OECD Science, Technology and Innovation Outlook 2016

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.

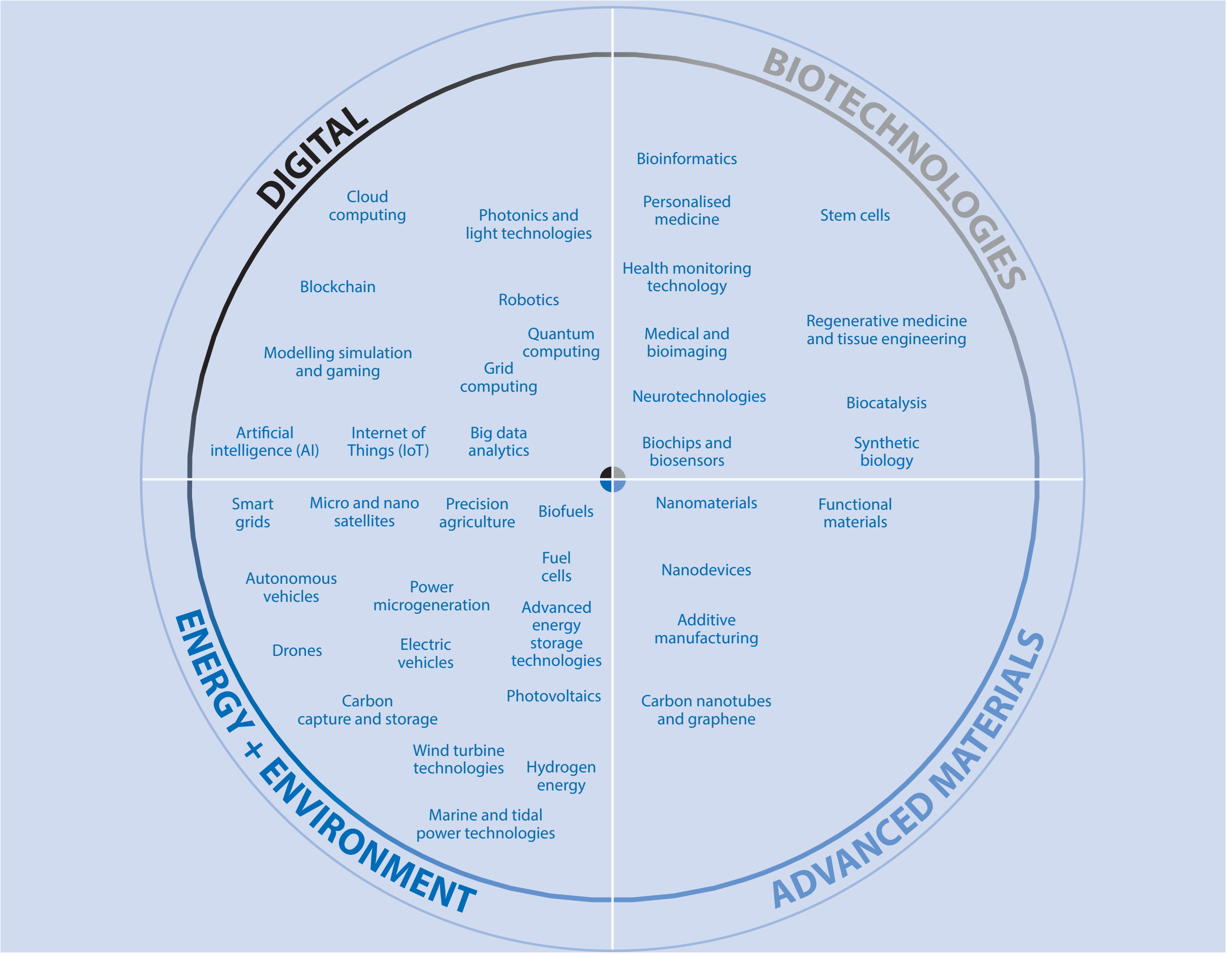
Over the last two decades, technology foresight has emerged as a complementary approach to forecasting. It tends to take a more active stance on the future, eschewing forecasted predictions in favour of multiple futures, often in the form of scenarios, and embracing uncertainty. With an emphasis on co-creating 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

