financing public research").

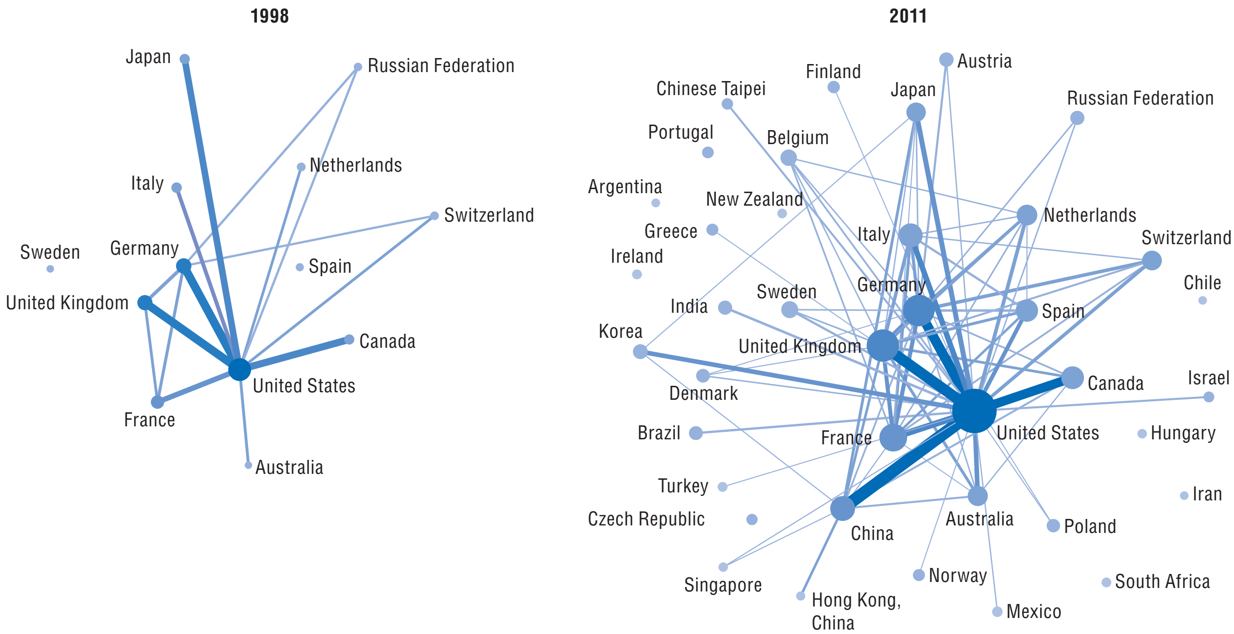
The field of research infrastructures is probably one of the areas that has benefitted most from increased international policy co-ordination in recent years (OECD, 2014c). This is because building and operating large infrastructures requires large amounts of public research funding, providing a strong incentive for collaboration and cost sharing. To facilitate such co-ordination, various policy structures have been set up. The roadmaps of the European Strategy Forum on Research Infrastructures play a crucial role in determining priorities and collaborations within and beyond Europe (for the latest, from March 2016, see ESFRI, 2016). The Carnegie Group of G8 + 5 Science Advisers has established an advisory group tasked with reaching a common understanding on matters such as the governance, funding and management of global large-scale research infrastructures (see the policy profile "Cross-border science, technology and innovation governance arrangements"). The role of such international entities is likely to grow as international co-operation in research deepens.

Internationalisation in research goes beyond large, multinational research infrastructures, of course, and research co-operation and academic mobility have internationalised sharply in recent decades (Figure 3.10). National research policy frameworks are increasingly shaped by a more global context, as STI networks extend beyond national frontiers. Countries, firms, universities and researchers are increasingly organised in open and collaborative networks that connect local research and innovation hubs across frontiers. Ideas, assets and resources concentrate in these pockets of excellence. With new technologies, collaborators in different countries can communicate easily and cheaply, and it is easier than ever to obtain information about research communities in other countries. The global scale of grand challenges could lead to further expansion in international research projects and international co-ordination, as exemplified by recent G7 initiatives on Alzheimer's disease, poverty-related diseases and anti-microbial resistance. Governments will also face pressure to continue efforts to remove barriers in national funding regimes to further international research collaboration. The international mobility of researchers is already high and could increase. Both of these trends could however be countered by wider societal pressures to retrench behind national borders and curb international migration.

Digital technologies are set to radically modify the way science is conducted and the way the results of research are disseminated. A new paradigm of "open science" is emerging, which encompasses: 1) open access to scientific journals; 2) open research data; and 3) open collaboration enabled by ICTs (OECD, 2015a).[4] In parallel, the availability and scale of data available for, and produced by, science have massively increased, as has the ability to interrogate and analyse those data. "Big data" and data-driven research are now ubiquitous across scientific disciplines and open exciting possibilities to address previously inaccessible scientific challenges (see the policy profile "Open science").

Figure 3.10. **International collaboration networks in science are extending and deepening**

Whole counts of internationally co-authored documents



Note: The position of selected economies (nodes) exceeding a minimum collaboration threshold of 10 000 documents is determined by the number of co-authored scientific documents published in 2011. A visualisation algorithm has been applied to the full international collaboration network to represent the linkages in a two-dimensional chart on which distances approximate the combined strength of collaboration forces. Bubble sizes are proportional to the number of scientific collaborations in a given year. The thickness of the lines (edges) between countries represents the intensity of collaboration (number of co-authored documents between each pair). The positions derived for 2011 collaboration data have been applied to 1998 values. New nodes and edges appear in 2011 as they exceed the minimum thresholds.

Source: OECD (2013a), *OECD Science, Technology and Industry Scoreboard 2013: Innovation for Growth*, *http://dx.doi.org/10.1787/sti_scoreboard-2013-en* based on Scopus Custom Data, Elsevier, version 5.2012, June 2013.

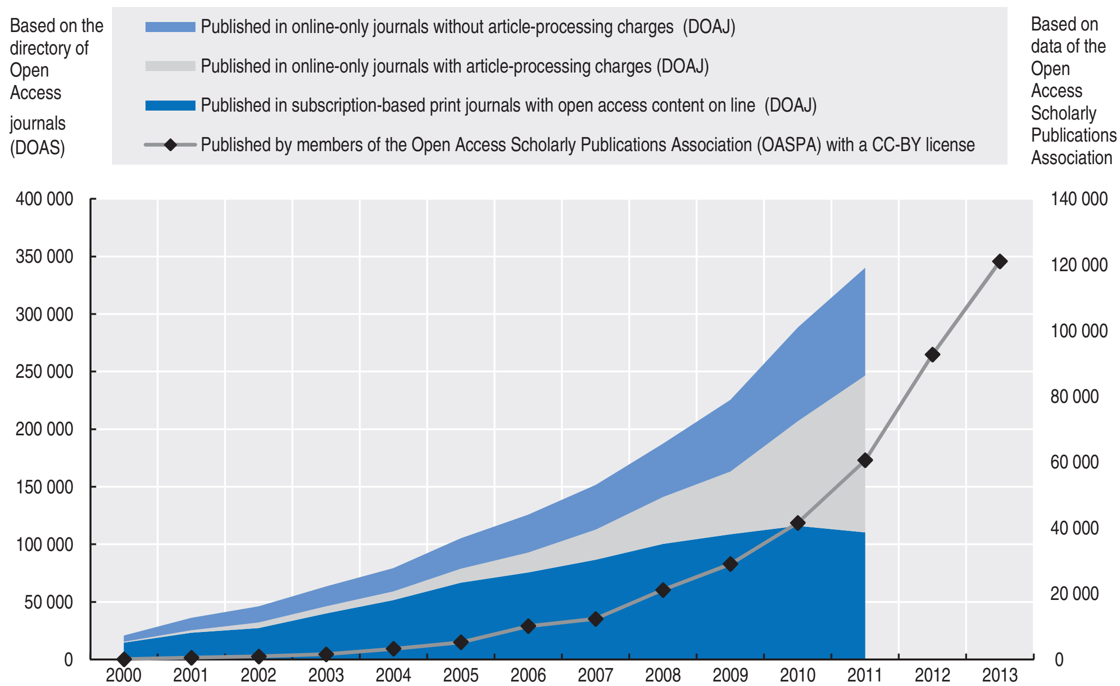
StatLink http://dx.doi.org/10.1787/888933433434

Opening up science is increasingly seen as a means for accelerating research, making it more efficient and promoting the public acceptance of science. There is a general recognition that scientific outputs generated with taxpayer money are public goods and should be made public with a view to increasing their social return. Indeed, one implication of open science is that a given body of data could generate more research and more opportunities for domestic and global participation in the research (OECD, 2014a). And provided that domestic firms have human capital and finance to translate research into usable knowledge, open science could give emerging economies further opportunities to accelerate technological catch-up and possibly leapfrog to nearer the knowledge frontier. There is also some evidence that, as regards open access to scientific publication, sharing data can raise the citation rate of scientific papers (Piwowar, Day and Frisma, 2007; Piwowar and Vision, 2013) and foster good scientific behaviour.

Open access (OA) practices are on the rise (see Figures 3.11 and 3.12), enabled by the low costs of online dissemination. At the same time, the traditional model of publishing in scientific journals has been severely criticised for limiting access to the outputs of publicly-funded scientific research to an exclusive club of higher education and research institutes,

Figure 3.11. **Open access publishing is on the rise**

Number of papers, 2000-13



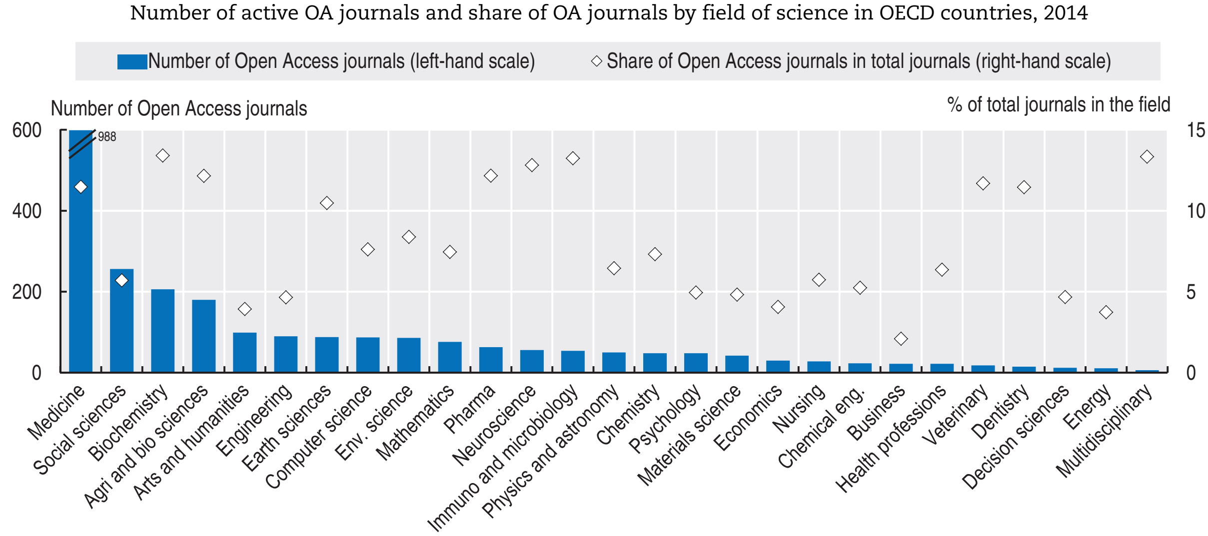
Note: Laakso and Björk describe the results of a study that focuses on measuring the longitudinal development of gold OA publication volume for the years 2000 to 2011. The study is founded on the assumption that the full population of OA journals is listed in the Directory of Open Access Journals (DOAJ). Figures of the Open Access Scholarly Publications Association (OASPA) include a total of 399 854 articles that were published with the CC-BY license by its members during the 2000-13 period. 30% of those articles (120 972) were actually published in 2013 alone. These OASPA numbers include only articles that were published in journals whose entire content is OA, so articles that were published in hybrid OA journals are not included.

Sources: Based on Laakso, M. and B.-C. Björk (2012), "Anatomy of open access publishing: A study of longitudinal development and internal structure", *www.biomedcentral.com/1741-7015/10/124* (cited in OECD, 2015a and accessed 11 June 2015); website of the Open Access Scholarly Publications Association (OASPA), *http://oaspa.org/growth-of-fully-oa-journals-using-a-cc-by-license/* (accessed 30 May 2016).

StatLink http://dx.doi.org/10.1787/888933433448

Figure 3.12. **Open access publishing practices vary across fields of science**

Number of active OA journals and share of OA journals by field of science in OECD countries, 2014



Source: OECD (2015b), *OECD Science, Technology and Industry Scoreboard 2015: Innovation for growth and society*, *http://dx.doi.org/10.1787/sti_scoreboard-2015-en*.

StatLink http://dx.doi.org/10.1787/888933433454

many of which have themselves been protesting the rising costs of journal subscriptions (OECD, 2015a). Two models of OA have emerged: "gold open access" and "green open access" (Box 3.2). Both have pros and cons, and it remains unclear which will emerge in the longer term as the dominant solution.

Box 3.2. **Two main publishing models have emerged to promote open access to scientific articles**

Green open access refers to the "self-archiving" of a published article or the final peer-reviewed manuscript by a researcher after or alongside its publication in a scholarly journal. Public access to such an article can be delayed by a stipulated period of embargo that may vary considerably (generally up to 24 months). Green OA articles do not typically have full reuse rights under a Creative Commons license (CC-BY); pre-print versions deposited online have not been subjected to peer review and the maintenance costs of repositories are substantial. However, articles can be uploaded in multiple venues (from institutional or disciplinary repositories to personal websites) and authors are free to choose their publishing venues. In addition there is no extra cost for authors.

Gold open access or "author pays publishing" refers to a model in which a publication is immediately provided in an OAmode online by the scientific publisher. In this case, the associated costs are shifted from the reader to the author or the research institute to which the author is affiliated. The agencies sponsoring the research may also make provision for the costs of OA. In this model, publishing costs need to be covered and there is limited choice of publishing venue. But the article is immediately available with no embargo periods and typically gets full reuse rights under Creative Commons (CC-BY). In addition, publishers are increasingly offering innovative services and some even offer fee waivers to authors without institutional funding.

Source: OECD (2015a).

Scientists are also rapidly adopting alternative channels to disseminate their work, using blogs, social media and multimedia to share their results. This move is driven by new digital technologies and their burgeoning popularity, as well as by a desire for fast publication that circumvents the slower traditional journal routes and a desire to increase the impact of scientific work by reaching out beyond the limited readership of scientific journals.

As scientific information is increasingly discussed and disseminated in this way, patterns in publishing and recognition are changing. The emergence of new channels of scientific dissemination means that citation databases cover a decreasing part of the scientific literature, which will increasingly challenge their use for measuring scientific output and impact. Still, the dominance of a narrow concept of excellence that relies upon such databases to signal research quality (important for funding and career progression) means traditional publication routes will not quickly disappear, though these are undergoing some changes that speed up publication, allow OA in some circumstances, and embed certain multimedia features. A greater emphasis on social challenges in national research agendas and the concomitant use of public value criteria to assess research impacts will also challenge the current reliance on bibliometrics. Alternative metrics, or altmetrics, as they become accessible from a broader range of digital supports and practices, are likely to be increasingly used alongside more traditional bibliometrics to assess research impacts.

Despite its costs and burden, peer review will remain an important means of assessing research quality. It is likely to undergo some changes – for example, crowdsourced post-publication peer review may emerge as a useful complement to more traditional types of review – but it will remain under close scrutiny, not only because of its costs, but also because of concerns over quality, particularly in light of the apparent lack of reproducibility of much research published in scientific journals.

The digitalisation of science will facilitate greater access to scientific data in the future. Open data has the potential to make the research system more effective and efficient by reducing duplication and by allowing the same data to generate more research (OECD, 2015a). Open data could also help address concerns about the rigour and reproducibility of published scientific results by ensuring OAonline to the underpinning research data.

While the principle of OA to scientific data is already well established in OECD countries, the scope of access still varies greatly (OECD, 2015a). This is because data sets are not as easily identified and defined as scholarly research articles. The diversity of scientific data and differing traditions and standards in their treatment also hamper the accessibility and interoperability of systems. However, these technical issues should be gradually resolved in the next few years, and it is likely that a handful of dominant digital platforms will emerge to support the research system in data sharing (Box 3.3).

Box 3.3. **Platform science: towards a single "operating system of science"?**

As science and research management become increasingly digitised, new opportunities arise for linking datasets covering diverse areas of activity and impact, including research funding, equipment inventories, research data, publications and citations, researcher profiles and social media presence. Could such datasets one day be bundled and vertically integrated into a single "operating system of science" (Heller, 2016)?

The emerging research data infrastructure landscape is made of many different actors, including research performers and funders with their own institutional repositories and information systems, large established academic publishers, but also new firms offering Facebook-like services (notably ResearchGate and Academia.edu). Among recent initiatives to further develop this data infrastructure, the international, government-backed, not-for-profit Open Researcher and Contributor ID (ORCID) project seeks to provide researchers with unique identifiers. These allow better tracking of research and innovation activities (e.g. grant applications, articles submission) and will create new data for analytics. Recognising the benefits of having standardised unique identifiers, funders and publishers around the world are increasingly integrating ORCID into their systems and requirements.

Although there is some overlap between these initiatives, they often draw from different information sources, and no one provider as yet has all the data that would make the others redundant (Heller, 2015). But this could change in the future, and the large academic publishers are perhaps the most advanced in developing, acquiring and integrating different data services. For example:

- The Holtzbrinck Publishing Group, which owns Springer Nature and Digital Science, includes in its portfolio access to online repositories for OA, collaborative writing and publishing software, unique identifiers for research-performing organisations, information management systems to support decision making in research organisations, altmetrics to monitor articles' impact beyond the academic context, and decision support systems for science funders.

Box 3.3. **Platform science: towards a single "operating system of science"?** *(cont.)*

- Another big player is Elsevier Research Intelligence, which offers a variety of services, including a bibliographic database, information management systems to support decision making in universities and PRIs, analytics software for benchmarking and trend analysis, an expert identification tool, and a free reference manager and academic social network.

Could these initiatives led by large academic publishers become the "walled platforms" of science, akin to the likes of Google, Apple, Facebook and Amazon? Or will collaborative, bottom-up and more open alternatives emerge based on open standards and application programming interfaces (APIs)[5] (Heller, 2016)? This is an as yet unanswered question. Open standards can technologically ensure interoperability, data sharing and reuse, but other factors (e.g. network effects, preferential attachment or personal data ownership) could lock users into a single or a few commercial platforms (EC, 2014a).