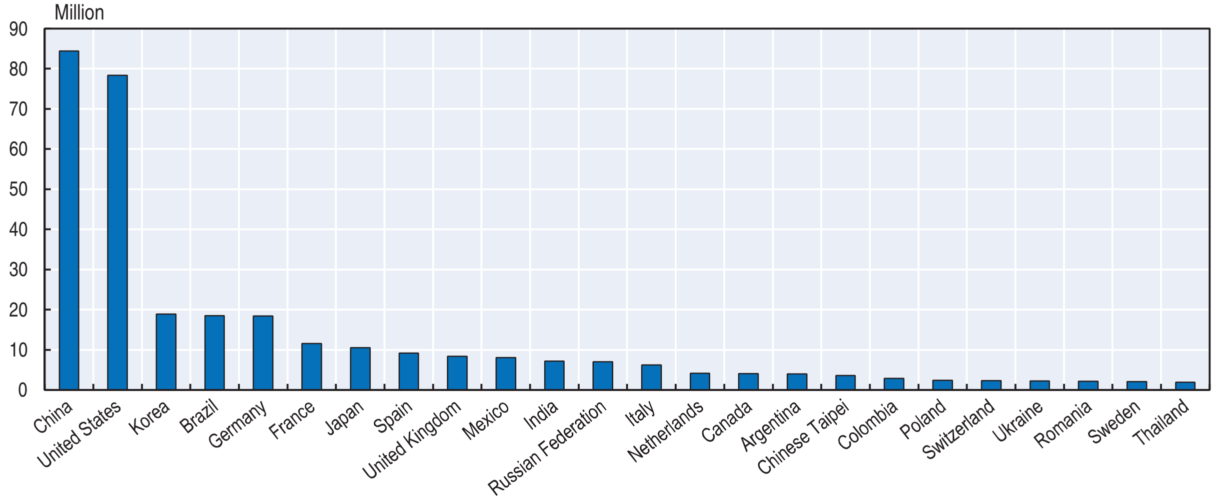
The number of connected devices in and around people's homes in OECD countries will probably increase from 1 billion in 2016 to 14 billion by 2022 (OECD, 2015a). Figure 2.2 shows a country breakdown of 363 million connected devices crawled and surveyed by Shodan, a search engine for Internet-connected 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.

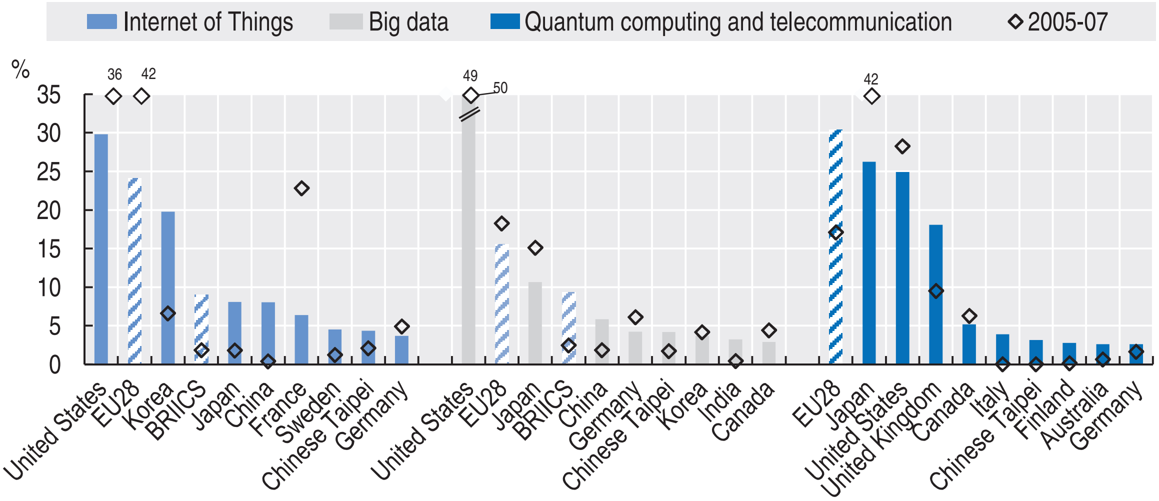
Big data analytics offers opportunities to boost productivity, foster more inclusive growth and contribute to citizens' well-being (OECD, 2015b). Firms, governments and individuals are increasingly able to access unprecedented volumes of data that help inform real-time decision-making by combining a 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

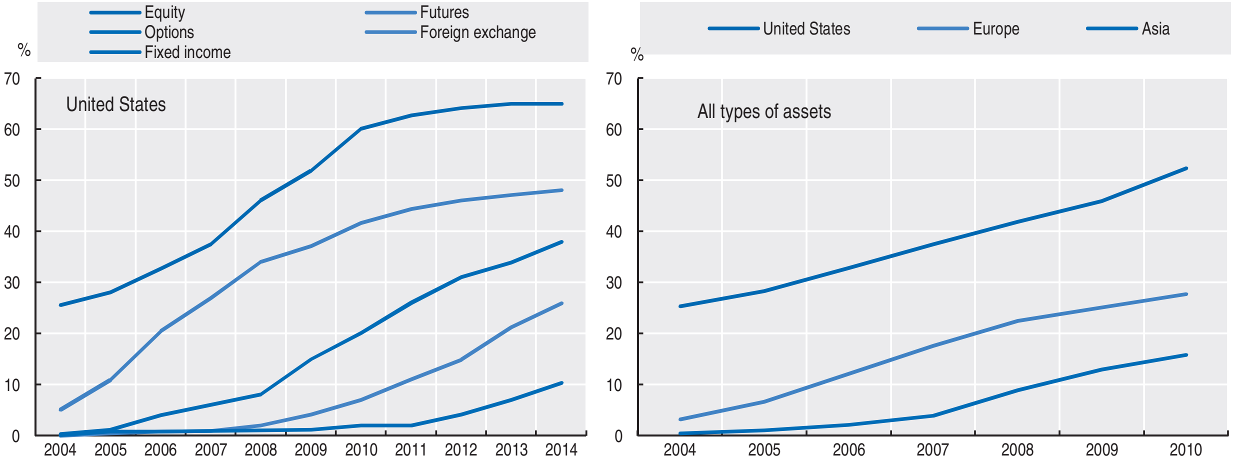
AI-enabled robots will become increasingly central to logistics and manufacturing, displacing human labour in productive processes (OECD, 2015b). AI is expanding the roles of robots, which have been traditionally limited to monotonous tasks requiring speed, precision and dexterity. Sensors are increasingly 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

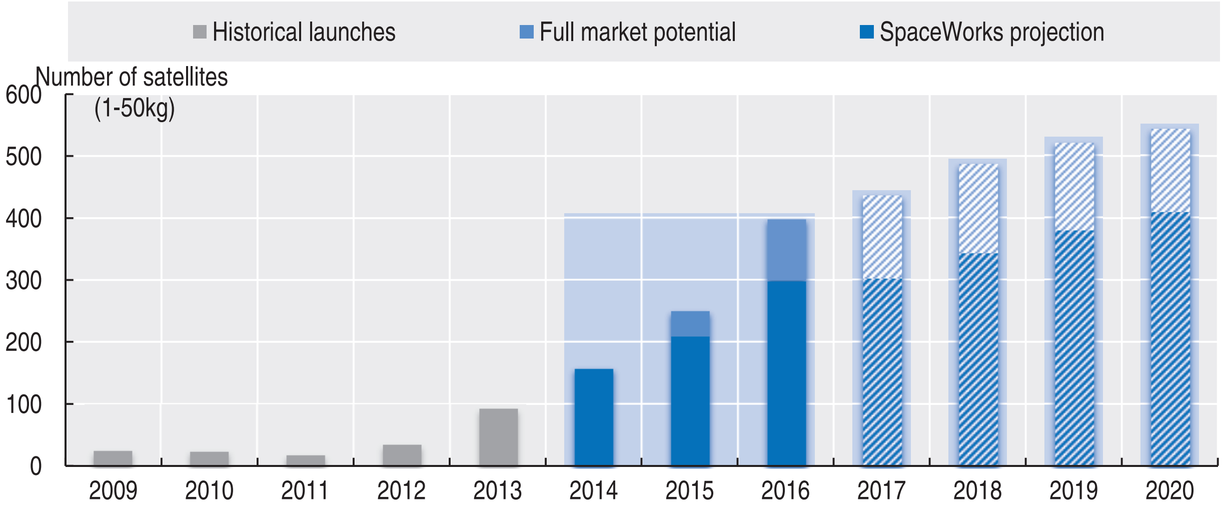
The last few years have witnessed the start of a revolution in the design, manufacture and deployment of satellites. Small satellites, which have become very popular, weigh less than 500 kilogrammes (kg) (a typical communications or meteorological satellite placed in geostationary orbit, at an altitude 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.