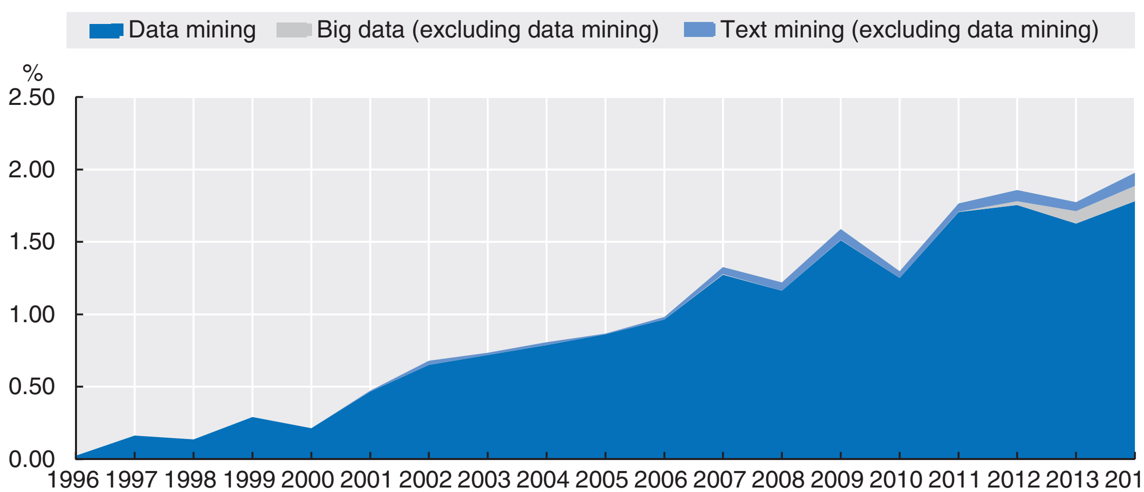
At the same time, many hurdles will remain over the next decade. For example, public research organisations that have incurred most of the storage, preservation and access costs until now will be challenged to find sustainable funding and business models. Legal issues around ownership of large-scale datasets, potentially collected or generated by machines or software providers, and issues around privacy, confidentiality and security will be difficult to resolve, but they will attract considerable policy attention as all spheres of the public research system (including researchers, publishers, funders and policy makers) embrace open data. Sharing results openly online and reusing results and data produced by others also pre-supposes a radical shift in academic culture that will take time to occur and will need to be incentivised. Whilst science is collaborative, it is also intensely competitive. Individual scientists and their institutions are to a very large extent judged by their publication outputs, often using standardised journal bibliometric measures. They therefore have little incentive to share data and experimental material. Mechanisms that accredit the publication of datasets and other collaborative efforts will be essential for promoting open data (see the policy profile "Open science").

Big science creates "big data". The vast expansion of sensors across societies (e.g. through the Internet of Things, the "quantified self" movement and citizen science) and the rapid opening-up of government data will significantly add to this. While the greater availability of data will offer new opportunities and challenges for science, it will also require dedicated infrastructure and skills, which are currently in short supply. In addition there are key challenges in data governance per se. A recent report on big data for advancing dementia research identified seven of those, namely data availability, interoperability, accessibility, ownership, quality, traceability and privacy and security (Deetjen et al., 2015). Novel research fields will develop around data mining, data privacy and security, machine learning, artificial intelligence, database interoperability and related fields. Cheaper processing power, lower equipment costs and massive digitalisation will support faster and more affordable experimentation, while digitalisation will enable replication at a greater speed and with more fidelity (Brynjolfsson and McAfee, 2011). More broadly, public R&D will be increasingly automated, making greater use of robotics and rapid processing, and increasing the scale and efficiency of research.

Pattern-recognition technologies will enhance the analysis of causalities**,** with direct applications in many scientific fields (Figure 3.13). Indeed, much science will be driven by the testing of computer-generated hypotheses based on patterns extracted from massively dimensional databases. Data will increasingly precede the research idea and guide experimental research design (EC, 2014b). The scientific method to date has been built on hypothesis testing. Hypothesis testing is informed by explanatory models which, in turn, are revised through scientific discovery. However, the process and utility of model development is likely to change because, in some fields, the data will contain all objects of interest (data will be comprehensive, not representative). Traditional approaches through hypothesis and "grand theories" development will be complemented by data-driven research that starts with massive amounts of data and may utilise hybrid methodologies and algorithms from different research areas. Change in this direction is already apparent.

Figure 3.13. **Data-driven research is growing rapidly**

Data mining-related scientific articles per thousand articles, 1996-2014



Source: OECD (2014d), *Measuring the Digital Economy: A New Perspective*, *http://dx.doi.org/10.1787/9789264221796-en*, based on ScienceDirect repository, *www.sciencedirect.com*, July.

StatLink http://dx.doi.org/10.1787/888933433466

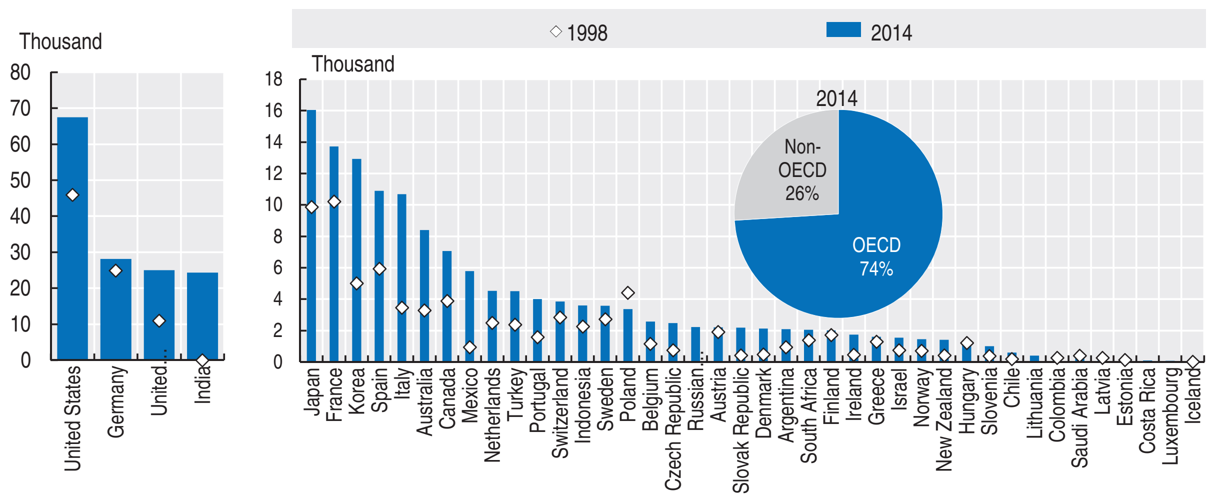
3.6. What will public research careers look like?

The last two decades have seen large increases in the numbers of new doctorates worldwide (Figures 3.14 and 3.15). The United States remains the largest producer of PhDs followed by Germany, the United Kingdom and India and far ahead of Japan. Large emerging economies have greatly expanded their higher education training capacities, including at the most advanced tertiary levels, and non-OECD countries accounted in 2014 for more than a quarter of new doctorates awarded globally. In China in 2014 the share of the relevant age cohort entering doctoral programmes was higher than the average in OECD countries (OECD, 2016c) (see the policy profile "Strengthening education and skills for innovation"). In natural sciences and engineering in particular, China ranked second, between the United States and Germany, in terms of average annual number of doctorates graduating over the 2008-12 period (OECD, 2015b).

Certain scientific fields are more popular among doctorates. About 40% of new doctorates in the OECD area graduate in sciences, engineering and mathematics (STEM), and this percentage increases to 58% of all new graduates if doctorates in health are included (OECD, 2016d). Doctoral programmes are particularly oriented towards natural sciences and engineering in France (59%), Canada (55%) and China (55%).

Figure 3.14. **There are more new doctorates worldwide, including in emerging economies**

Number of doctoral graduates and world's share, all fields, 1998 and 2014



Note: World estimates include countries for which data are available, i.e. 35 OECD countries, Argentina, Colombia, Costa Rica, India, Kazakhstan, the Russian Federation, Saudi Arabia and South Africa. Mexican value for 1998 corresponds to 1999 value.

Source: Based on OECD (2016c), *Education At a Glance 2016, OECD Indicators, http://dx.doi.org/10.1787/eag-2016-en.*

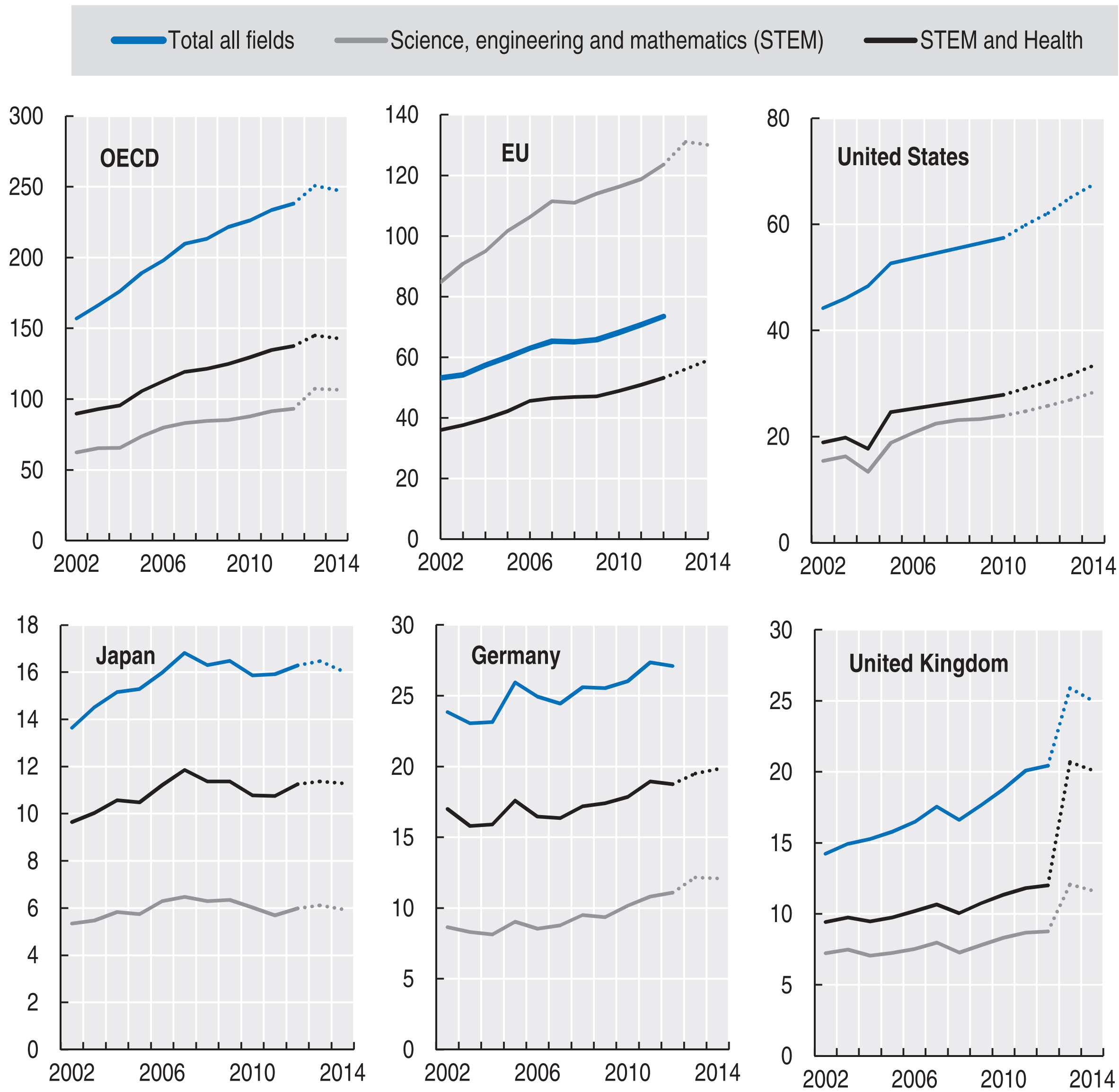
StatLink http://dx.doi.org/10.1787/888933433477

The balance between the supply of and demand for scientists over the next 15 years is uncertain. Population ageing and fears of a disinterest in science among youth have raised concerns among policy makers about the sustainable supply of STI talent, especially in view of the time required for education systems to train new cohorts. A scarcity of relevant skills, if it emerged, could require a greater reliance on sources of talent from abroad, especially from emerging and developing economies with more favourable demographics. However, as research systems in these economies further develop, the global competition for talent is likely to intensify.

On the other hand, falling public investments and growing automation in laboratories could reduce demand for new researchers. Until recently, growth in PhD numbers was viewed as overwhelmingly positive and actively encouraged by policy. Furthermore, the erosion of core funding in universities and public labs and its replacement with more short-term competitive project-based funding created significant demand for relatively mobile and cheap PhD students and post-doctoral researchers employed on short-term contracts. But this era may now be drawing to a close, as many doctorate holders face difficulties finding work that matches their high level of skills. There are also some signs of a slowdown in STEM doctorate graduation in recent years, in relative terms as compared to the number of new graduates in other fields, especially in the largest doctoral education systems (Figure 3.15) (see the policy profile "Building a science and innovation culture").

Figure 3.15. **The supply of doctorates in science and engineering shows some signs of slowdown**

Number of doctoral graduates in STEM and health in major supplying systems, thousand, 2000-14



Source: Based on OECD (2016d), *OECD Education and Skills Database*, extracted from OECD.Stat on 23 Septembre 2016.

StatLink http://dx.doi.org/10.1787/888933433485

A "dual labour market" has emerged in universities and PRIs as a result of these dynamics, consisting on the one hand of relatively well-paid established researchers who often have permanent civil servant or public employee contracts, and on the other hand a growing number of cheaper temporary staff recruited with soft money at centres of excellence or on competitively-funded research projects (Kergroach and Cervantes, 2006). A recent survey of 38 EU and EU-partner countries shows a persisting duality, with a significant proportion of researchers in the higher education sector employed on fixed-term contracts, or no contracts at all, the situation being most pronounced during early career stages (Deloitte, 2014). In 2012, the proportion of researchers with "no contract at all" or on a less-than-one-year contract was ten times higher among PhD students and young graduates

(31%) than at the latest research career stages (3%). Almost 90% of PhD researchers were in precarious working conditions with no or less-than-two-year contractual horizons, while 90% of leading senior researchers were on permanent positions. This duality has created problems for the individuals involved, who have little long-term job security and increasingly face few opportunities to obtain permanent or tenured positions. Beyond issues of contract status, these individuals also have less rewarding remuneration packages, lower access to research funding, training and career development programmes and, overall, weaker career prospects. It is not unusual for researchers to do two or three post-doctoral positions before attaining a permanent position in their late-30s – assuming they have remained in the profession for that long. In fact, an increasing number are edged out of research careers, which raises questions over the return to costly public investments in their training. The duration of PhD training is still quite long in a number of countries and means that the social and private costs of producing new graduates is high; the long duration also reduces the speed at which the system can respond to changes in demand.

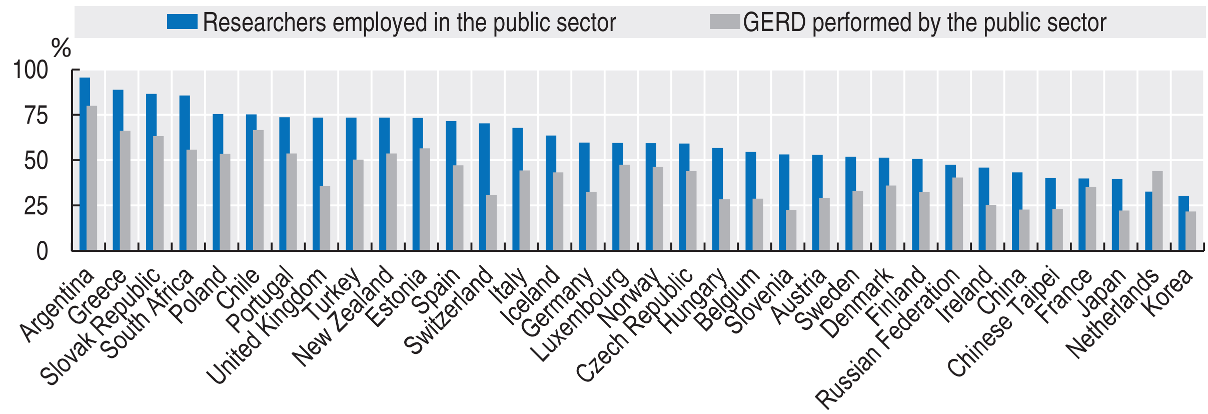
In summary, while project-based competitive funding remains the dominant mode of research funding, there will continue to be strong rigidities in the labour market for established researchers, and short-term employment contracts will continue to dominate early-to-mid-career paths. But the substantial growth in PhD and postdoc positions seen over the last few decades has recently come under close scrutiny as many struggle to establish long-term careers in science. Yet a decline in the number of PhDs and postdocs flowing through the system would cause problems for public research labs, whose current set-up depends on a constant stream of PhD students and post-doctoral researchers to do much of the work.

Given that many PhDs (and increasingly, postdocs) are leaving the research profession, there is growing recognition that they should receive training to provide transferable skills and exposure to industry and other employment sectors. Still, in many countries, there is scope for matching PhD training more closely with market needs and diversifying career paths through internships, as well as allowing the portability of PhD fellowships to industry. This need for better matching will attract greater policy attention in coming years. Training new researchers through the PhD and postdoc process will therefore need to broaden because many are discontinuing public R&D careers and moving into other parts of the economy. However, this shift will likely meet resistance from laboratory heads who rely heavily on over-worked PhD students and postdocs to perform much of the day-to-day research that is carried out in their labs. In the absence of inducements or a wider cultural change, they have few incentives to allow their staff the time to participate in non-core laboratory research.

As major employers of R&D personnel, and through performance agreements with universities and PRIs, governments can influence research careers. The public sector accounts for a disproportionate share of employed researchers, even in countries where most R&D is performed by the business sector (Figure 3.16).[6] Governments also have capacity to intervene upstream, through the redesign of doctoral programmes that are increasingly a key stepping stone in research careers (Cervantes, Kergroach and Nieto, forthcoming). However, their capacity to make research careers more attractive, as well as the policy instruments at their disposal for that purpose, are likely to evolve as more R&D is performed by the business sector, policies to encourage the recruitment of researchers in the private sector bear fruits, and more researchers are employed in non-public organisations.

Figure 3.16. **The public sector accounts for a disproportionate share of employed researchers**

Share of GERD and researchers respectively performed and employed in the public sector, 2014 or latest year available

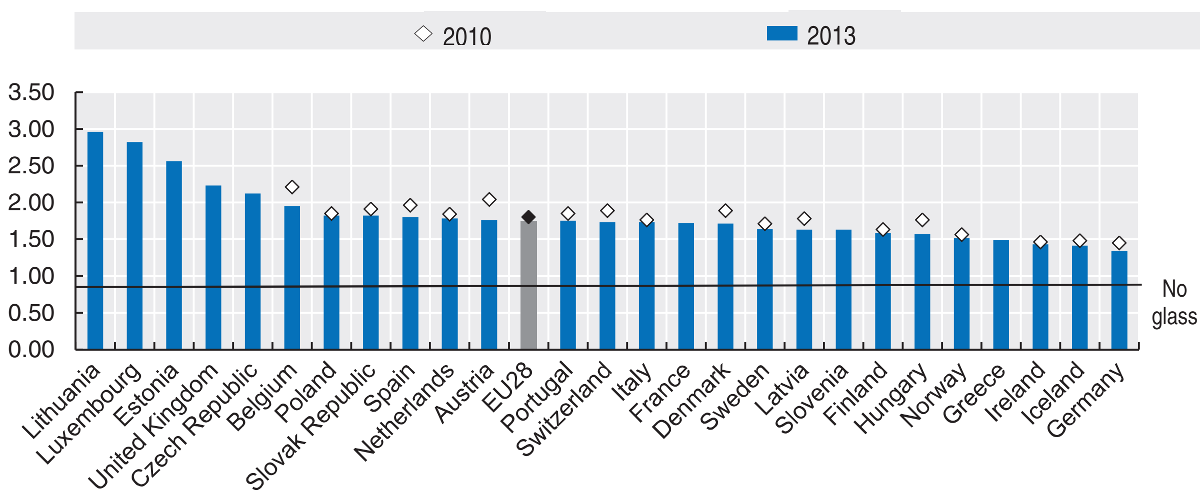


Source: Based on OECD (2016a), *OECD Main Science and Technology Indicators (MSTI) Database*, June, *www.oecd.org/sti/msti*.

StatLink http://dx.doi.org/10.1787/888933433495

Figure 3.17. **Women remain away from top academic positions in Europe**

"Glass ceiling" index, 2010 and 2013



Note: The Glass Ceiling Index (GCI) is a relative index comparing the proportion of women in academia (grades A, B, and C) with the proportion of women in top academic positions (grade A positions, equivalent to full professors in most countries) in a given year. The GCI can range from 0 to infinity. A GCI of 1 indicates that there is no difference between women and men in terms of their chances of being promoted. A score of less than 1 means that women are more represented at the grade A level than in academia generally (grades A, B, and C) and a GCI score of more than 1 indicates the presence of a glass ceiling effect, meaning that women are less represented in grade A positions than in academia generally (grades A, B, and C). In other words, the interpretation of the GCI is that the higher the value, the stronger the glass ceiling effect and the more difficult it is for women to move into a higher position.

Source: EC (2016), *SHE Figures 2015*, *https://ec.europa.eu/research/swafs/pdf/pub_gender_equality/she_figures_2015-final.pdf* (accessed 22 April 2016).

StatLink http://dx.doi.org/10.1787/888933433507

Following gradual improvements in recent years (Figure 3.17), the public R&D workforce will become more female, and more women will hold senior positions. This change will continue to occur slowly, however, despite sustained policy attention. Barriers to female participation in science will likely persist. Gender stereotypes are hard to change; workplace practices will remain insufficiently family-friendly, and discriminating selection and promotion arrangements (e.g. exclusively or predominantly male boards, procedures that disregard activities women are more widely represented in, like teaching), will still exist. In many countries, women still face a glass ceiling in the research profession. Even though they outnumber men at bachelor and masters levels of education, they are considerably less likely to enter advanced programmes in science, are less likely to occupy senior academic positions and are even less likely to head a university or PRI (Figure 3.17).

Digital and open science will require the deployment of new skills. Data-related skills development will be essential for making efficient use of new scientific datasets, tools and methods. As these tools will become pervasive in all scientific disciplines, including the humanities, there may be a significant need for re-training researchers. The more open nature of science and the closer links science is building with industry will require researchers to reinforce their “soft” skills, including in project management, team-working, and business and intellectual property awareness. Recent surveys on the behaviour of scientists reveal that not all researchers are necessarily aware of the possibilities offered by open science, for example (OECD, 2015a).

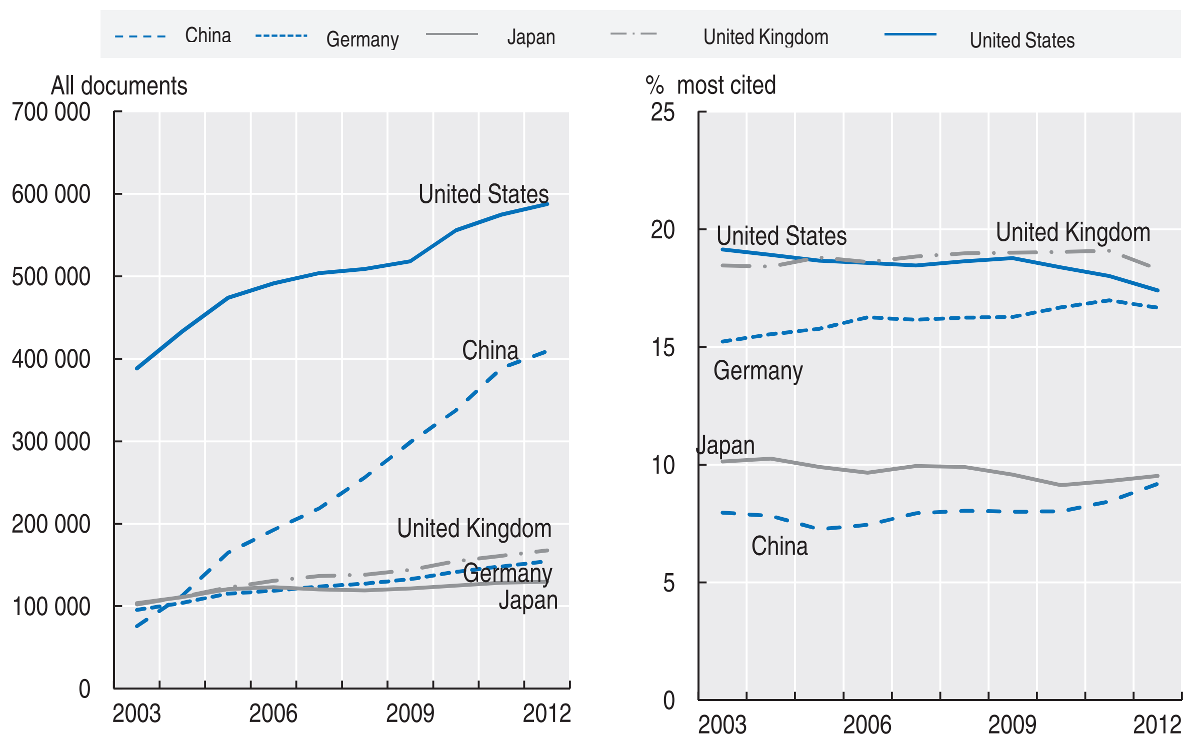
3.7. What outputs and impacts will be expected of public research?

The increased investment in public research over the last 15 years or so has also led to a growing number of scientific publications (Figure 3.18, Panels 1 and 2). This has been especially so for China, where the number of publications over the ten-year period 2003-12 increased more than four-fold. China’s share of publications among the 10% most cited rose only slightly over the same period and, though roughly on a par with Japan’s share, remains well below the United States, the United Kingdom and Germany. Raising research excellence will remain a major challenge for China in the medium term, and matching the citation rates of the long-established scientific powers is most likely some way off. However, Germany shows that it is possible to increase citation rates, though its expansion of scientific output is on a far more modest scale than China’s for the same period.[7]

Parallel to and in synergy with the evolution of strategic research for major societal challenges, the global trend towards more competitive funding has seen most governments introduce performance-based elements in core institutional funding and move towards more contractual arrangements (OECD, 2014e). Accordingly, governments have resorted to using tools such as performance agreements, new funding mechanisms and performance metrics to orient public research activities towards national research priorities and to strengthen scientific performance (OECD, 2014a). Further developments along these lines can be expected, though this will likely meet challenges and even resistance. The limits of performance metrics, including what they fail to measure, the costs of the associated data collection, and the scope for gaming measurement systems and adversely distorting behaviours, means that their use will continue to be contested (Box 3.4).

The commercialisation of public research has become a major goal of national S&T policies over the last few decades and a key function of universities and public labs (OECD, 2013b). A growing number of policy initiatives aim to foster co-operation between industry and science and accelerate the transfer of public research results to society, while a growing number of research system intermediaries aim to smooth and improve transfers (e.g. technology transfer offices, patent funds, intellectual property brokers, etc.). These efforts have only been partially successful, in part because of their inappropriateness in many settings where knowledge and technology transfer occur more effectively through other channels. The very rapid growth in patenting seen in the last 15 years has already begun to tail-off as universities and public labs become more strategic and selective in building their intellectual property portfolios. The mixed success of university-owned

Figure 3.18. **Scientific production has increased worldwide but rankings of excellence are slower to change**



Note: Scientific production/Output/Number of documents is the total number of documents published in scholarly journals indexed in Scopus (whole counts of all document types by author affiliation). Excellence indicates the amount (in %) of an institution's scientific output included in the set of 10% of the most-cited papers in their respective scientific fields. It functions as a measure of high-quality output of research institutions. Albeit imperfect, this indicator is commonly used to capture research excellence.

Source: OECD (2015b), *OECD Science, Technology and Industry Scoreboard: Innovation for growth and society*, *http://dx.doi.org/10.1787/sti_scoreboard-2015-en.*

StatLink http://dx.doi.org/10.1787/888933433519

Box 3.4. **Paving the way for better metrics and more appropriate use**

While recent years have seen the use of science and innovation metrics proliferate, there is increasing alarm among scientometricians, scientists and research administrators at the pervasive misapplication of indicators in research assessment (Hicks et al., 2015). Among the most frequent criticisms are the skewed nature of citation distributions across journals or fields of science, and the poor relevance of journal impact for assessing an individual's or a team's merit. Likewise, there is evidence of a rise in strategic citation practices (e.g. self-citation, influence of interpersonal networks).

Promoting the idea that research should be assessed on its own merits, three recent landmark initiatives set out several recommendations for improving the use of metrics in research assessment:

The San Francisco Declaration on Research Assessment (2012) calls on all research actors to avoid using journal-based metrics as a surrogate measure for the quality of scientists or their work. For funding agencies particularly, the Declaration calls on them to consider the

Box 3.4. **Paving the way for better metrics and more appropriate use** *(cont.)*

value and impact of all research outputs and to use a broad range of impact measures, including qualitative indicators. Both individuals and organisations are invited to indicate their support by adding their names to the Declaration (*www.ascb.org/dora*), which had more than 12 000 signees by the end of 2015.

The Leiden Manifesto (2015) is a compendium of ten principles for metrics-based research assessment that builds on the idea that research assessment is increasingly implemented by organisations without knowledge of, or advice on, good practice and the interpretation of metrics. The Manifesto's ten principles, which have been published in the leading journal *Nature* (Hicks et al., 2015), stress the complementarity of quantitative evaluation and qualitative expert assessment; recognise the idiosyncrasies of performance conditions and the need to adjust evaluation accordingly; encourage protection of locally-relevant research (e.g. non-English literature); highlight the desirability of open and transparent evaluation practices, as well as the importance of their integrity and accuracy; call for better taking into account well-known biases in publication and citation; suggest to disseminate evaluation results in a precise and informed manner to avoid potential negative effects on research systems as a whole (e.g. gaming, goal displacement); and, finally, recall the need to regularly revise and update metrics to reflect shifts in research missions and assessment goals.

The Metric Tide (2015) provides recommendations on research assessment on the basis of a UK review of the potential future roles that quantitative indicators could play in the governance, assessment and management of research. The review found that a "variable geometry" of expert judgement, quantitative indicators and qualitative measures that respect research diversity is necessary for robust research assessment. The Metric Tide's recommendations also underpin the notion of "responsible metrics", which would fit criteria of robustness, humility, transparency, diversity and reflexivity. More recently, an independent review of the UK Research Excellence Framework stressed that, with the exception of some sub-disciplines, metrics capture only some dimensions of output quality (UK Department for Business, Energy and Industrial Strategy, 2016). Its recommendations highlight the need for widening and deepening the notion of impact to include influence on public engagement, culture and teaching as well as policy and applications more generally; the under-representation of interdisciplinary research; and the benefits of a more productive use of assessment data and insights for both institutions and the United Kingdom as a whole.

While it will no doubt prove difficult for the research community to wean itself off using traditional bibliometrics, these three initiatives may mark a turning point towards more varied and robust assessment arrangements over the next ten years.

Sources: ASCB (2012); Hicks et al. (2015); UK Department for Business, Energy and Industrial Strategy (2016); Wilsdon et al. (2015).

technology transfer offices over the last 15 years or so has also seen new arrangements emerge, including technology transfer "platforms" that are both cross-institutional, such as the Sociétés d'accélération du transfert de technologies in France, and specialised in particular areas of research or technology.

Policy will take an increasingly broad approach to the socio-economic benefits of public research over the next 15 years, which will coincide with the deeper and more extensive engagement of universities and public labs with society, both locally and further afield. As research and innovation landscapes become more open and complex – with more actors and interactions – universities and PRIs will further develop research relationships with the likes of patient groups, "maker communities" and environmental groups. Student entrepreneurship is also likely to grow, supported by a broadening of PhD training curricula.

3.8. What will public research policy and governance look like?

The trends and issues outlined in this chapter all have implications for STI policy and governance arrangements. Indeed, the expected changes in the public research system over the next 10-15 years will demand a policy response and will be shaped by policy changes. Funding arrangements between the government, on the one hand, and universities and PRIs, on the other, will continue to be both the most important channel for delivering public research policy and a major driver of change in the public research landscape. Regulation and governance arrangements will also play crucial roles.

The final part of the chapter considers four trends that are specific to future STI policy practices. The first trend is the growing influence of so-called "responsible research and innovation", which places greater emphasis on broader public engagement in STI policymaking. The second trend concerns the rise of design thinking and experimentation in policy formulation and delivery, with a view to creating a more agile STI policy. The third trend is the growing digitalisation of STI policy, including the opportunities from big data analytics for more evidence-based policy. Staying with the theme of evidence, the fourth trend concerns changing arrangements for scientific advice to policy.

The risk and ethical implications of research and technological change will most likely lead to a more active engagement of wider society with science. Public values will become more prominent as criteria for assessing research. The greater attention paid to the ethical and societal dimensions of research is already being reflected in the framing of more "responsible research and innovation" (RRI) policies. These seem to reflect a shift away from simply educating the public, to better aligning STI with social goals. One way governments have been doing this is to find ways to engage the public early and often in the process of research and to feed that into STI policy (see the policy profile "Public engagement in STI policy"). In the last few years, a number of countries have put in place participatory and bottom-up approaches to setting STI strategies (EC/OECD, forthcoming). Through this new RRI approach, governments intend to anticipate and assess the potential implications and societal expectations associated with research and innovation, with the aim of making research and innovation more inclusive and sustainable. Operationalising this vision in new practices and governance arrangements will nevertheless remain a major challenge. Furthermore, scientists' and policy makers' fears that RRI will hamper and delay scientific progress and weaken the competitive capacity of national research institutes will continue to be a powerful force shaping future moves in this direction.

As part of a movement towards public sector innovation (Box 3.5), design thinking and experimentation will become more commonplace in policy-making and delivery as governments seek to become more agile and innovative. Piloting, prototyping and other experimental design tools will be increasingly used to implement new approaches safely and to minimise the risks associated with policy innovation. Such arrangements will support learning and allow for "fast-failure" before significant resources are invested. Learning from pioneers such as Denmark's Mindlab and the United Kingdom's Policy Lab, many countries will set up "policy lab" type units that apply design concepts to public

Box 3.5. **Public sector innovation**

In recent years, innovation has become a more significant imperative in policy programmes and initiatives. Experimentation is increasingly embedded in policy design and service delivery as a way to better keep up with increasing complexity and user expectations. New tools and approaches – from data analytics to prototyping and design thinking – are being applied across the public sector to manage uncertainty, and to respond to changing user demands for personalised digital services and convenient automatised processes that rival the efficiency and effectiveness of industry. Around the world, public innovators are being celebrated through events, awards and prizes.

At the same time, the promise of public sector innovation will continue to face challenges. While progress has been made, gaps remain. Innovators across the world are still fighting cumbersome administrative procedures and cultures that inhibit action. Professionals lack direct access to expertise and tools for innovation. Managers are left with the difficult task of selecting, recruiting and hiring public servants with the right skills and attitudes. And there is limited understanding of risk, and its management, which inhibits innovators in the public sector.

Source: Abridged from Daglio, M. (2016), "Public Sector Innovation: the Journey Continues…", OPSI blogpost *www.oecd.org/governance/observatory-public-sector-innovation/blog/page/publicsectorinnovationthejourneycontinues.htm*.

services. Enacting these changes will not be easy. Notable challenges include the need to strengthen the skill sets of public servants to monitor, evaluate and adjust experiments; and, in an era of constrained public spending, to ensure resources and capabilities are available for the public sector to innovate (Daglio, Gerson and Kitchen, 2014).

Recent trends in the codification and opening of government data will provide opportunities to better understand how science and innovation take place and to trace STI policy decisions and impacts. New digital technologies will support new data infrastructures and further open the dissemination, linking and re-use of various types of data. Such infrastructures will affect the practices and organisation of government. They will, for example, offer new evaluation possibilities through better linking of inputs and outputs, and will also offer the prospect of better cross-government co-ordination as well as participation by non-state actors through information and data sharing.

Many countries already implement quantitative and qualitative data infrastructures to support more evidence-based STI policy making. Some of these are initiated as part of broader open government and big data initiatives. Others are more specific to the STI policy domain, such as the various "science of/for science policy"-type projects started over the past five to ten years (see the policy profile "Evaluation and impact assessment of STI Policies"). New commercial and non-profit infrastructures are also increasingly present and may play a pivotal role in future STI data infrastructure developments. The roles of national statistical organisations will likely evolve as the science and innovation data landscape fragments among several government agencies and private repositories.

Realising the potential of new STI data infrastructures faces numerous challenges, however. Among these challenges are the need to develop standards that will allow for the disambiguation and linking of unstructured data.[8] Leveraging the potential of administrative data for science and innovation policy will also require new specific skills and capacities, such as data analytics, among civil servants as well as a culture of data use across the policy cycle. And new approaches will be needed to facilitate the visualisation and understanding of data.

The scientific community will continue to be called upon to provide evidence and advice to government policy-makers across a range of issues, from short-term public health emergencies to longer-term challenges, such as population ageing and climate change. However, science advisory structures will likely undergo some overhaul if, as seems likely, they are increasingly called upon to deal with issues of a global, multidimensional, fast-evolving and complex nature.

The moves towards more responsible research policies will likely open the academic enterprise to closer surveillance and critique (see the policy profile "Building a science and innovation culture"). This may put additional pressure on science to provide clear and unambiguous answers and solutions, though it is perhaps just as likely that it will not, since involved citizens may come to better appreciate the provisional nature of much scientific evidence. Science advice could become more widely debated, and contested in some instances, especially on sensitive topics like genetically modified foods, childhood vaccinations, shale gas drilling and gene editing. As scientific evidence, societal values and beliefs, economic considerations and policy-decisions overlap and diverge, strong tensions may arise (OECD, 2015c).

The international dimension of scientific advice will also be reinforced through new or renewed international structures and greater internationalisation of existing national arrangements. For instance, the role of international advisory bodies will continue to expand to reflect the growing number of transnational issues (e.g. climate change, water-energy-food security, epidemics, etc.) in which science, technology and society are tightly intertwined. In parallel, governments will encourage stronger connections between their scientific advisory structures and international counterparts, with a view to better exchanging data, information, expertise and good practices (OECD, 2015c).

Notes

1. Global gross R&D expenditure (GERD) is estimated by the sum of GERD performed by OECD countries, Argentina, the People's Republic of China, Chinese Taipei, Colombia, Latvia, Lithuania, Malta, Romania, the Russian Federation and Singapore. The estimates made for Argentina, Australia, New Zealand, the Russian Federation, Singapore, South Africa, Switzerland and the United States are in 2014 constant prices. In 2010 constant prices, the world estimate would amount therefore to approximately USD 792 billion PPP in 2000 and USD 1.54 trillion PPP in 2014.
2. Government budget appropriations or outlays for R&D (GBAORD) measure the funds that governments allocate to R&D for various socioeconomic objectives. These are defined according to the primary objective of the funder. In some countries, a medical science component can be identified from non-orientated funds for research, including from general university funds. In these cases, R&D budgets dedicated to health may underestimate total government funding of health-related R&D. Efforts to account for funding of medical sciences via non-oriented research and general university funds could help provide a more complete picture. Such analysis has been intended in the latest OECD STI Scoreboard (OECD, 2015b).
3. According to Sarewitz (2012), "Although the NIH is in some respects a mission agency, its priorities, its work force and the image it has cultivated focus on fundamental science".
4. Other aspects of an open science system include post-publication peer review, open research notebooks, open source software, citizen science and the crowdfunding of research (OECD, 2015a).
5. An API (application programming interface) facilitates the sharing of content and data between applications, so that content that is created in one place can be dynamically posted and updated in multiple locations on the web.