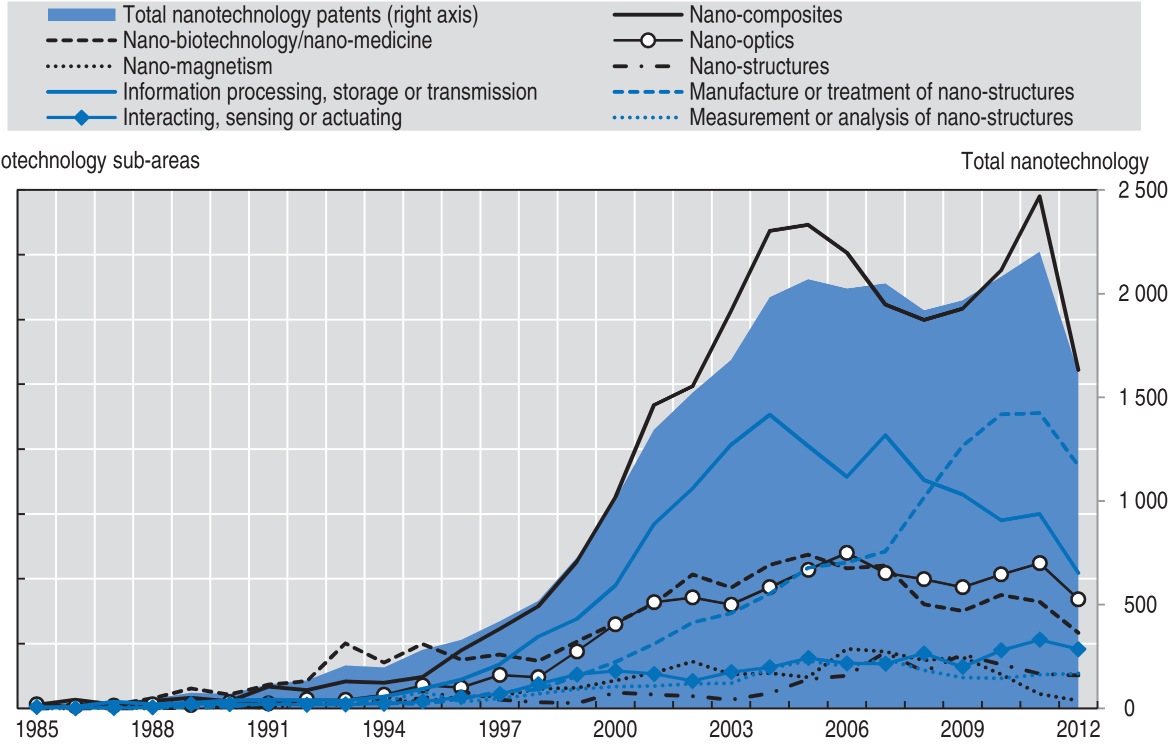
Nanomaterials are expected to have many areas of application

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).

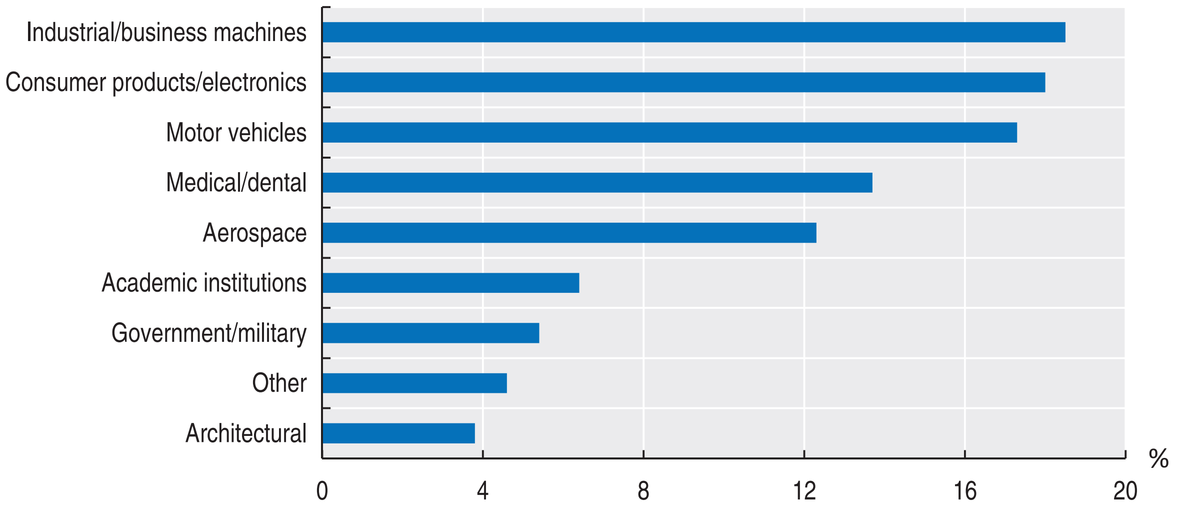
It is estimated that the global AM market will grow at a compound annual rate of around 20% from 2014 to 2020 (MarketsandMarkets, 2014). Wohlers Associates (2014) estimates sales of AM systems and services at USD 21 billion in 2020. As 3D-printing processes continue to mature and grow, they can potentially 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