6. OECD survey data collected in 2009 across 16 OECD countries showed that the main sector of employment for doctorate holders working as researchers was often higher education, signalling doctorates' preference to pursue academic careers (Auriol *et al.*, 2013).
7. This expansion is still considerable though, and similar rates of growth in scientific publications have occurred in the other major scientific powers as well. Assuming that the vast majority of scientific publications emanate from public research, this growth outstrips the growth in public research budgets and researchers and reflects changes in publication behaviour that have been evident for at least two decades. This is perhaps best illustrated with the data from the United Kingdom, where public research budgets have barely grown while at the same time the number of scientific publications has risen considerably. A performance culture that values scientific publication largely explains these figures, but there is surely a limit to the number of scientific publications.
8. Unstructured data are by definition not structured, i.e. not organised in a pre-defined manner and along a pre-defined model. They are typically not stored in relational databases and are therefore difficult to search, link or analyse.

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OECD Science, Technology and Innovation Outlook 2016

Chapter 4

Recent trends in national science and innovation policies*

Many governments, across the OECD and beyond, are facing unprecedented economic and societal challenges and consider science and innovation as part of the response. New data from an EC/OECD survey on science and innovation policies shows that governments have particularly focused policy attention and action in recent years on addressing more immediate economic imperatives and building more effective, impactful and responsible policies. Against a background of slow economic growth and tight budgetary conditions, many governments have shifted attention and support away from public research towards business innovation and entrepreneurship, with a view to promoting firms' potential to drive a stronger and more sustainable recovery. Efforts have also been made to reinforce national policy evaluation capacity so as to gain efficiency and to better orient science, technology and innovation (STI) policies towards societal goals.

This chapter presents recent trends in national science and innovation policies across OECD member countries and major emerging economies, including Brazil, China, India, Indonesia, the Russian Federation and South Africa. It considers the economic and financial conditions that determine innovation behaviour and that currently shape the innovation policy agenda. It presents the "hot" STI policy issues in countries as well as the most recent shifts in national policy mixes. This chapter builds on countries' responses to the latest European Commission (EC)/OECD International Survey on Science, Technology and Innovation Policies (STIP) and recent OECD work on science and innovation policies.

* Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".
Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Key messages

- Recent global growth performance has been disappointing. Weak market prospects have dampened business investments, including in innovation activities. There are signs that investment in knowledge-based capital (KBC) and research and development (R&D) is levelling off in many countries, even though this had been comparatively dynamic during and since the crisis. Although business R&D expenditure are back to pre-crisis levels after the sharp 2009 decline, small and medium-sized firms (SMEs) are still facing financial difficulties in most countries.
- Countries have been following different paths in building their innovation capacity as national economic conditions have varied: some countries have been on a slow growth path for over a decade (e.g. Japan, several EU members) while others have experienced stronger economic growth (e.g. Korea, Israel, Australia, United States). Noticeable cross-country differences in investment in innovation have also been growing within Europe, signalling a growing threat to the continent's future economic cohesion. Countries trapped on a low-growth path are likely to fall further behind and the gap with global innovation leaders will likely widen.
- Government investment in R&D and exceptional recovery packages partially offset the drop in business R&D during and after the crisis. But in view of prospective budgetary constraints, as well as recent developments in public R&D budgets, which are likely to continue slowing down or retracting in the coming years, the recovery in R&D cannot be driven by public investment any longer.
- Policy makers are increasingly focused on improving the ability of firms to invest in R&D and innovation, as well as on improving the efficiency of the science, technology and innovation (STI) policy mix. Governments have been particularly active in four STI policy areas during 2014-16:
  1. Financing business innovation and entrepreneurship, especially through a remodelling of the policy mix, and increasing support to SMEs and their internationalisation
  2. Rationalising public research spending, improving ties between public and private research and encouraging interdisciplinary research and open science
  3. Ensuring the future supply of talent and building a culture for innovation
  4. Improving STI policy governance, with strong attention given to policy evaluation and the design of responsible research and innovation (RRI) policies.
- To escape the slow growth trap, governments have sought to restore the terms of domestic competitiveness. Raising the transformative innovative capacity of domestic industry is at the core of national STI plans in many OECD countries and emerging economies.
- Globally, STI policy action has slightly changed focus, form and target in recent years. A growing share of public spending for R&D has been allocated to the business sector, instead of the public research system, signalling a shift in strategic objectives (to increasing business capacity to innovate), instruments and targets (firms).

- Streamlining business innovation policy programmes has become a key issue, aiming to make access to public support easier and encourage its broad diffusion. Many countries have consolidated and merged existing support schemes while the total volume of public support was maintained or even increased.
- Governments have implemented a "no spending" approach by privileging policy tools that do not require additional public spending in the short term, particularly public procurement and tax incentives for R&D and innovation.
- Public procurement has become a major feature of innovation agendas and initiatives to spur business innovation through public procurement have multiplied, making this STI policy area one of the most active over the period. Further reforms are likely as a growing number of countries expect demand-side instruments to become more prominent in the future.
- Much policy attention remains focused on the articulation of direct and indirect support to business innovation, essentially through competitive grants and R&D tax incentives, both instruments being of high relevance in the policy mix overall. But the perceived relevance of R&D tax incentives is related to the fiscal cost they generate and their use remains extremely uneven across countries.
- R&D tax schemes have gone through more substantial changes during 2014-16 than in the previous period. As in the past, special features have been introduced to make schemes more generous and better adapted to SMEs and young firms. One more recent trend has been the growing policy intention to aim them more at supporting technology transfer.
- Many countries have refurbished their policy portfolio to assist SMEs and start-ups in accessing global markets. And the internationalisation of clusters, another key channel for SMEs to connect to global knowledge networks, has received greater policy attention.
- Some countries are reviewing their public research policy to improve its efficiency. While there is a global trend towards more competitive funding and contractual arrangements, a small number of countries, particularly in northern Europe, have reversed the trend and increased block funding.
- The sources of public research funding have also changed as a result of greater involvement by industry. Public-private partnerships (PPPs) offer opportunities for sharing risks, resources and orientation. Philanthropic and private science foundations, although still small, are playing an increasingly important role in complementing public funding as well.
- Many countries have readjusted their strategic priority research areas with a view to tackling societal challenges. In addition to lower cross-disciplinary barriers, some countries have reformed the governance of public research and restructured research agencies and actors.
- Efforts towards open science have focused on creating enabling legal frameworks and providing policy guidance for open access and open data. The number of countries with mandatory open access provisions is increasing. Half more countries are engaged in upgrading their infrastructures, or revising their legislation and research funding mechanisms, to encourage open access and open data in 2014-16 than during the previous 2012-14 period.
- Education policy has evolved to reflect the wider range of skills required to innovate. This includes increased budgets to boost science, technology, engineering and mathematics (STEM) education, initiatives to make STEM more attractive to young people, or revised

curricula to develop generic skills, problem-solving capacity and entrepreneurial behaviour.

- Many countries have sought to build "cultures" of science and innovation that will help reinforce public participation in and support for science and entrepreneurship. For instance, there have been efforts to build capacity for the popularisation of science, and to foster an entrepreneurial spirit and increase creativity in the work place.
- Recent trends in policy evaluation include the more intensive use of administrative data and online technology for collecting data ("big data"), smaller and more rapid evaluation exercises and a growing complexity in the concepts and practices employed. In response to the rising risks of misallocation of public resources or negative interactions between instruments, systemic evaluations have spread globally.
- Overall, general efforts have been directed towards building a more evidence-based knowledge base, through the systematisation of evaluation, a whole-of-government approach to evaluation, more harmonised practices and new data infrastructures and expert communities.
- While much STI policy attention is currently focused on the economic slowdown, the ethical and societal dimensions of research have come to the fore and are increasingly reflected in the framing of more "responsible research and innovation" (RRI) policies.
- Governments have paid attention to fostering a comprehensive approach to governance by enhancing co-ordination arrangements across the board and involving industry and society upstream in the policy debate. RRI principles have been integrated into the formulation of innovation policy agendas, mainstreamed in existing funding programmes or have targeted the agencies and institutions in charge of policy delivery (e.g. funding agencies).

Introduction: the legacy of recent years

This chapter presents recent global trends in STI policies.

OECD countries are facing unprecedented challenges. These include growing income inequalities in a context of slow global economic growth, ageing populations, climate change, the depletion of natural resources and other environmental issues, the further fragmentation of global value chains (GVCs), and shifting lifestyle and societal expectations, to name but a few. STI has the potential to trigger a new production revolution and boost productivity, to mitigate climate change and decouple growth and environmental degradation, and to help tackle a broad range of societal challenges and build a more equitable and cohesive society (see Chapters 1 and 2). Acknowledging this potential, governments in the OECD and beyond have strengthened their national STI capacities and moved innovation higher up on the policy agenda (OECD, 2014a).

The way that governments have responded to the recent 2008-09 financial crisis confirms the high status of innovation in national policy agendas (OECD, 2012). Recovery plans in many countries have contained an important dimension of research and innovation (OECD, 2009). Substantial public investment has been dedicated to upgrading STI infrastructures, while public research expenditure played a buffering role in the turmoil by partially offsetting the drop in business spending on R&D. Many governments also strengthened the "green" component in their policy schemes (OECD, 2010). However, in many countries, post-crisis budgetary austerity was already in place by 2013-14, cutting public R&D

budgets and often eroding governments' capacity to act in the field. At the same time, governments have also substantially revised financial support for business innovation and entrepreneurship over the past decade, partly aiming to address the drop in conventional sources of corporate SMEs funding.

This chapter considers a number of issues, including: the recent economic and financial conditions that determine innovation behaviours and that shape innovation policy agendas. It discusses the conditions of public intervention in this STI policy field and presents the "hot" STI policy issues in capitals as well as the most recent shifts in national policy mixes. Recent policy initiatives have been aimed at addressing more immediate economic imperatives, for example by boosting firms' potential to innovate and by achieving more impactful policies; the reorientation of public research systems, for instance towards greater openness; and, attempts to improve STI policy governance, for example through the design of more responsible and ethical STI policies.

The chapter is based on countries' responses to the joint European Commission (EC)/ OECD International Survey of Science, Technology and Innovation Policies (STIP) (Box 4.1). This survey investigates current STI policy challenges, orientations and actions in all OECD member countries as well as in certain non-member economies. More detailed analysis of the survey results is provided in the online *STI Outlook 2016* policy profiles and country profiles.

Box 4.1. **EC/OECD International Science, Technology and Innovation Policy (STIP) Survey**

Starting in 2015, the OECD and the European Commission have joined forces to produce a common survey and database of national STI policies. The survey and the database are unique in their nature, scope and coverage. The survey aims to review on a biennial basis major changes in national STI policy portfolios and governance arrangements. It builds on conceptual work carried out under the aegis of the OECD Committee for Scientific and Technological Policy (CSTP) for mapping the policy mix on innovation (Kergroach et al., forthcoming-a). The survey expands on the former OECD STI Outlook Policy Questionnaire and includes questions relevant to the European Union's research and innovation policy agenda. The scope of the survey covers all areas of STI policy, including initiatives spread across different ministries and national agencies, with competence over domains as broad as research, innovation, education, industry, environment, labour, finance/budget, and others. The responses are provided by government representatives. The CSTP and the European Research and Innovation Committee (ERAC) jointly guarantee the relevance of national input. The responses are harmonised and then incorporated in the STIP Database.

This EC/OECD co-operation brings the survey's coverage to 54 countries, including 35 OECD member countries, key emerging economies (i.e. Argentina, Brazil, the People's Republic of China, Colombia, Costa Rica, Egypt, India, Indonesia, Lithuania, Malaysia, Peru, the Russian Federation, South Africa and Thailand), non-OECD EU member states (i.e. Bulgaria, Croatia, Cyprus, Malta and Romania), plus the European Commission. Taken together, the countries covered in the STIP survey and database account for an estimated 98% of global R&D.

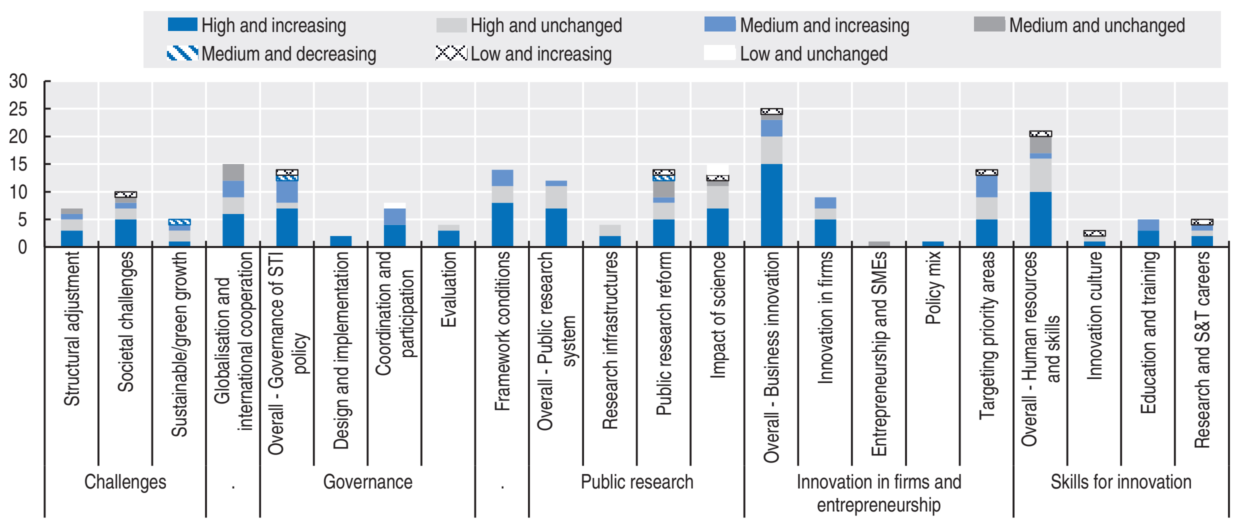
The 2016 STIP Survey took place between the end of October 2015 and early March 2016. 52 responses were submitted over this period of time, i.e. a 95% response rate. The responses were collected through an Excel-based enhanced questionnaire specifically designed for this purpose.

4.1. Overview of the STIP survey results

Country responses to the 2016 EC/OECD International STIP Survey show a high and often growing interest of many governments in strengthening the foundations of the knowledge triangle, i.e. public research, business innovation and entrepreneurship, and skills (Figure 4.1). The most topical STI policy issue ("hot" issue) in 2016 is the role governments could play in encouraging business innovation and entrepreneurship, the topic having become of high and increasing importance in a large number of countries.

Figure 4.1. **Overall STI policy attention is focused on business innovation, research and skills**

Priority areas by degree of importance, total of 52 responses to the 2016 STIP survey



Note: STI policy priorities are defined by a country's self-assessment of the following questions: "1) What are the current major STI policy priorities in your country? Please select three (maximum five) STI policy priorities in the drop-down lists below and rate the degree of importance of each issue. 2) How has the relative importance of these policy priorities evolved in the past five years? Are they of increasing or decreasing importance? Please rate how this importance may have changed in the past five years." The indices of policy priority are calculated on the basis of country ratings. Responses are provided by country delegates to the OECD Committee for Scientific and Technological Policy (CSTP) and the European Research and Innovation Committee (ERAC).

Source: Based on EC/OECD (forthcoming and 2014), *International Database on STI Policies (STIP)*, *www.innovationpolicyplatform.org/sti-policy-database*.

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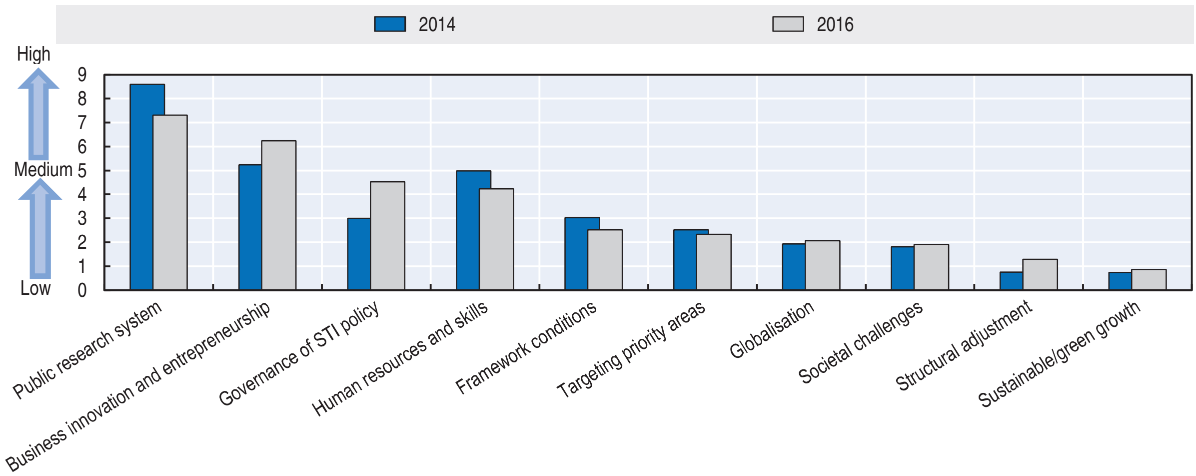
A comparison of 2014 and 2016 responses signals a growing concern among policy makers about improving the ability of firms to innovate and STI policy governance (Figure 4.2). Aggregated responses from the countries for which data were available at these two dates show a slight shift in policy priorities across main policy areas, with business innovation and entrepreneurship, STI policy governance and to a lesser extent structural adjustment gaining in relative importance compared to other policy issues.

Globally, STI policy action has also slightly changed focus, form and target in recent years (Figure 4.3).[1] The STI policy portfolio, i.e. the set number of active STI policy initiatives, has changed in all countries, although some countries have undertaken a deeper overhaul in their policy mix than others. This seems to have been the case in Australia, the Netherlands, New Zealand, Spain or Turkey where new agendas and programmes have been implemented since 2014 and previous initiatives have sometimes been extensively repealed (see also the country profiles).

Changes have also been more substantial in some policy areas than others (Figure 4.3). Policy areas in which governments have been particular active during 2014-16 include:

Figure 4.2. **STI policy focus has shifted towards more immediate economic imperatives and policy efficiency gains**

Index of policy priority by main area, average of the 44 countries participating in the 2014 and 2016 STIP surveys



Note: Comparisons between 2014 and 2016 have been made only for countries that participated in both surveys. 52 countries plus the European Commission (out of the 54 invited to do so) participated in the STIP survey in 2016. The chart thus excludes countries that did not provide ratings in 2014 (Brazil and Egypt) or in 2016 (Denmark and India), and new participants in 2016 (Croatia, Cyprus and Thailand). The index of policy priority is a simple average of country ratings. The values for countries that do not report the field as a priority are null (Kergroach, forthcoming-b).

Source: Based on EC/OECD (forthcoming and 2014), *International Database on STI Policies (STIP)*, *www.innovationpolicyplatform.org/sti-policy-database*.

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1) financing of business innovation and entrepreneurship, especially a remodelling of the policy mix and increased support to SMEs and their internationalisation; 2) public research policy, especially rationalising of public spending and reforms to encourage interdisciplinary research and open science (open science related issues are developed in Chapter 3); 3) skills policy to ensure future supply of talents and to build a culture for innovation; and 4) improved STI policy governance, with a focal attention given to policy evaluation and the design of responsible research and innovation (RRI) policies.

The following sections will provide some contextual information on how the drivers of growth and innovation have weakened since the early 2010s and they will consider the four most active STI policy areas since 2014, as mentioned above, based on policy information drawn from the STIP survey.

4.2. The drivers of growth and innovation have weakened

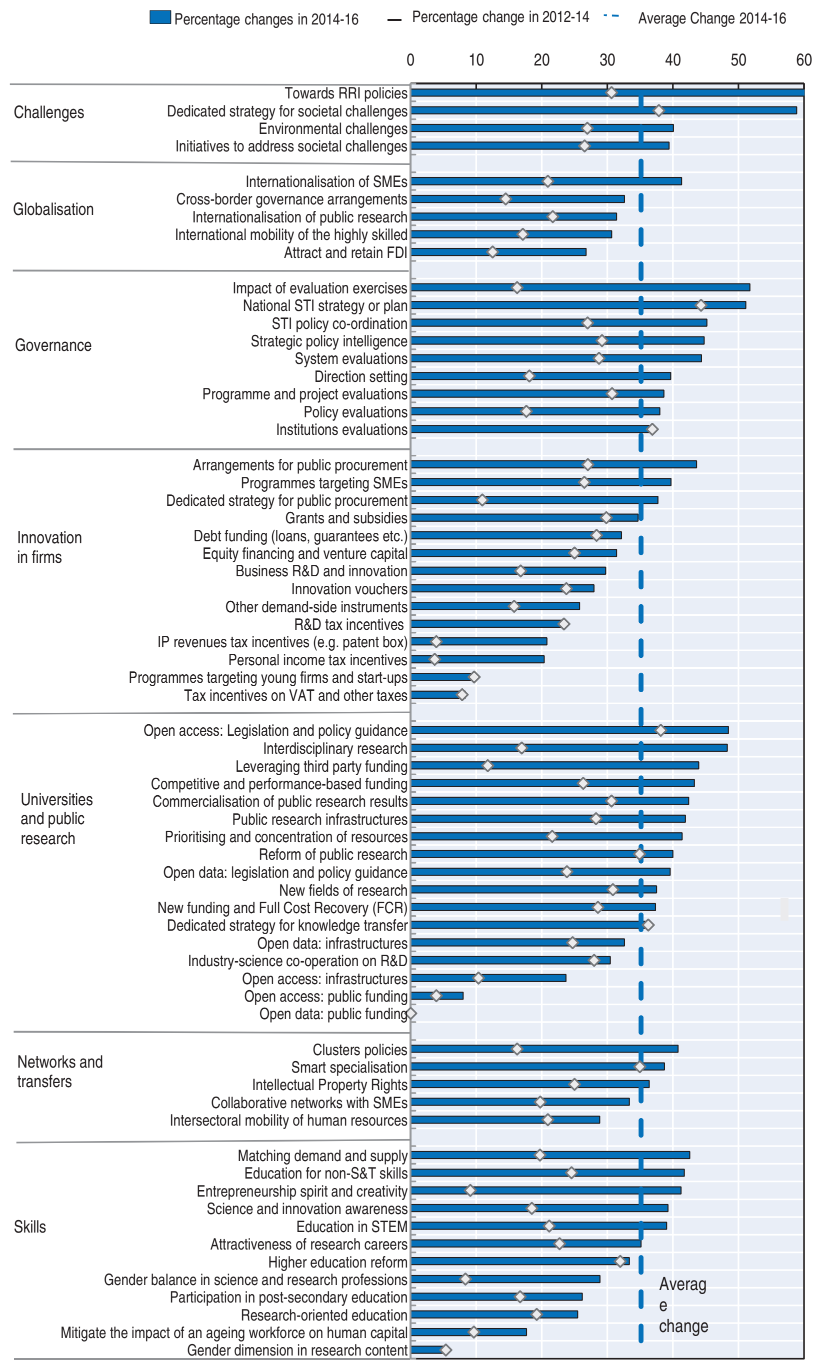
Recent growth performance has been disappointing

Some eight years after the start of the financial crisis, economic growth remains modest in much of the world. Global GDP growth in 2016 (+3.0%) has stabilised at around the 2015 rate, the lowest rate in the past five years (OECD, 2016a).[2] GDP growth rates are well below long-run averages and much lower than would be expected during a recovery phase. And growth forecasts have recently been revised down in light of disappointing recent data.

A rise in global risk aversion led to a sharp retrenchment in global capital and trade flows (IMF, 2016; OECD, 2016a) (Figure 4.4). And the global trade rebound that followed the downturn did not last long. As from 2011, growth in the exports of products and services slowed significantly. Weaker international growth and a slowdown in domestic demand

Figure 4.3. **STI policy action has slightly changed focus, form and target in recent years**

Changes in the policy mix for innovation by policy area, % of policy measures newly introduced, substantially revised or repealed over the period 2014-16



Note: This is an experimental indicator that accounts for the number of major policy initiatives implemented, repealed or substantially revised during 2014-16 as a share of total policy initiatives active at the beginning of the period (Kergroach et al., forthcoming-b). Although simple counts do not account for the magnitude and impact of policy changes, this ratio reflects STI policy focus and activity in specific policy areas and over specific periods of time.

Sources: Based on EC/OECD (forthcoming and 2014), *International Database on STI Policies (STIP);* and Kergroach et al. (forthcoming-b), "Mapping the policy mix for innovation: the OECD STI Outlook and the EC/OECD International STIP Database", *OECD Directorate for Science, Technology and Innovation Working Paper*.

StatLink http://dx.doi.org/10.1787/888933433549

have weighed on Chinese production, pulling exports down and hitting emerging markets through commodity trade. The contraction of imports in China and other major emerging economies has also lowered export demand for the advanced economies.

Figure 4.4. **Synopsis of current economic conditions and impact on innovation capacity, selected countries**

Annual growth rates and projections (%), 2000-17

Notes: Exports include products and services. Investments comprise gross fixed capital formation in intellectual property products (including computer software and databases and research and development) and machinery, equipment and weapons systems (including Information and Communications Technology [ICT] investments on computer hardware and telecommunications equipment). Labour productivity is measured as GDP per hour worked. Public R&D budgets comprise government budget appropriations and outlays for R&D. Growth rates are calculated based on values at constant prices.

Sources: Based on OECD (2016a), *OECD Economic Outlook*, June; OECD(2016b), *National Accounts Database*, June; OECD (2016c), *Productivity Database*, July; OECD (2016d), *R&D Statistics Database (RDS)*, April. Data extracted from OECD.Stat on 20-21 July 2016.

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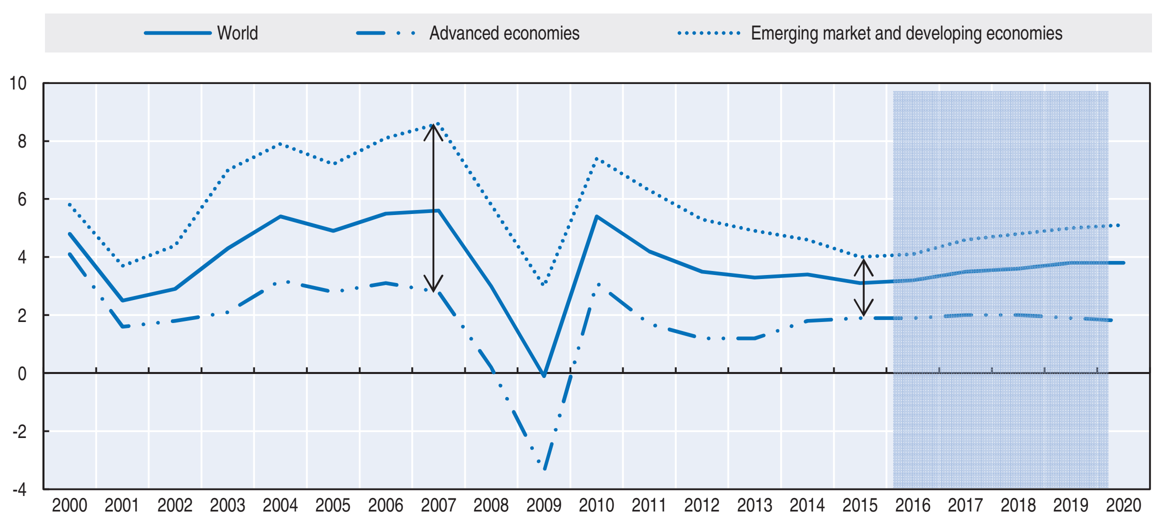
The above developments have all contributed to the lacklustre recovery in the advanced economies. In the United States, the recovery has been led by the private sector and continues to have momentum, but impetus from domestic demand and employment gains are expected to fade as the labour market approaches full employment. In Japan, economic growth and the general outlook remain fragile due to weaker activity in the country's key trading partners, weak private consumption and the further tightening of policies aimed at stabilising the debt-to-GDP ratio.

In the euro area, GDP growth is expected to pick up only slowly, with investment remaining weak and unemployment high. The euro area remains stuck on a low-growth path and is struggling to build confidence to attract investment that could help promote innovation, productivity and employment. The European Union is also facing major political challenges (including refugee crisis, external security threats, unpopular austerity measures, anti-European movements, and the implications of the recent United Kingdom decision to exit the Union). These challenges jeopardise cohesion and may further dampen investment (ESPAS, 2015). The slow European recovery is an important factor dragging on the global recovery and leaves the zone vulnerable to global shocks.

Growth has slowed in the catching-up emerging economies, following the pattern of recent years (Figure 4.4). The structural shift towards services in China, together with overcapacity in Chinese industry, will continue to affect that country's growth outlook (Figure 4.5). The recession in Brazil is likely to deepen, with the country plagued by political uncertainty and rising inflation. The contraction in Russia may have bottomed out, but recovery is still tied to fluctuating oil prices. The growth outlook is more robust in India, although recent flooding threatens progress. The deterioration of growth prospects has led to falling equity prices and greater market volatility, worsening some emerging markets' vulnerability to exchange rate movements and high domestic debt.

Figure 4.5. **Shrinking growth gaps between advanced and emerging economies**

GDP growth, annual rates and projections (%), 2000-20



Source: IMF (2016), *World Economic Outlook*, April.

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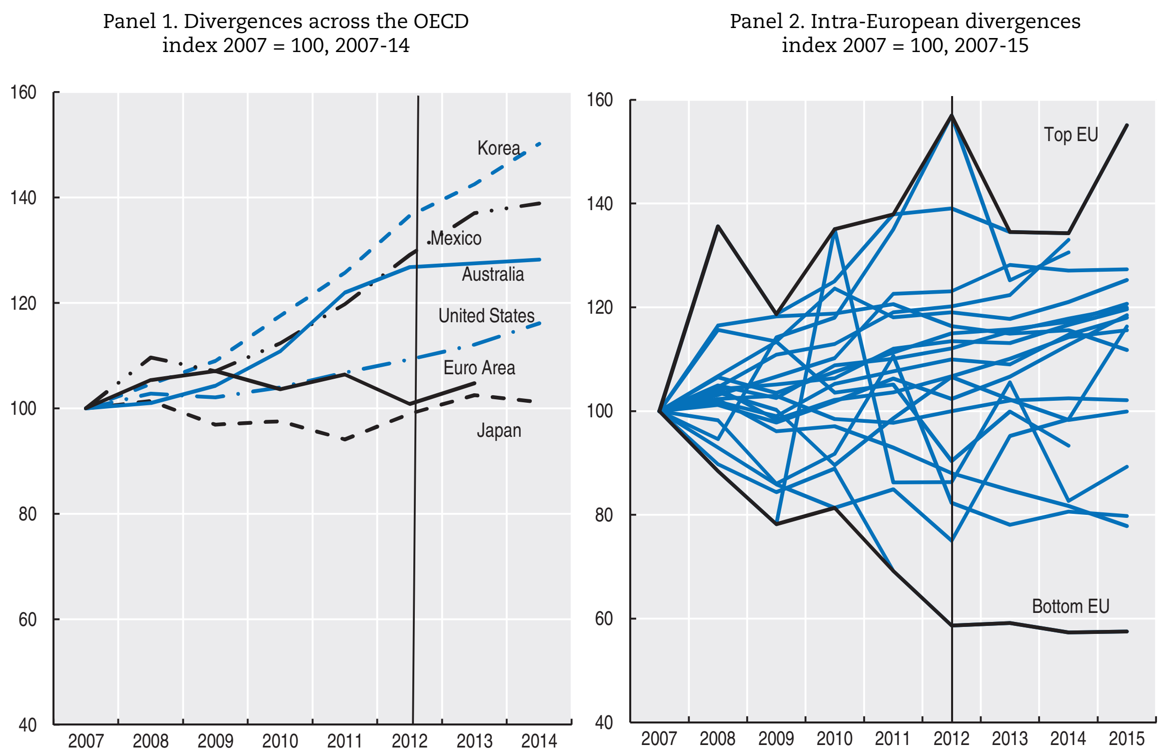
Investment in intangible assets seems to be slowing

Despite difficult funding conditions and adverse market prospects, economic actors have ring-fenced their investments in intellectual property products (e.g. computer software and databases, and R&D) as compared to other types of physical investments, including in ICT (Figure 4.4). While investments in machinery and equipment have fallen sharply, investments in intangible assets[5] have weathered the crisis better and recovered earlier (OECD, 2014a). For example, R&D spending in the OECD had risen to pre-2007 levels by 2012.

However, there are signs that investment in knowledge-based capital (KBC) is levelling off in many countries, especially since 2012 (Figure 4.6). National accounts data, which have recently included R&D in gross fixed capital formation, indicate that such investment has been slowing in Australia, Israel, Japan and many European countries, even though these areas had experienced strong growth in their intellectual assets portfolio over recent years (Figure 4.4 and 4.5). Likewise, recent OECD calculations based on data from the INTAN-Invest network show a continuous downward trend in spending on organisational capital of firms and in firm-specific training in the European Union and the United States since 2007 (OECD, 2015a).

Figure 4.6. **Cross-country investments in intellectual assets**

Gross fixed capital formation, intellectual property products, index 2007 = 100, 2007-14/2007-15



Source: Based on the OECD (2016), *OECD National Accounts Database*, July. Data extracted from OECD.Stat on 20 July 2016.

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The picture nevertheless differs greatly across economies. Several countries, including Estonia, Korea, the United Kingdom and the United States, continue to increase their investment in KBC portfolios. Consequently, cross-country divergences in innovation capacity are growing (Figure 4.6). Previous editions of the *STI Outlook* noted that the uneven economic recovery was expected to widen the gap between countries experiencing flat or low growth (and which may have difficulty maintaining R&D expenditure) and countries experiencing higher growth (and thus good conditions for expanding national R&D) (OECD, 2014a). The same National accounts data show that intangible assets investments have been very dynamic during the crisis, including in recent years, in Korea, Israel and Australia (Figure 4.6). Such investments have also recovered markedly in the United States since 2010, but have grown only slowly in Japan and the euro area. Noticeable cross-country differences in investment profiles exist even within Europe, signalling a growing threat to the continent's future economic cohesion.

Innovation results from an accumulation process, i.e. accumulation of knowledge, capital and technology. If economic conditions remain weak, as the expected slowdown of global growth foreshadows (see Chapter 1), countries trapped on a low-growth path could struggle to maintain their innovation investments and capacity. In the medium-term, the gap between the global innovation leaders and the many others is likely to further enlarge.

Productivity growth is low and public budgets are under pressure

The decline in business dynamics combined with a general slowdown in KBC accumulation has amplified a slowdown in productivity growth (Figure 4.4) (OECD, 2015b). This slowdown started in many OECD countries before the financial crisis, due partly to the structural shift towards services and to a slowdown in investment which began in the 2000s. Productivity is the driving factor of economic growth in the medium- and long-term, and the slowdown in productivity has been the main driver of the lacklustre growth performance over the past decade.

Weak economic conditions have also reduced tax revenues and public budgets, including for STI. Increased government support for national R&D efforts has partially offset the drop in business R&D during and after the crisis (OECD, 2014a). But, in view of the budgetary outlook and developments in public R&D budgets generally, the recovery in R&D cannot be driven by public investment. Indeed, OECD government budget appropriations and outlays for R&D (GBAORD) have tended to fall in 2014-16 (Figure 4.2), receding or levelling off in almost all OECD countries and the major emerging economies and following immediate post-crisis trends (OECD, 2014a, 2016e).

A low-growth equilibrium, characterised by low demand, low investment, low inflation, low wage growth and weak productivity growth, is hampering further improvements in living standards, income redistribution and the consolidation of public budgets. To address this situation, a recovery in private sector investment and wage growth is needed (OECD, 2016f forthcoming), with innovation playing an important part to reactivate business dynamics and productivity growth.

4.3. Escaping the slow growth trap and strengthening economic growth

Restoring the terms of competitiveness

National innovation strategies are increasingly integrated into countries' competiveness agendas and raising the transformative capabilities of domestic firms is at the core of national STI plans. Some major initiatives have recently been implemented by some of the large innovation players and at EU level (see also the policy profile "National strategies for science, technology and innovation").

- Australia has adopted its National Industry Investment and Competitiveness Agenda (IICA) in 2014 and established a ministerial taskforce to promote productivity through innovation and R&D. As part of this new agenda, the government has made industrial policy and the translation of publicly funded research into commercial outcomes key pillars of its approach to strengthening economic dynamism. The release of the National Innovation and Science Agenda (NISA) in 2015 further builds on the IICA. The NISA aims to boost Australia's science and innovation in the four key areas of capital and culture, collaboration, talent and skills, and government as an exemplar.
- Germany's High-Tech Strategy has been revised in 2014 with a view to better integrating market perspectives on specific technology areas and the need to address societal challenges. The 2014 revision places an emphasis on innovative small and medium-sized enterprises (SMEs).

- In Japan, the 5th S&T Basic Plan (2016-20) provides the medium- to long-term orientation of national STI policy and addresses *inter alia* the policy challenges of increasing the competitiveness of manufacturing.
- Korea released its Action Plan for implementing its 3rd S&T Plan in 2015. USD 21 billion (KRW 19 trillion) have been earmarked for national R&D investment and, among other objectives, to develop strategic technologies and create new industries.
- The new UK Productivity Plan aims to provide the necessary environment and infrastructure to facilitate innovative processes in the research and business-to-business sectors. As part of it, the Competition Plan sets out a number of policies to improve the business environment and ensure wider competition.
- The United States updated its Strategy for American Innovation in 2015 to serve as a guiding reference for investing in the building blocks of US innovation and promote competitive markets and productive entrepreneurship.
- A 2014 Communication at the EU level provides an assessment of how the innovation economy promotes competitiveness and provides an evidence base for identifying priority investments and making research and innovation new sources of growth.

The potential of research and innovation to contribute to economic performance and productivity has also been further emphasised in key emerging economies. The 13th Five-Year Plan (2016-20) aims to strengthen China's science and technology (S&T) competitiveness and international influence and develop breakthroughs in core and critical technology areas in order to support economic restructuring and industrial upgrading. Brazil's new National STI Strategy (ENCTI) (2016-19) intends to address its technological gap and targets a few promising industries (renewables, subsea oil, space, ICT etc.). The Russian Federation announced in 2015 its National Technology Initiative, a new long-term model to achieve technological leadership, through novel technology-based markets (for instance non-piloted drones for the industrial and services sectors, neurotechnological products, network-based solutions for customised food delivery). Mexico's Special Programme for STI (PECiTI) (2014-18), Peru's National Plan for Production Diversification (PNDP) (2014 onwards), Thailand's Ten-Year STI Plan or Turkey's Tenth Five-Year Development Plan (2014-18) are similar initiatives aimed to raise national competitiveness through R&D and innovation.

Boosting firms' potential to innovate

Financing conditions for innovation remain weak, especially for SMEs. Finance for entrepreneurship was affected heavily by the crisis (OECD, 2012; 2014a; 2015c). Small firms are still struggling to restore their profit margins, which remain their main source of financing (Figure 4.11, Panel 1). External sources of funding, such as bank credit, venture capital and business angels investment, have become more accessible, but at a slow rate and unevenly across countries.

The situation of large firms is different. First, large businesses depend less on bank loans for investment in innovation, notably multinational companies. They have therefore been less sensitive to banks' restrictive policies in past years. Second, their profitability also recovered rapidly after the crisis and some firms have large cash reserves that are not being invested. Uncertainty on the demand side and risk aversion on the supply side contribute to relatively poor business prospects and low investments, and limit the potential for an upswing in innovation activities.