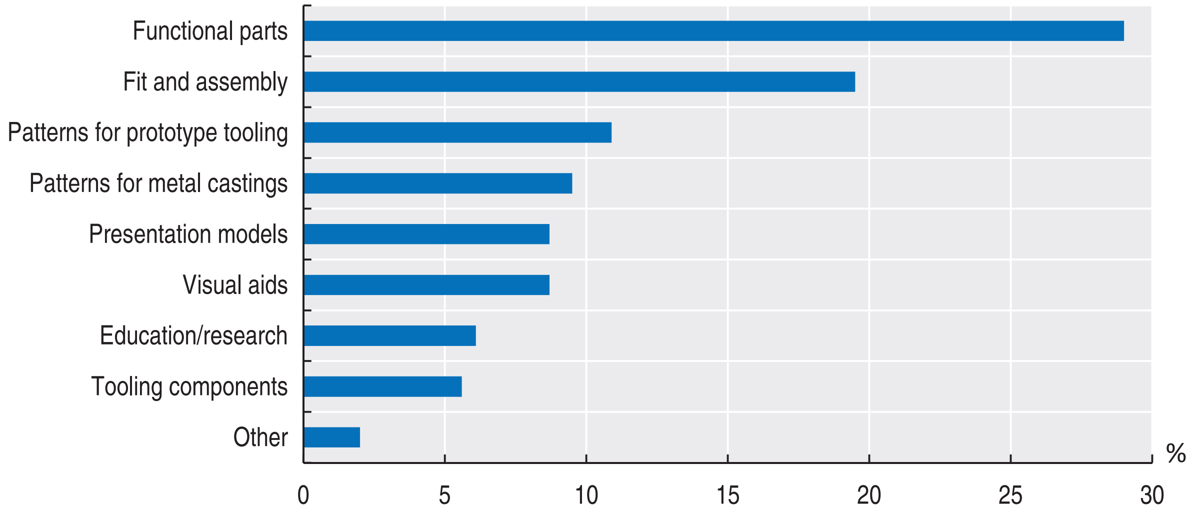


Source: Wohlers Associates (2014), *Wohlers Report 2014: 3D Printing and Additive Manufacturing State of the Industry: Annual Worldwide Progress Report*.

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.

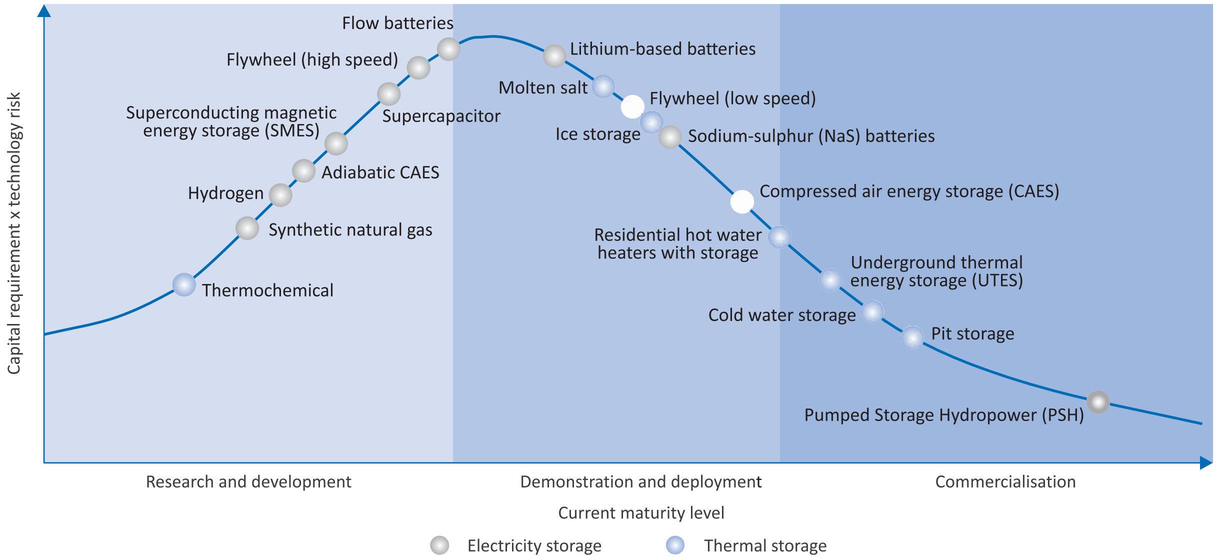
Energy storage technologies are essential to bridge temporal and geographical gaps between energy demand and supply