Although most business-performed R&D is still financed by industry (on average 86.5% for OECD countries in 2013; OECD, 2016f), public funding support has increased significantly over the past decade, both in absolute and relative terms (Figure 4.7) (OECD, 2014a; 2015a). In Canada, Chile, France and Hungary, more than a quarter of business R&D is funded through combined direct and indirect financial support and the public contribution peaks at 62% in the Russian Federation (Figure 4.7, Panel 1). The share of business expenditure on R&D (BERD) publicly funded has increased markedly in Belgium, Ireland, Iceland, France and Canada over the period. The intensity of public support has also increased as a percentage of GDP in almost all countries since 2006 and the increase has been particularly marked in Slovenia, Belgium, France and Ireland (Figure 4.7, Panel 2) (see also the policy profile "Government financing of business R&D and innovation").

A growing share of the government budget for R&D has been allocated to the business sector, instead of public research, signalling a policy shift in strategic objectives (increasing firms' capacity to innovate), instruments and target (firms).[3] The policy shift has been driven by increasingly generous R&D tax arrangements (Figure 4.8). Between 2006 and 2013, the amount of tax revenues foregone for R&D has increased in most countries for which data are available. In these countries the share of government funds going to business R&D has also increased faster than the share going to public research.

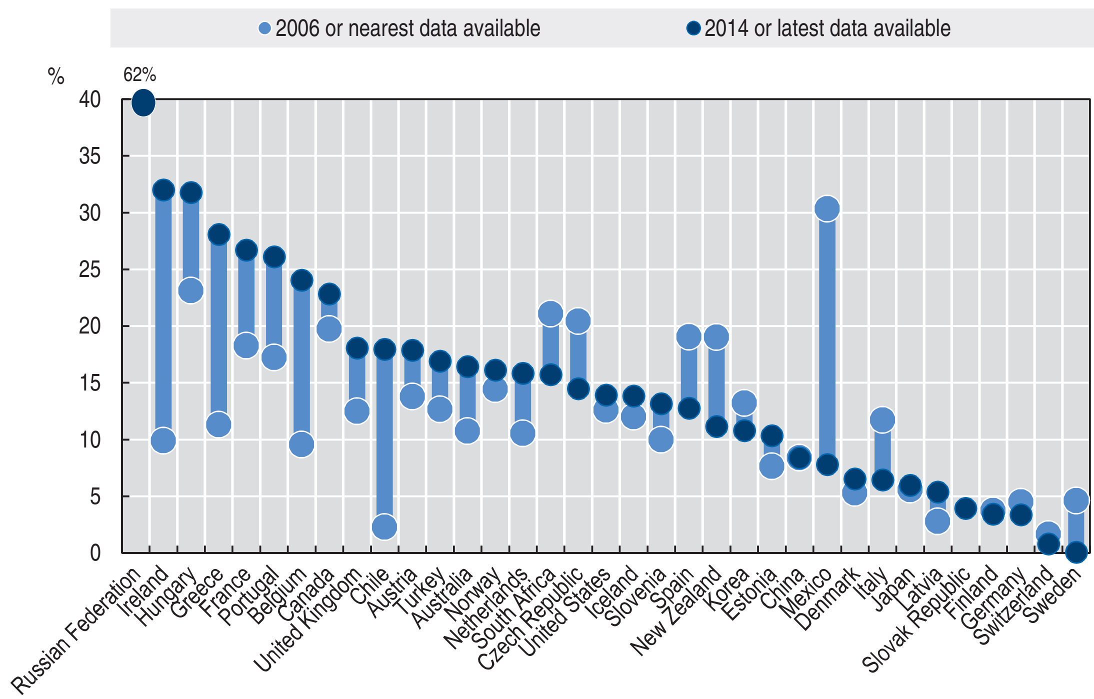
Still, direct funding through grants, debt financing and public procurement remains the main channel of public support for business R&D in many countries. Grants, equity financing and debt financing instruments (e.g. loans, guarantees and risk-sharing mechanisms) are the most frequently used policy instruments in the 52 countries that participated in the 2016 STIP Survey (Figure 4.9). They are also, together with tax incentives and technology consulting, of growing relevance in the policy mix in many countries. Yet, much policy attention remains focused on the use of competitive grants and tax incentives for R&D, both instruments being considered the most relevant in the policy mix in a majority of countries.

Yet, the mix and relative balance between STI funding instruments vary significantly across countries and although there are some converging trends in STI policy globally (see Chapter 1 on "Megatrends affecting science, technology and innovation"), there are also well-established national archetypes of business innovation policy. For example, Belgium, Canada, France and the Netherlands have adopted a strong indirect funding approach towards business support, in using R&D tax incentives. But Estonia, Finland, Germany, Mexico, Switzerland and Sweden provide only direct support. China stands as an exception with its large equity funding portfolio (see also the policy profile "Government financing of business R&D and innovation").

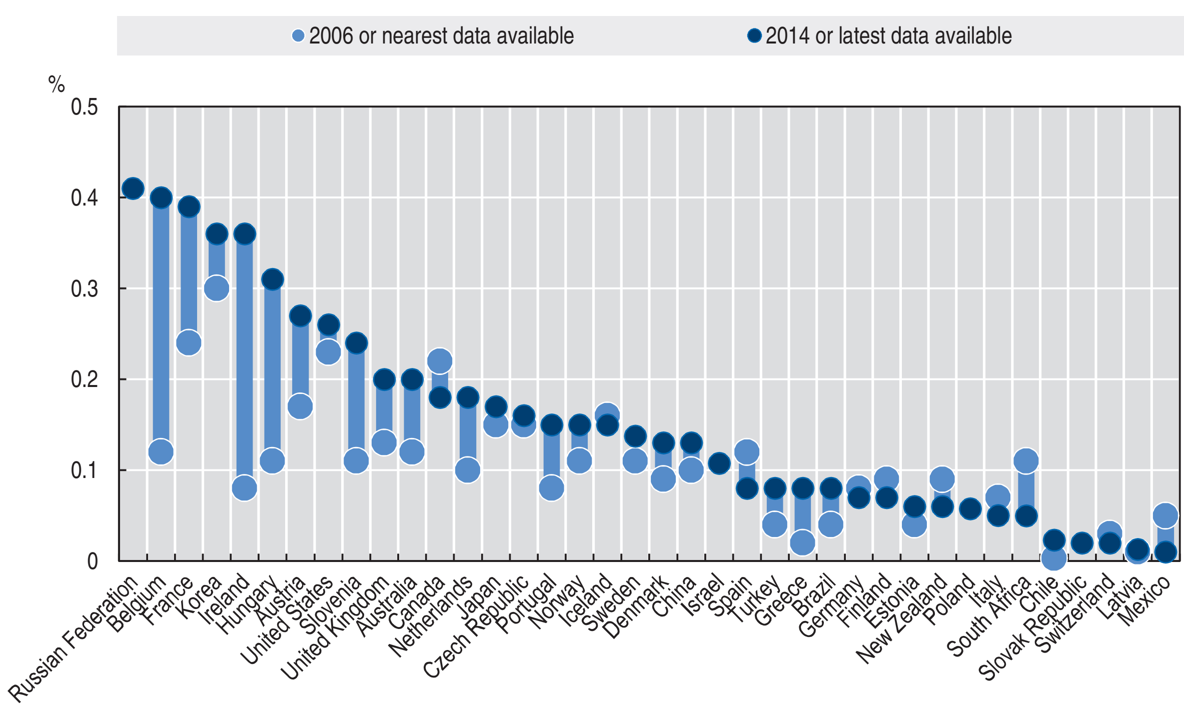
Recent developments in direct funding rely more on market-friendly approaches, encouraging competition-based selection and streamlining public support schemes (OECD, 2012; 2014a). Streamlining science and innovation policy has become a key issue in many OECD countries and non-OECD economies due to the growing complexity of innovation policy and the budgetary austerity that currently weigh on national public accounts. Streamlining policy programmes also contributes to making access to public support easier and encouraging their broad diffusion. In 2014-16, this trend towards a simplification of policy delivery continued and many countries, including those previously engaged in streamlining their portfolio, have consolidated and merged existing support schemes. Yet, only few saw a negative impact on the total volume of public financial support allocated (Figure 4.10). On the contrary, for several countries, including Belgium, Sweden, Turkey and emerging economies (Brazil, Colombia, Costa Rica and Indonesia), these revisions in the

Figure 4.7. **Public support to business R&D has increased significantly over recent years**

Panel 1. Combined direct and indirect financial support, as a percentage of BERD, 2006 and 2014



Panel 2. Combined direct and indirect financial support, as a percentage of GDP, 2006 and 2014



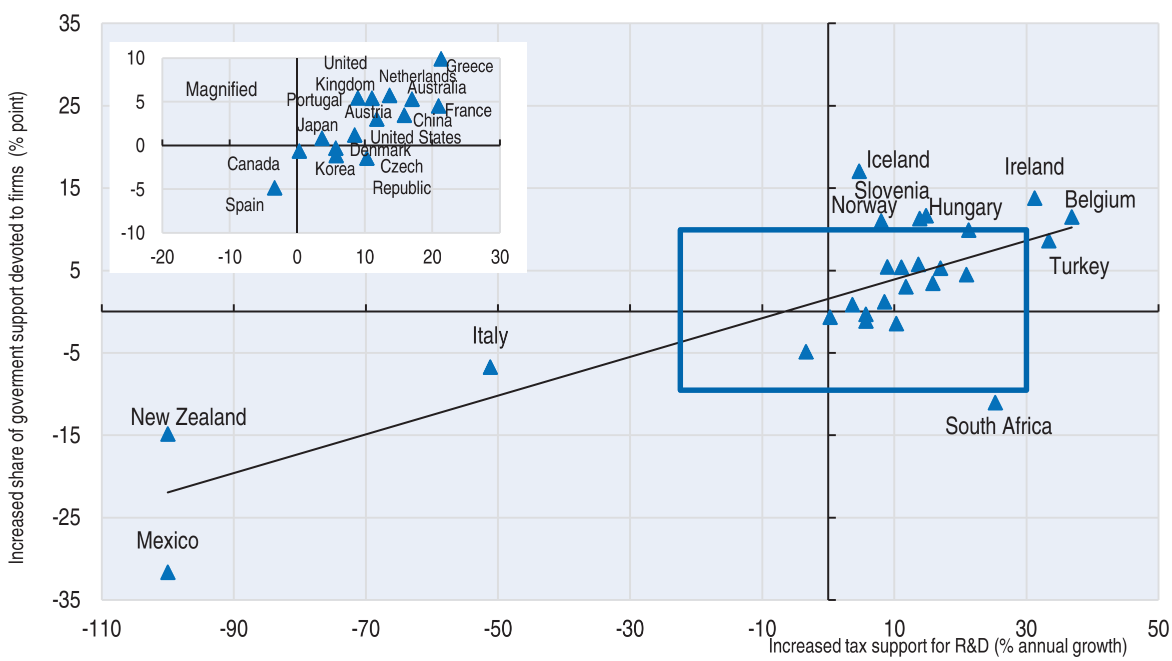
Sources: Based on OECD (2016f), *OECD Research and Development Statistics (RDS) Database*, April, *www.oecd.org/sti/rds*; and OECD (2016g), *OECD-NESTI data collection on R&D tax incentives*, July, *www.oecd.org/sti/rd-tax-stats.htm*. Data retrieved from IPP.Stat on 8 August 2016.

StatLink http://dx.doi.org/10.1787/888933433581

policy mix have come with further increases in public support. Finland stands as an exception as the only country reporting a cut in the total number of schemes in place and the total amount of public support provided.

Figure 4.8. **More public support has gone to firms through more generous R&D tax incentives**

Percentage change in the relative share of public support granted to firms (y-axis) and annual growth of R&D tax cost estimates (x-axis), 2006-14 or nearest years available



Note: Countries for which two data points were not available for a comparison in time are not represented in the chart.

Sources: Based on OECD (2016f), *OECD Research and Development Statistics (RDS) Database*, January 2015, *www.oecd.org/sti/rds*; EC/OECD (forthcoming), *International Database on Science, Technology and Innovation Policies (STIP)*, 2016 edition, *www.innovationpolicyplatform.org/sti-policy-database*; and OECD (2016g), *OECD-NESTI data collection on R&D tax incentives*, July, *www.oecd.org/sti/rd-tax-stats.htm*. Data retrieved from IPP.Stat on 11 September 2016.

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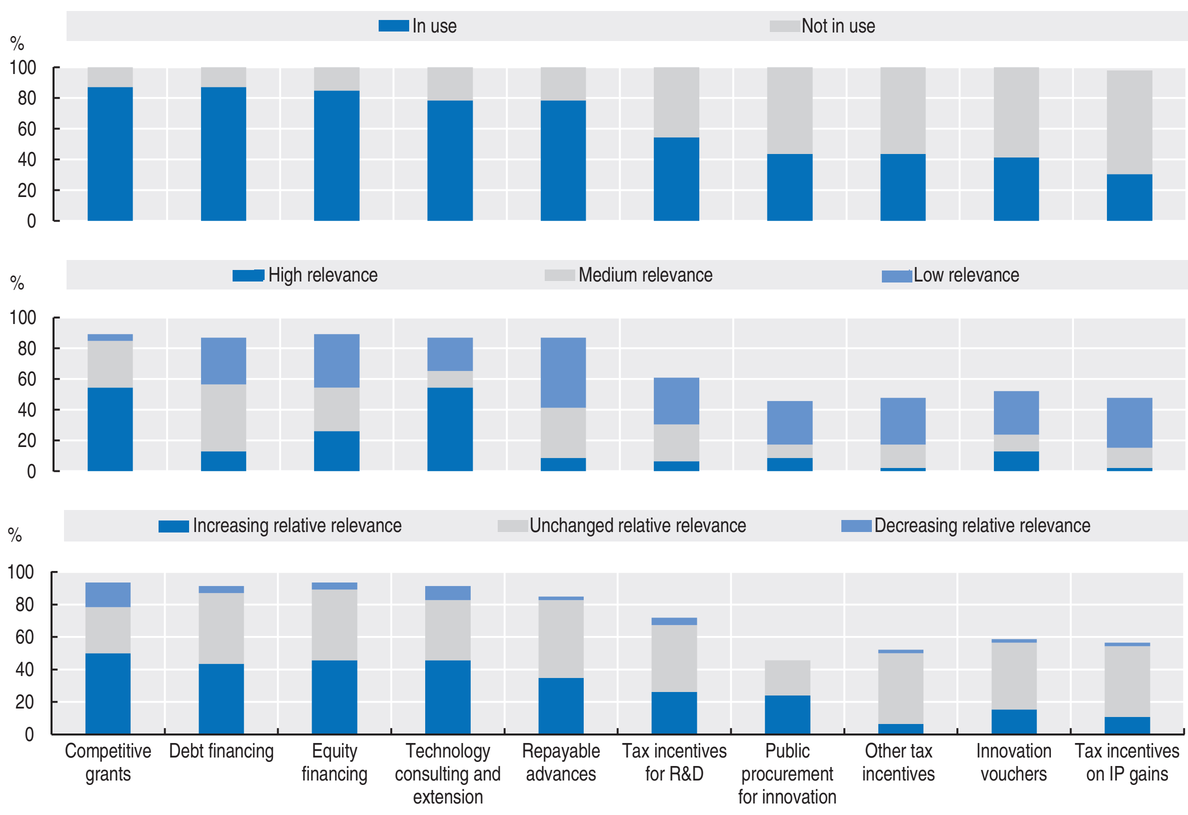
In the aftermath of the crisis, countries have increasingly emphasised debt and equity financing in their policy mix for innovation and entrepreneurship in order to compensate for limited private funding (OECD, 2014a).

Credit conditions have been easing slowly recently, as banks have achieved required levels of deleveraging, and the overall perceived availability of bank loans improved (ECB, 2016; OECD, 2016h). Nevertheless, many countries are struggling to replenish their credit offer to SMEs and the stock of outstanding SME business loans held by banks is still shrinking in many countries, including Canada, the United States and several European countries (Figure 4.11, Panel 2). Governments have extensively used loan guarantees and risk-sharing mechanisms to give SMEs easier access to funding (OECD, 2014a; 2016h). And further recent efforts have been made in this direction between 2014 and 2016 in Austria, Latvia, Poland and the United Kingdom.

The financial crisis widened the investment gap, particularly at the seed and early stages of business development when firms lack collateral to access bank funding. Equity investments fell sharply during the downturn, and have been slow to recover since (OECD, 2012; 2014a). In 2014, venture capital (VC) investments were back to their pre-crisis levels only in Hungary, Korea, the Russian Federation, South Africa and the United States (OECD, 2015c). The dynamism of the US private equity market is striking, as investments doubled in 2014-15. The situation in the EU area is more lacklustre, especially at the earlier stages of business development (Figure 4.11, Panel 3). In contrast, business angel activities generally rose from 2007 to 2015 (OECD, 2016h; EBAN, 2016). Angel investors play a key role in the start-up ecosystem (OECD, 2011). They typically provide the first round of equity capital, after funds from founders, friends and family have been exhausted. They also provide services beyond financing that are key to success, such as mentoring, business advice and access to networks. Angel activities are also more resilient to business cycles than VC investments and bank credit. The number of business angel groups and networks increased steadily in the United States and the EU area over the past decade. US angel investments reached an estimated USD 24.1 billion in 2014. Angel groups and activities are also gaining ground in many emerging economies.

Figure 4.9. **Major funding instruments in the policy mix for business innovation, 2016**

As a percentage of total country self-reported responses, 52 countries participating in the STIP survey 2016



Note: Simple counts of country responses to the question: "Please describe your country's policy mix. Which of the following public funding instruments of business R&D and innovation are in use in your country? Which are the principal instruments of public funding of business innovation in your country? How has the relative balance between these instruments changed recently, if at all? Please rate the relative relevance of the following financial instruments in your country's policy mix and indicate whether their share in the total has increased/decreased or is remained unchanged". Responses are provided by delegates to the OECD Committee for Scientific and Technological Policy (CSTP) and the European Research and Innovation Committee (ERAC).

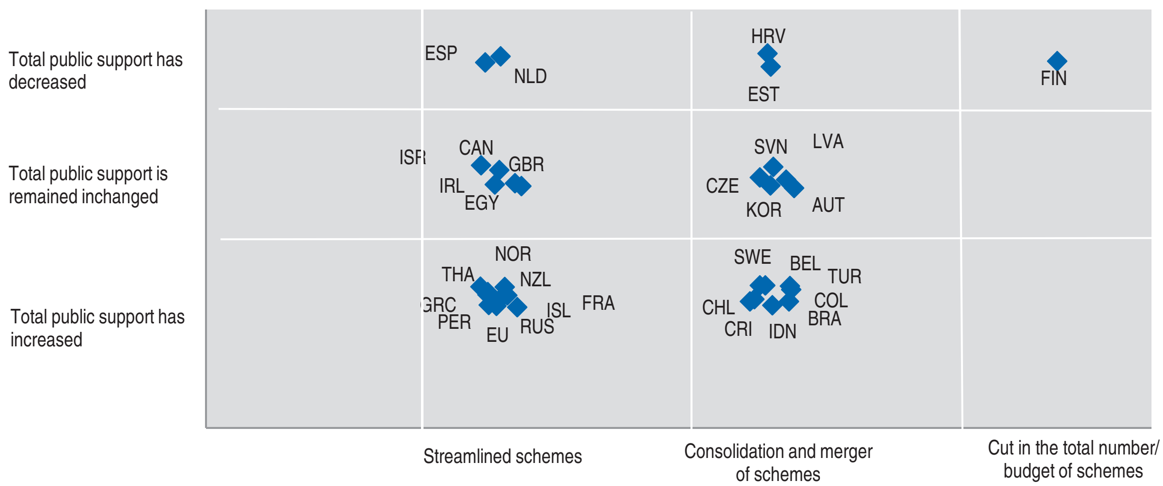
Source: Based on EC/OECD (forthcoming and 2014), *International Database on STI Policies (STIP)*, *www.innovationpolicyplatform.org/sti-policy-database*.

StatLink http://dx.doi.org/10.1787/888933433609

Governments have consolidated domestic equity markets, especially for seed capital, through new or refunded venture capital funds and funds-of-funds (Belgium, Czech Republic,

Figure 4.10. **Many countries have consolidated and merged existing support schemes**

Country self-reported assessment



Note: Country positions on the chart are defined by a country's self-assessment of the following questions: "Have business innovation support schemes been streamlined?, consolidated? or cut in the past two years?" and "From a fiscal perspective, has the total volume of public financial support to business innovation remained unchanged? Or has this policy streamlining/consolidation led to increases/ decreases in public support?". Only countries that answered both questions are presented in the chart.

Source: Based on EC/OECD (forthcoming), *International Database on STI Policies (STIP)*, *www.innovationpolicyplatform.org/sti-policy-database*.

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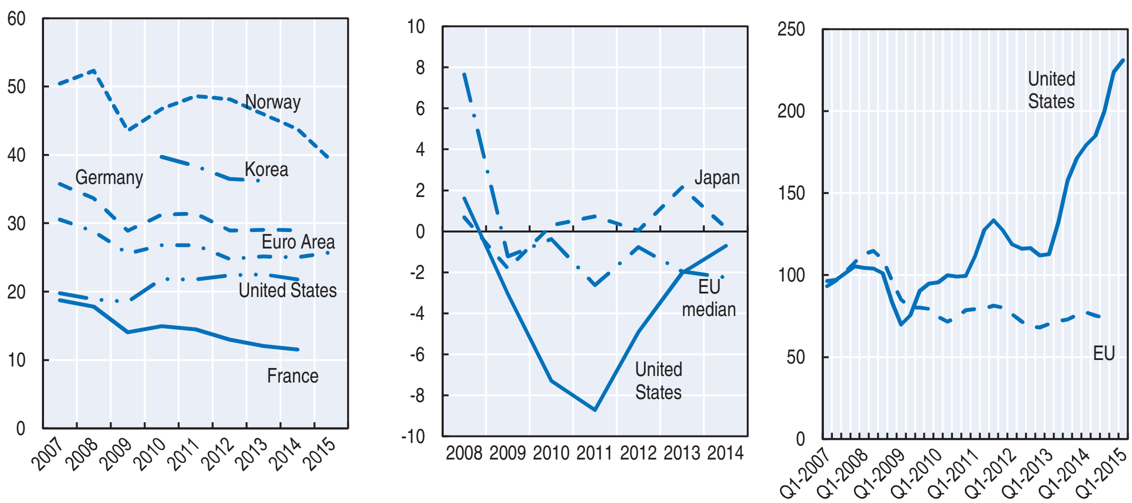
Figure 4.11. **Addressing the slow recovery of financing conditions for innovation and entrepreneurship**



Note: The profit margin rate is the net operating surplus as a percentage of net value added of non-financial corporations.

Source: Based on OECD (2016f forthcoming), *OECD National Accounts at a Glance 2016.*

Note: The EU median is calculated using countries for which data are available. See methodology and notes in OECD (2016h).

Source: Based on OECD (2016h), *Financing SMEs and Entrepreneurship 2016.*

Source: Based on OECD (2015c), *Entrepreneurship at a Glance 2015.*

StatLink http://dx.doi.org/10.1787/888933433623

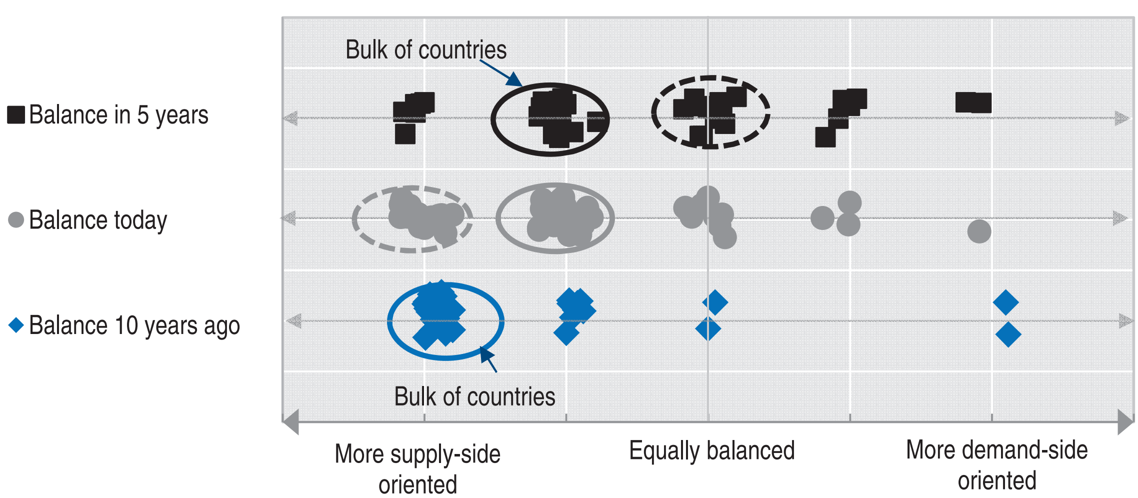
France and Italy). There are also new support schemes for business angels and new co-investment facilities (Australia, France, Iceland, Poland, Spain and at the EU level). Some countries have deployed both types of instruments so as to cover the full spectrum of needs for funding innovation (Greece, Netherlands). Portugal has launched a mezzanine fund that combines elements of debt and equity funding (see also the policy profile "Government financing of business R&D and innovation").

While much of recent policy attention has further focused on the potential of business innovation and entrepreneurship to boost economic growth (Figure 4.1), government support in the area has slightly changed its focus, forms and targets (Figure 4.3). In view of their current budgetary situation, many governments have implemented "no spending" policy approaches. They have favoured policy tools that do not require additional public expenditure in the short term, particularly public procurement, and tax incentives for R&D and innovation[4] (see also the policy profiles "Government financing of business R&D and innovation" and "Tax incentives for R&D and innovation").

Governments have increasingly adopted a broader approach to innovation policy by stimulating demand for innovation, especially in areas of pressing societal need where government action can complement market mechanisms with minimal financial outlays (see the policy profile "Stimulating demand for innovation"). Public procurement, which accounts for an average 12% of GDP in the OECD area, has been a focal point of policy attention across ministries in recent years (OECD, 2015d). In the STI policy domain, there has been a notable shift away from the long-standing focus on supply-side instruments over the past decade (Figure 4.12). Many countries indicated in 2014 that the next five years would see increased emphasis on demand-side instruments, though the majority expected supply-side instruments to remain dominant (OECD, 2014a). Since this time, governments' initiatives to spur business innovation through public procurement have multiplied, which make this STI policy area one of the most active over the period (Figure 4.3).

Figure 4.12. **Towards a stronger focus on demand-side approaches in the policy mix**

Changing balance in the policy mix for business innovation, country self-reported assessment



Note: The balance in the policy mix for business innovation is defined by country self-assessment answers to the question: "What is the balance between different types of policy instruments in the policy mix for business R&D and innovation? How has this balance shifted over time and is forecasted to change in the coming years? Please rate the balance between the following types of policy instruments according to their relative importance/significance in the innovation policy mix". Responses are provided by delegates to the OECD Committee for Scientific and Technological Policy (CSTP) and the .European Research and Innovation Committee (ERAC).

Source: Based on EC/OECD (forthcoming), *International Database on STI Policies (STIP)*, *www.innovationpolicyplatform.org/sti-policy-database*.

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Many countries have revised their governance arrangements for using public procurement to stimulate innovation. Public procurement has become a major feature of innovation agendas (Australia, Canada, Croatia, Korea, Latvia and New Zealand), entrepreneurship plans (Estonia), smart specialisation strategies (Greece, Hungary), industrial plans (Turkey) and public sector innovation policies (Israel). Sweden is currently working on a strategy for public procurement and has set up a National Agency for Public Procurement. The Netherlands has published a new action plan and committed itself to public procurement which is fully sustainable. Public procurement initiatives to improve dialogue between procurers and suppliers (Ireland), to disseminate best practices (France, Netherlands) and to design and respond to innovation-friendly public tenders (France) have sprung up. Some countries are also offering targeted financial support: Korea has introduced a 20% discount on procurement fees for high-quality products. And legal frameworks and procedures have been revised to simplify access to procurement markets (Italy, Latvia, Turkey), especially for small firms and start-ups (Japan, Korea). Further reforms in public procurement practices are likely as more countries – in 2016 compared to 2014 – expect demand-side instruments to become more prominent in the future (Austria, Chile, Costa Rica, Germany, Korea, Lithuania, Portugal and Thailand).

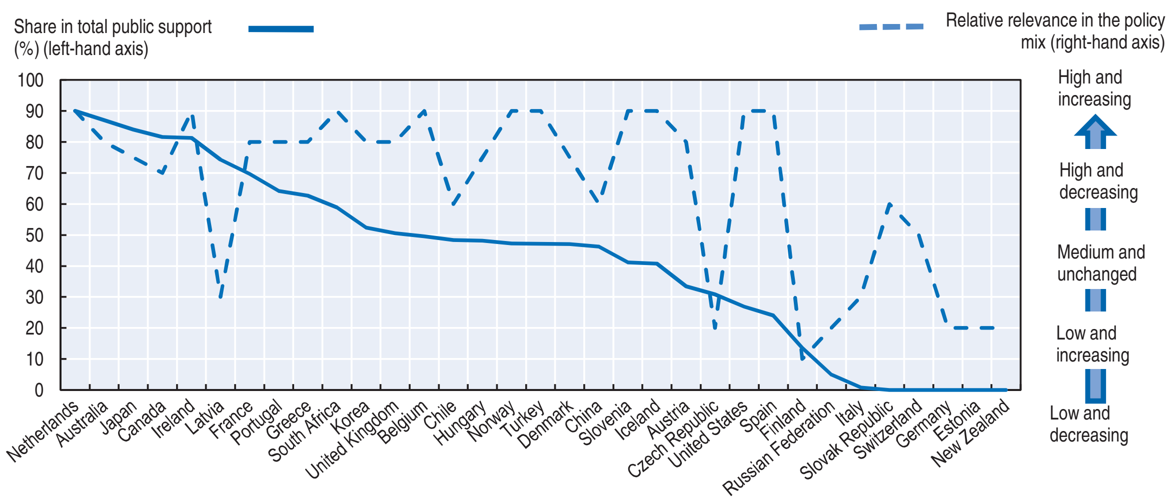
Although less commonly used than grants and other direct funding instruments overall, R&D tax incentives have increasingly complemented direct subsidies as international restrictions (e.g. European Union, WTO) capped the volume of direct state aid. Since the early 2000s, R&D tax reliefs have been simplified (e.g. by abandoning incremental design) and made more generous (e.g. by increasing the tax relief rate) and more accessible to a larger number of recipients (e.g. by raising or removing the ceiling on eligible expenditures). The policy shift has been particularly noticeable in some countries where indirect support has even replaced direct funding (e.g. France). The growing popularity of R&D tax incentives has also given a considerable boost to global efforts to build evidence on their incidence and impact (for a comprehensive summary, see Appelt et al., forthcoming).

If more governments have introduced favourable tax schemes for innovation over time, the relative relevance of these schemes in the overall policy mix remains extremely uneven across countries. In many countries, tax relief accounts for a minor share of total public support granted to business innovation, the OECD average being around 33% (Figure 4.13). At the top of the ranking are countries giving high and increasing importance to this type of instrument. At the bottom of the ranking are countries giving these instruments medium or low importance. The perceived relevance of R&D tax incentives is closely related to their relative cost, as compared to other direct funding instruments in the total public envelope for R&D. It is, however, worth noting that many countries in the middle of the ranking – those where indirect funding accounts for 10% to 50% of total public funding – considers the issue with greater attention than their level of fiscal concessions would suggest.

R&D tax schemes were relatively stable over the 2012-14 period, making them one of the STI policy areas that changed least globally (OECD, 2014a). More changes have nevertheless been observed between 2014 and 2016. New R&D tax schemes (Latvia, Slovak Republic) and payroll withholding tax credits (Spain) are now in place. As in the past, special features have been introduced to make existing schemes more generous, e.g. through a higher tax relief rate (Austria), an increased expenses deduction rate (Russian Federation, Thailand), or a higher ceiling on the limit of the tax liability that can be offset with R&D tax credits (Norway, Spain). New schemes and revised features also aim to make tax relief more accessible and better adapted to SMEs and young firms (Croatia, Latvia and the Netherlands), e.g. by reducing the administrative burden for applicants or allowing loss-making firms (typically at early stages of development) to benefit (see also the policy profile "Tax incentives for R&D and innovation").

Figure 4.13. **The use and policy relevance of R&D tax incentives remain extremely uneven across countries**

Tax support as a percentage of combined direct and indirect public support to firms in 2014 (left-hand axis) and relative policy relevance of tax incentives in 2016 (right-hand axis)



Note: The index of relevance reflects the relative importance of tax incentives for R&D in the policy mix and how the relative balance between instruments may have changed recently. Rating is provided by country self-assessment. Countries for which an index of relevance is not available (i.e. Japan, Denmark, Hungary, Russian Federation, Poland, Luxembourg and Mexico) are marked with a dotted line.

Sources: Based on EC/OECD (forthcoming and 2014), *International Database on STI Policies (STIP)*, *www.innovationpolicyplatform.org/sti-policy-database*; OECD (2016f), *OECD Research and Development Statistics (RDS) Database*, April, *www.oecd.org/sti/rds*; and OECD (2016g); OECD-NESTI data collection on R&D tax incentives, July, *www.oecd.org/sti/rd-tax-stats.htm*. Data retrieved from IPP.Stat on 8 September 2016.

StatLink http://dx.doi.org/10.1787/888933433645

One key trend in tax concessions for innovation is the policy intention to use them to encourage technology transfer. This has entailed preferential treatment for collaborative R&D expenditures or knowledge services purchased from universities and public research institutes (Italy, Latvia), accelerated depreciation for the acquisition of new technologies and new knowledge (Poland, Russian Federation) and preferential tax treatment for the acquisition of intangible assets (Australia). In addition, the Russian Federation has deployed a range of VAT or property tax exemptions for research centres located in clusters. In Turkey, firms in Technology Development Zones (TDZs) benefit from a range of tax incentives and are required to establish an incubation centre and a technology transfer office.

Tax concessions are also more closely tied to job creation and labour costs in several countries. The Italian Stability Law 2015 foresees a range of incentives on labour tax and local taxes to encourage job creation and reduce workforce costs. The new Spanish payroll withholding tax credit aims to foster R&D-related employment by business firms and innovative organisations.

R&D tax incentives have become a way to increase the attractiveness of the national research ecosystem and to engage in tax competition to attract foreign R&D centres. In 2013, the United Kingdom introduced an R&D expenditure credit (RDEC) to attract large company investments. From 2016 this scheme fully replaced the previous tax credit.

Some governments have increasingly combined these expenditure-based instruments with so-called "patent boxes" to encourage the co-location of R&D and manufacturing activities. Patent boxes offer tax relief on intellectual property (IP) revenues and aim to boost the domestic exploitation of new technologies and knowledge so as to better appropriate the benefits, including job creation and knowledge spillovers. Patent boxes particularly target large multinational companies that have the capacity to develop global tax optimisation strategies and to decouple the production of knowledge from its use. Recently, Indonesia, Ireland, Portugal, Thailand and Turkey introduced corporate tax exemptions for income derived from the use of intellectual property. In the Russian Federation, operations involving the protection and commercialisation of intellectual property rights (IPRs) have been exempted from VAT since 2015. The US Congress is also considering introducing an innovation box as part of a broader corporate tax reform (KPMG, 2015). However, patent or innovation boxes are increasingly denounced as harmful tax practices that could encourage global tax competition and result in corporate profit shifting and tax base erosion. At the end of 2015, the United Kingdom published draft legislation with a view to better align its patent box regime with OECD standards on harmful tax practices (see the policy profile "Tax incentives for R&D and innovation" for further dicussion).

Governments have also sought to encourage less conventional funding approaches. Indeed, the financing of innovative entrepreneurship will remain a major issue in the coming years. SME dependence on bank finance is increasingly viewed as problematic (OECD, 2016h). Alternative forms of funding are on the rise, driven by the deployment of information and communication technologies (ICTs), peer-to-peer practices and the growing valuation of intellectual assets. Asset-based funding allows firms to obtain financing against the value of the specific assets they produce in doing business, including intangible assets. Similarly, crowdfunding allows entrepreneurs to raise external funds from a large audience, rather than a small group of specialised investors, with each individual providing a small portion of the total funding needed. Typically, internet platforms help match investors with businesses.

While these mechanisms remain small and marginal, they are developing rapidly and may bring new opportunities provided that the right regulatory frameworks are in place (Box 4.2). Australia has passed new legislation to allow crowd-sourced equity funding and provide tax incentives to investors. Austria has adopted a regulatory framework for improving alternative means of financing of innovation, especially crowdfunding. Legal requirements regarding the basic information required and administrative declarations (e.g. simplified capital market prospectus) have been reduced. Standards have also been introduced to ensure investor protection.

Keeping pace with global competition

A country's prosperity has long depended on its participation in the global economy and more recently on its integration into global value chains (GVCs). Countries and firms enter GVCs through foreign direct investment (FDI) and trade in goods and services that offer channels to access a broader portfolio of technologies, skills and knowledge-intensive assets. GVCs have changed the nature of global competition, as companies and countries no longer compete only for market share in high value-added industries, but also increasingly for high value-added activities within GVCs. GVCs also provide opportunities for internationalisation to new types of enterprises, including young innovative firms (see the policy profile "Attracting international science and technology investments by firms").

Box 4.2. **The rise of crowdfunding**

Estimates of the level of crowdfunding in North America, based on data from 1 250 active crowdfunding platforms, show that volumes increased by 145% between 2013 and 2014, to a total of approximately USD 9.5 billion. Europe enjoyed similar growth (+141%), but from a lower base, reaching a total of EUR 3.3 billion. Crowdfunding activities have boomed in Asia (+340%), totaling USD 3.4 billion in 2014, and the region is expected to drive future global expansion. Africa, Oceania and South-America have also registered notable progress, but the volumes were all below USD 100 million in 2015. Crowdfunding faces one limitation, however: for the time being, more than half of its transactions fund social or artistic causes and real estate activities, rather than broader for-profit businesses.

Crowdfunding platforms could also have a major impact on other funding channels, as they are more widely used to find investment opportunities and share risks (OECD, 2016h). For instance, business angel investors, who tend to invest more locally than venture capitalists, have the capacity to sponsor start-ups across a wider geographical area. The same platforms will also reinforce a growing trend among angel investors to co-invest with other early stage players, so as to diversify risk. Similarly non-equity crowdfunding (donation and reward-based) platforms create opportunities for innovators while creating low risks for backers, which have no financial interests attached to their contribution (OECD, 2015e).

Major regulatory challenges remain though (OECD, 2015e). Opportunities raised by crowdfunding should be examined together with risks, notably for investors, who may have uneven access to information and be less well-trained for such transactions than professional investors. The question should also be raised what the (future) product or "community benefits" are. Given the potential for early stage funding of start-ups, a clear regulatory framework is necessary to minimise such risks and foster the potential of crowdfunding (Wilson and Testoni, 2014 cited in OECD, 2015e).