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

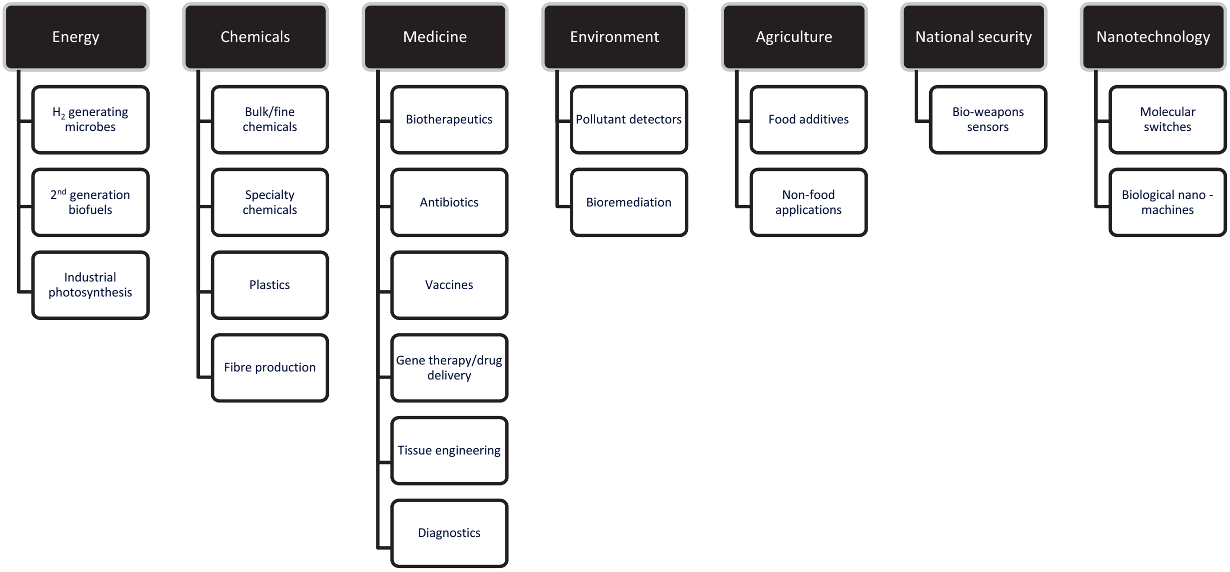
While humans have been involved in genetic manipulation by selective breeding for 10 000 years, it was only in the 1970s that the direct manipulation of DNA in organisms became possible through genetic engineering. Synthetic biology is a recent field of research that has introduced an engineering approach 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

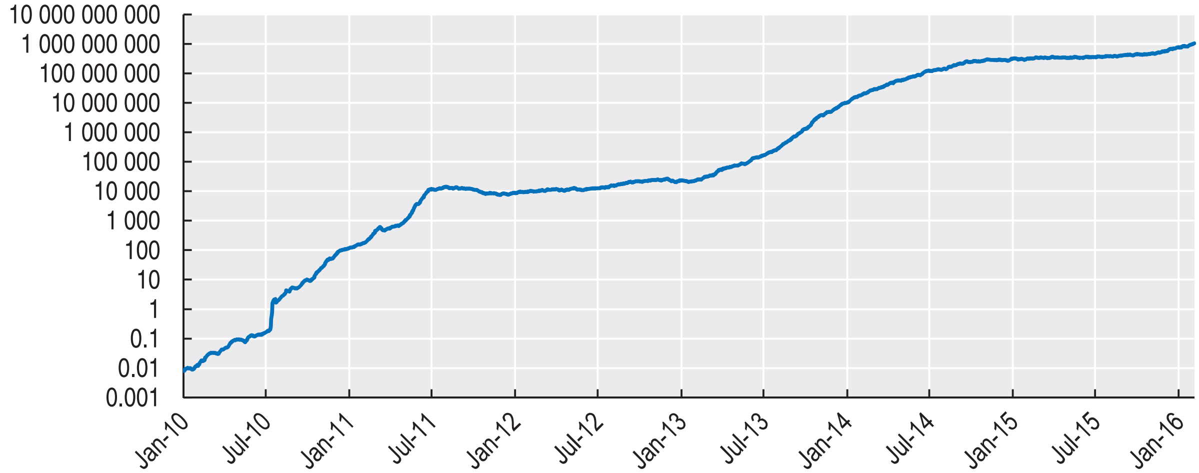
Blockchain technology offers the opportunity to append additional data to value transactions. These data could specify that certain rules must be met before the transfer takes place. In this way, a transaction works as an invoice that would be cleared automatically upon the fulfilment of certain conditions. 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 underdeveloped 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.

References

Akyildiz, I.F. et al. (2015), "The Internet of bio-nano things", *IEEE Communications Magazine*, Vol. 53/3, pp. 32-40.

Alivisatos, A.P. et al. (2015), "A national network of neurotechnology centers for the BRAIN Initiative", *Neuron*, Vol. 88, pp. 445-448, *http://dx.doi.org/10.1016/j.neuron.2015.10.015*.

Anderson, G. and J. Oderkirk (eds.) (2015), *Dementia Research and Care: Can Big Data Help?*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264228429-en*.

BASF (2015), "Research" (website), *www.nanotechnology.basf.com/group/corporate/nanotechnology/en/microsites/nanotechnology/research/index* (accessed 7 May 2016).

Bechtold, S. (2015), "3D printing and the intellectual property system", *Economic Research Working Paper*, No. 28, World Intellectual Property Organization, Economics and Statistics Division.

Bheemaiah, K. (2015), "Block Chain 2.0: The renaissance of money", *Wired*, 17 February, *www.wired.com/insights/2015/01/block-chain-2-0/* (accessed 7 May 2016).

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

Brynjolfsson, E. and A. McAffee (2015), "The jobs that AI can't replace", BBC News, 13 September, *www.bbc.com/news/technology-34175290* (accessed 7 May 2016).

Brynjolfsson, E. and A. McAffee (2014), *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, W.W. Norton & Company, New York.

Carlson, R. (2014), "Time for new DNA synthesis and sequencing cost curves", *SynBioBeta*, *http://synbiobeta.com/news/time-new-dna-synthesis-sequencing-cost-curves-rob-carlson/* (accessed 7 May 2016).

Carrington, D. (2016), "From liquid air to supercapacitors, energy storage is finally poised for a breakthrough", *The Guardian*, 4 February, *www.theguardian.com/environment/2016/feb/04/from-liquid-air-to-supercapacitators-energy-storage-is-finally-poised-for-a-breakthrough* (accessed 7 May 2016).

Chavez-Dreyfuss, G. (2015), "Honduras to build land title registry using bitcoin technology", Reuters, 15 May, *http://in.reuters.com/article/2015/05/15/usa-honduras-technology-idINKBN0O01V720150515* (accessed 7 May 2016).

Coeckelbergh, M. (2010), "Robot rights? Towards a social-relational justification of moral consideration", *Ethics and Information Technology*, Vol. 12/3, pp. 209-221.

Collins, F. (2012), "Win-win investments: Synthetic biology for growth and innovation", paper presented at the Science and Technology Options Assessment (STOA) workshop on "Synthetic biology", European Parliament, Brussels, 6 June, *www.europarl.europa.eu/stoa/cms/home/events/workshops/synthetic_biology* (accessed 7 May 2016).

Collins, L. and P. Baeck (2015), "Crowdfunding and cryptocurrencies", *Nesta*, 13 July, *www.nesta.org.uk/blog/crowdfunding-and-cryptocurrencies* (accessed 7 May 2016).

Crabtee, G. (2015), "Perspective: The energy-storage revolution", *Nature*, Vol. 526/7575, p. 92, *http://dx.doi.org/10.1038/526S92a*.

Daboussi, F. et al. (2014), "Genome engineering empowers the diatom *Phaeodactylum tricornutum* for biotechnology", *Nature Communications*, Vol. 5/3831, *http://dx.doi.org/10.1038/ncomms4831*.

Darling, K. (2012), "Extending legal rights to social robots", paper presented at We Robot Conference, Miami, 23 April, *http://robots.law.miami.edu/wp-content/uploads/2012/04/Darling_Extending-Legal-Rights-to-Social-Robots-v2.pdf* (accessed 7 May 2016).

Das, S., B. Sen and N. Debnath (2015), "Recent trends in nanomaterials applications in environmental monitoring and remediation", *Environmental Science and Pollution Research*, Vol. 22/23, pp. 18333-18344, *http://dx.doi.org/10.1007/s11356-015-5491-6*.

de Filippi, P. (2015), "Digital Europe: Peer-to-peer technology for social good", *Nesta*, 12 November, *www.nesta.org.uk/blog/digital-europe-peer-peer-technology-social-good* (accessed 7 May 2016).

de Lorenzo, V. and A. Danchin (2008), "Synthetic biology: Discovering new worlds and new words", *EMBO Reports*, Vol. 9/9, pp. 822-827, *http://dx.doi.org/10.1038/embor.2008.159*.

Depoorter, B. (2013), "Intellectual property infringements & 3D printing: Decentralized piracy", *Hastings Law Journal*, Vol. 65, p. 1483.

Dernis, H., M. Squicciarini and R. de Pinho (2015), "Detecting the emergence of technologies and the evolution and co-development trajectories in science (DETECTS): A 'burst' analysis-based approach", *Journal of Technology Transfer*, 24 October, pp.1-31, *http://dx.doi.org/10.1007/s10961-015-9449-0*.