Sources: Massolution (2015), *2015CF Crowdfunding Industry Report*, *http://reports.crowdsourcing.org/?route=product/product&product_id=54*; OECD (2016h), *Financing SMs and Entrepreneurs 2016: An OECD Scoreboard*, *http://dx.doi.org/10.1787/fin_sme_ent-2016-en*; OECD (2015e), *OECD Digital Economy Outlook 2015*, *http://dx.doi.org/10.1787/9789264232440-en*.

Many countries have recently refurbished their policy portfolio to assist SMEs and start-ups in accessing global markets. Most initiatives have focused on providing such firms with marketing intelligence and assistance for commercialisation, promotion and branding (Czech Republic, France, Iceland, Italy, Korea, Spain, Turkey and the United Kingdom). Governments also offer access to risk finance and loan guarantees (France, Malaysia), access to one-stop-shops for information and expert advice (Korea, Spain and the United Kingdom), support for finding international partnerships (United Kingdom), and training to gain skills and knowledge on international markets (Iceland). Slovenia is running a full programme of assistance and, along similar lines, Austria, Korea and Turkey have created global incubators and accelerators.

Financial support has also been granted to encourage the participation of small firms in international market-oriented R&D projects (Austria, Canada, Chile, Lithuania, Spain, Turkey and at the EU level) or to help them bridge the financial gap in order to enter markets abroad (Canada, Ireland), e.g. through internationalisation vouchers (Austria, Italy and Portugal). The budget of the European Eurostars Joint Programme of Horizon 2020 (2014-20) has been significantly increased with a view to promoting market-oriented transnational research activities involving SMEs. Costa Rica delivers innovation and sector-based grants with a certification for participation in GVCs.

Governance arrangements have also been revised for that purpose. France has merged existing promotion agencies into the new Business France that will assume a central function of communication and aim to strengthen the attractiveness and the brand image of the country. Germany has released its International Cooperation Action Plan that aims to give a ministry-wide perspective to the planning and implementation of its international co-operation activities, including international monitoring and evaluation. The Action Plan mobilises a broad variety of instruments, from mobility schemes to strategic alliances and partnerships.

The internationalisation of clusters is another key channel for SMEs to connect to global knowledge networks, and this has received particular policy attention (see the policy profile "Cluster policy and smart specialisation"). The specialisation and internationalisation of clusters have been fostered by deeper globalisation and growing competition and, as finance remains limited, governments have refocused policy action on areas with high potential for positive spillovers.

In addition, national guidance documents and action plans for STI have strengthened the attention given to internationalisation (Australia, Germany and Hungary). For example, a major priority of the newly revised German High-Tech Strategy is the integration of firms and science into global knowledge flows. This Strategy has also set up a new funding programme for the "Internationalisation of Leading-Edge Clusters". The Baltic Sea Region (BSR) Stars programme (2015-17), mentioned below, aims to initiate and enhance transnational co-operation between Denmark, Sweden, Norway, Finland, Germany, Lithuania, Estonia, Latvia, Poland and Iceland by linking cluster organisations. Recently, Australia, Belgium (Flanders), Croatia, Poland, Portugal, Slovenia and Turkey have revised their cluster policies or introduced cluster support programmes to promote the internationalisation of key clusters and improve capabilities to engage in international markets and global supply chains. The Global Centres of Expertise programme is a part of the Norwegian Innovation Clusters programme and directed at mature clusters with a global position. Its objective is to improve the clusters' competitive position, *inter alia* their attractiveness within GVCs.

4.4. Reorienting public research

Rationalising public research spending and accelerating knowledge transfer

Universities and public research has also been an important area of policy change (Figure 4.3). Some countries are now reviewing their overall research policy with the common goal of improving public funding efficiency, but using diversified approaches (see the policy profile "Financing public research"). For some years there has been a clear global trend towards more competitive funding approaches, with the introduction of performance-based elements in core institutional funding and a move towards more contractual arrangements (OECD, 2014b). This trend has been reinforced since 2014 in Austria, Canada, Greece, Ireland, Italy, New Zealand, Turkey and Central and Eastern Europe (Estonia, Poland). However, a reverse trend towards increased block funding has also been observed in a small number of countries, particularly in northern Europe.

A number of factors are pushing countries to prioritise and concentrate their financial contributions to public research, including progress in scientific research and the consequent opening up of new opportunities, intensifying global competition for talent and resources and scarcer public resources. In that respect, the recent financing conditions of public research are particularly worrying. Public R&D budgets are levelling off, or have started to recede in many countries where governments are the main funders of public research (OECD, 2014a). The United States, the world's largest public research system, has recorded the longest multi-year decline in federal funding for academic R&D since the early 1970s (NSF, 2015). In addition, long-term international trends indicate that public R&D budgets are likely to plateau around current ratios (see Chapter 3). Unless strong economic growth drives a recovery in government spending, the amount of public money made available to public research is likely to increase only slowly. Competiting policy priorities, such as the growing focus – and funding – given to business innovation and R&D tax incentives, could put public R&D budgets under further pressure. It is also likely that the decline of governments' support to universities and higher education institutions may have negative impact on the quality and inclusiveness of education systems due to subsequent cuts in educational services and increases in tuition fees.

Policy makers face the continuous conundrum of balancing resource distribution between different fields of science, long-term and short-term needs, big science and individual investigators, infrastructure and personnel, and national and international needs (see the policy profile "Public research missions and orientation"). Latvia is undertaking structural reforms so as to increase its institutional research capacity, while Turkey has launched an evaluation of the country's research infrastructure in order to enhance its efficiency. Peru has adopted the Innovate Perú Plan, which manages national STI budgets and places emphasis on the training of highly specialised human resources.

Recently, many countries have readjusted their strategic priority research areas with a view to tackling societal challenges (Australia, Belgium-Flanders, Denmark, Italy and Norway). China's 13th Five-Year Plan (2016-20) aims to double the proportion of funding dedicated to basic research (to 10%), and Korea has the ambition to raise the share of public research spending granted to basic research to 40% by 2017. The Netherlands has increased its budget for fundamental research as well. France has raised the relative contribution of its National Research Agency to generic programmes. Denmark has simplified its research funding system by merging former institutions into the Innovation Fund, which will support projects throughout the entire value chain from strategic research to commercialisation.

The sources of public research funding have also changed as a result of greater involvement by industry, for example, in Germany, Ireland, Italy and Luxembourg. This is due to higher investment incentives and reduced government budgets in certain countries, as well as a better alignment of the public research agenda with societal needs. In that respect, and as mentioned above, tax incentives for R&D are increasingly used to leverage private funding for public research (Iceland, Italy). Other instruments include new governance arrangements (e.g. Belgium's ministerial overhaul of economic affairs and science, Hungary's new higher education strategy, and Iceland's S&T Policy and Action Plan), new legal frameworks (Greece), innovation vouchers (Czech Republic, Portugal), a requirement for minimum co-financing in public support programmes (Latvia, Netherlands) and revised block funding allocation mechanisms to incentivise third-party funding (Norway). Ireland operates the Spokes programme, which offers extra funding to existing research centres for publicly funded projects so long as they involve industry partners.

Public-private partnerships (PPPs) offer opportunities for sharing risks, resources and orientation. PPPs are encouraged through funding consortia (e.g. Ireland, Peru and Spain) and joint research initiatives/centres. Sweden and the United Kingdom have recently injected research capital, USD 35 million and USD 725 million respectively, into large-scale strategic partnership initiatives with the potential to raise an equivalent amount of private funding. At the EU level, new PPPs include the long-term Joint Technology Initiatives (JTIs), which are expected to receive USD 12 billion from the private sector over the next seven years.

Philanthropic and private science foundations, although still small and marginal, are playing an increasingly important role in complementing public funding, especially in fundamental translational research and in selected research areas (e.g. health and well-being). Norway and Portugal have recently reintroduced or reinforced their donation support scheme. Spain has set up the Council of Foundations for Science to disseminate information on best practices for promoting investment in science and to engage other foundations in science. Australia has set up the Biomedical Translation Fund (BTF) with USD 174 million PPP (AUD 250 million), with a view to stimulating private sector investment and accelerating the translation of Australia's medical discoveries into health applications.

Countries have continued to introduce legislation and develop national strategies to further promote both the commercialisation of R&D and collaboration between academia and industry (Korea, Turkey). National directives are also directly embedded in wider STI strategies (Denmark, Ireland), including smart specialisation strategies (Croatia, France, Greece, Latvia, Lithuania and Portugal). Colombia, Croatia, the Netherlands, Norway and Slovenia are continuing to professionalise technology transfer offices. National technology platforms and hubs have sprung up in many countries, acting as physical and virtual spaces for businesses and public research institutes to connect and access resources, skills and technical assistance. At an international level, the above-mentioned Baltic BSR Stars Project (2015-17) aims to create strong linkages between research environments, clusters and SME networks across countries in that region. Governments have also introduced technology transfer programmes (Germany, Lithuania), technology holdings (Korea) and accelerators (Turkey) to help bring the outcomes of public research to market.

Enabling interdisciplinary research and open science

Complex global societal challenges require research that combines traditionally distant academic fields, whereas public research organisations (universities and public institutes), research funding organisations and evaluation arrangements (particularly peer review) are overwhelmingly organised along disciplinary lines. The possibility of lowering disciplinary barriers has attracted considerable policy attention over recent decades, and this is reflected in a restructuring of some research agencies and actors (Belgium, Japan, Korea, Netherlands, Sweden and the United Kingdom) and changing evaluation and selection practices (Iceland, Italy and Norway).

Initiatives to support open science are gathering pace through greater access to research results and data, including scientific publications (see the policy profile "Open science"). Most recent efforts have focused on creating enabling legal frameworks and providing policy guidance for open access and open data. The number of countries with mandatory open access provisions is increasing. In most cases, the lead is being taken by research funding agencies, but these mandates can also be embedded in legislation at national (e.g. Mexico) or federal (e.g. Germany) levels. Austria, Germany and the United Kingdom have recently amended their national copyright legislation to promote open science. Appropriate infrastructures have also been built, especially to support the sharing of research data. The planning and funding of major e-infrastructures are increasingly embedded in broader national (and European) procedures to map and fund research infrastructure. Finland, the United Kingdom and the United States have also started addressing the skills gap related to open science and big data analytics by promoting specific training and providing researchers with guidelines.

4.5. Broadening the skills and culture for innovation

Recently, several countries have renewed their policy portfolio with a view to strengthening innovation skills and building a broader science and innovation culture. These have actually been among the most active policy areas in the overall policy mix for innovation (Figure 4.3).

Expanding education in science, technology, engineering and mathematics (STEM) remains foundational for many OECD countries and partner economies. Public budgets to boost STEM education have been increased in Belgium (Federal), Croatia, Latvia, South Africa and the United States. Other recent policy initiatives include attempts to make STEM subjects more interesting and attractive to young people (Ireland, New Zealand and Portugal), new training programmes and recruitment criteria for teachers (Croatia, Korea, Ireland, Norway and Sweden), and new teaching methods and IT-based pedagogical tools (Czech Republic, Ireland, Lithuania, Portugal and Spain) (see the policy profile "Strengthening education and skills for innovation").

Education policy has also increasingly evolved to reflect the wider range of non-science-and-technology (S&T) skills required to innovate. Curricula have been revised to develop generic skills (Spain), problem-solving capacity (Korea) and entrepreneurial behaviours (Croatia, Ireland, Russia and Turkey). In Finland, entrepreneurship is linked to participatory, active citizenship and constitutes a cross-curricular theme at basic and upper secondary levels of education.

Many countries have also sought to reinforce public participation in and support for science and entrepreneurship. This has been a key component of national STI strategies in middle-income economies (Colombia, Chile, Costa Rica and Malaysia). But the same is true for some more advanced economies with traditionally high performance on STI indicators (Finland, Korea). There have also been efforts to build capacity for an S&T culture and the popularisation of science, e.g. communication events, museums and Internet-based resources (Czech Republic, France and the Russian Federation). Many new initiatives include large public events (Croatia, Australia, Greece and Korea), promotion campaigns (Chile), competitions and awards (Australia, Canada, China and Costa Rica). Greater policy attention has also been paid to fostering an entrepreneurial spirit and broadening the forms of creativity, with intervention extended to workplaces (see the policy profile "Building a science and innovation culture").

4.6. Improving policy governance

Towards more evidence-based policies

STI policy evaluation and impact assessment have gained more policy attention in recent years (see Figure 4.3 and the policy profile "Evaluation and impact assessment of STI policies"). This increased attention has been driven in part by growing fiscal constraints and the increasing need to demonstrate value for public money. Evaluation practices are very country-specific and path-dependent. This explains the persisting strong heterogeneity in the nature and level of development of evaluation and impact assessment among countries, as well as the slow pace of change. Some countries have evaluation and impact assessment capabilities that are still at an early stage of development (e.g. Colombia, Malaysia, Russian Federation and South Africa) (OECD, 2016i; 2016j), while in others evaluation and impact assessment are part of the policy culture and are institutionalised to a greater extent.

Recent trends in policy evaluation include the more intensive use of public administrative data and online technology for collecting data ("big data"), smaller and quicker exercises (New Zealand), more strategic use of evaluations (China) and the increasing complexity of the concepts and practices employed, which is often related to the multiplication of rationales, strategic objectives, actors, arrangements, targets and instruments.

The complexification of the portfolio of STI policies (more instruments, goals, actors) has increased the risk that public resources might be misallocated and raised the issue of a possible negative interaction between different policy measures. In response, systemic evaluations have spread globally, albeit in different ways according to the countries concerned. Colombia, Iceland, Lithuania, Luxembourg, Malaysia, Spain, Sweden and Thailand have recently undergone large-scale peer-review evaluation exercises conducted by international organisations, including the OECD. The European Union has conducted an evaluation of its Seventh Framework Programme and an interim evaluation of Horizon 2020 (EC, 2013). Some countries have mobilised national evaluation capacity to assess policy outcomes (e.g. China's S&T Development Plan, Estonia's R&D Strategy "Knowledge-Based Estonia"), sometimes focusing on parts of the national STI system (e.g. Ireland on its support system for enterprises, the Netherlands on its enterprise policy and Australia on its research system).

Overall, efforts have been directed towards building the knowledge base for STI policy, e.g. through the development of impact assessment studies and the systematisation of evaluation, the implementation of a whole-of-government approach to evaluation (e.g. the UK Treasury has set an evaluation framework to compare investment spending across areas of government), more harmonised practices (common methodologies and indicators) and the creation of data infrastructures and expert communities (OECD, 2012). Japan, Norway and the United States have been particularly active at setting up science of science and innovation policy (SciSIP) initiatives to develop models, analytical tools, data and metrics. The European Commission (Policy Support Facility) and the OECD/World Bank (Innovation Policy Platform) maintain web-based platforms that provide one-stop shop access to repositories of internationally gathered knowledge on innovation and policies, as well as tools for benchmarking and diagnostics (IPP, 2016).

Towards more responsible STI policies

Governments have paid attention to fostering a comprehensive approach to governance by enhancing co-ordination arrangements across the board (Austria, Colombia and Ireland) and involving industry and society upstream in the policy debate through participatory approaches to setting priorities (Argentina, Chile, Denmark, Greece, Netherlands and Turkey) (see the policy profile "Public engagement in STI policy").

While much STI policy attention is currently focused on the economic slowdown, governments also face unprecedented and increasingly pressing societal challenges. In the Daejeon Declaration on STI Policies for the Global and Digital Age (2015), ministers across a large number of OECD and non-OECD economies highlighted the essential role of STI in meeting global and societal challenges, such as environmental sustainability, food security and healthy ageing, and in achieving the Sustainable Development Goals agreed by the United Nations. As concerns have mounted, the ethical and societal dimensions of research have come to the fore and are increasingly reflected in the framing of more "responsible research and innovation" (RRI) policies. The RRI policy mix is complex, as multiple policy instruments should be mobilised at various stages of the policy cycle to achieve multiple strategic objectives. In practice, most recent policy efforts have tried to foster a comprehensive approach to governance, to define new national guidelines and orientation, to provide infrastructures and incentives for interdisciplinary research and open science, and to broaden the range of skills as well as the culture for innovation (see the policy profiles "Public engagement in STI policy" and "Building a science and innovation culture").

RRI principles have been integrated into the general formulation of innovation policy agendas (see the policy profile "National strategies for science, technology and innovation"). The EU Horizon 2020 research programme strongly focuses on societal challenges and acts as a federator for matching national strategies in several European countries (EC, 2013). Beyond the EU area, Japan has launched its 5th S&T Plan (2016-20), which aims to achieve sustainable growth and contribute to solving global problems. National foresight and technology assessment exercises anticipating long-term societal needs have helped inform policy formulation in the Czech Republic and Germany.

More downstream RRI policy initiatives are targeting the organisations in charge of policy delivery (e.g. funding agencies) (Norway, Peru). RRI principles are also sometimes mainstreamed in existing funding programmes, e.g. by increasing the share of funding for interdisciplinary research, by introducing gender considerations into the process of allocating funding (Ireland), by targeting the social sciences and humanities (Germany), and through new specific research funding (e.g. Austria's Top Citizen Science programme).

Notes

1. It is noteworthy mentioning that the exploitation of the STIP survey in a semi-quantitative approach for developing policy indicators is in progress. Further exploration is required as to better identify and assess possibilities and limitations in use and interpretation (Kergroach, forthcoming-b). Yet, some simple remarks could be made from a descriptive analysis of the STIP database.
2. This section is abridged from the *OECD Economic Outlook 2016*, otherwise references are stated.
3. The unit of observation of the STIP mapping is the "major policy initiative" that is defined as a public action that i) aims to achieve one or several public policy goals in the policy area of science, technology and innovation; ii) is expected to modify the behaviours of actors and stakeholders, being national, domestic or foreign, who are part of or influential on, the national innovation systems; and iii) is implemented with a minimum time horizon or on a continuous basis (i.e. not as a one-off "event"). The level of observation is national, central or federal, according to countries' specificities in governance arrangements. A policy initiative deserves a single (or multiple) policy goal(s). A policy initiative has several properties. Each policy initiative aims to achieve a single (or multiple) strategic objective(s), make use of a single (or multiple) policy instrument(s), is generic or targeted if it addresses a single (or multiple) target population(s) and/or a single (or multiple) sector(s) and/or technology(ies). A policy initiative also presents several characteristics in terms of the directionality of policy intervention (demand- or supply-side, top-down or bottom-up), and policy implementation (competitive or universal, selective or discretionary). It is worth noting that the characteristics of a policy initiative are also intrinsically linked to its strategic objectives, instruments and targets. The policy mix can therefore be described in terms of the relative articulation of these initiatives and their properties (Kergroach, S. et al., forthcoming-a).
4. Although they imply a fiscal cost due to foregone revenues, tax incentives for R&D represent in relative terms a small amount of public money compared to total taxes on corporate income and profits. R&D tax concessions accounted on average in 2014 for 4% – or less – of corporate income

taxes collected by central governments in most countries and less than 12% in the countries that have the most generous tax schemes for R&D in place (author's calculations based on OECD 2016b and 2016g).

5. Knowledge-based capital (KBC), also referred to as "intangible assets" or "intellectual capital", constitutes a long-lasting resource for companies and institutions. KBC assets are not physical in nature, and their main value stems from their knowledge content and their ability to add value to other assets. Investment in KBC can be subdivided into three main groups: computerised information (e.g. software and databases); innovative property (e.g. scientific and non-scientific R&D, copyrights, designs and trademarks); and economic competencies (e.g. brand equity, advertising and marketing, firm-specific human capital, and organisational know-how and capabilities). Some KBC types are now included in the System of National Accounts (SNA). These include: software, R&D, entertainment, literary and artistic originals, and mineral exploration. Other KBC assets, such as design, new product development in the financial industry, brands, firm-specific training and organisational capital, are the subject of methodological work aimed at measuring them in an internationally comparable way (OECD, 2015a).

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