EC (European Commission) (2014), "Preparing the Commission for Future Opportunities – Foresight Fiches: "Global Trends to 2030", *Working document*, *https://ec.europa.eu/digital-agenda/en/news/european-commission-foresight-fiches-global-trends-2030* (accessed 7 May 2016).

Element Energy (2012), *Cost and Performance of EV batteries: Final Report for the Committee on Climate Change*, Element Energy Limited, Cambridge, *www.element-energy.co.uk/wordpress/wp-content/uploads/2012/06/CCC-battery-cost_-Element-Energy-report_March2012_Finalbis.pdf* (accessed 7 May 2016).

Elsässer, M. (2013), "As solar costs drop, energy storage solutions take centre stage", Renewable Energy World.com, 24 July, *www.renewableenergyworld.com/articles/2013/07/as-solar-costs-drop-energy-storage-solutions-take-center-stage.html* (accessed 7 May 2016).

ESPAS (European Strategy and Policy Analysis System) (2015), *Global Trends to 2030: Can the EU Meet the Challenges Ahead?,* ESPAS, Brussels, *http://europa.eu/espas/pdf/espas-report-2015.pdf* (accessed 7 May 2016).

Evans, D. (2011), "The Internet of Things: How the next evolution of the Internet is changing everything", *Cisco White Paper*, CISCO IBSG (Internet Business Solutions Group), *www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf* (accessed 7 May 2016).

Fahlman, B.D. (2011), *Materials Chemistry*, 2nd edition, Springer, Netherlands.

Faircap (2014), "$1 water filter project" (website), *http://faircap.org/* (accessed 7 May 2016).

Faulkner-Jones, A. (2014), "Biofabrication: 3D stem cell printing", presentation at 3D Printshow 2014, London, 4-6 September.

Gibson I., D. Rosen and B. Stucker (2015), *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, 2nd ed., Springer, New York.

Giordano, J. (ed.) (2012), *Neurotechnology: Premises, Potential and Problems*, CRC Press.

Glancy, D.J. (2012), "Privacy in autonomous vehicles", *Santa Clara Law Review*, Vol. 52/4, pp. 1171-1239, *http://heinonline.org/HOL/LandingPage?handle=hein.journals/saclr52&div=38&id=&page=* (accessed 7 May 2016).

Hague, R.J.M. and P.E. Reeves (2000), "Rapid prototyping, tooling and manufacturing", *Rapra Review Reports*, Report 117, Vol. 10/9, Rapra Technology Ltd.

Helbing, D. (2015), "Societal, economic, ethical and legal challenges of the digital revolution: From big data to deep learning, artificial intelligence, and manipulative technologies", *SSRN (Social Science Research Network)*, *http://dx.doi.org/10.2139/ssrn.2594352*.

Hoffman, L. et al. (2015), "High-density optrode-electrode neural probe using Si(x)N(y) photonics for in vivo optogenetics" (Neuro-Electronics Research Flanders website), *www.nerf.be/assets/uploads/pages/IEDM-2015_Luis.pdf* (accessed 7 May 2016).

IEA (International Energy Agency) (2015), *Energy Technology Perspectives 2015*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/energy_tech-2015-en*.

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

IERC (European Research Cluster on the Internet of Things) (2015), "Internet of Things: IoT governance, privacy and security issues", *IERC Position Paper*, European Communities, *www.internet-of-things-research.eu/pdf/IERC_Position_Paper_IoT_Governance_Privacy_Security_Final.pdf* (accessed 7 May 2016).

ISO (International Organization for Standardization) (2012), *Definition 3.20 in Nanomaterials: Preparation of Material Safety Data Sheet (MSDS)*, *www.iso.org/obp/ui/#iso:std:iso:tr:13329:ed-1:v1:en* (accessed 7 May 2016).

ITF (International Transport Forum) (2015), *Automated and Autonomous Driving: Regulation under Uncertainty*, OECD Publishing, Paris.

ITF (2014), *Mobility Data: Changes and Opportunities*, OECD Publishing, Paris.

Koch, C. and G. Marcus (2015), “Neuroscience in 2064”, in G. Marcus and J. Freeman (eds.), *The Future of the Brain*, Princeton University Press, Princeton and Oxford.

Kravitz, A. and A. Bonci (2013), “Optogenetics, physiology, and emotions”, *Frontiers in Behavioral Neuroscience*, Vol. 7/169, pp. 1-4, *http://dx.doi.org/10.3389/fnbeh.2013.00169*.

Kuusi, O. and A.L. Vasamo (2014), *100 Opportunities for Finland and the World: Radical Technology Inquirer (RTI) for Anticipation/Evaluation of Technological Breakthroughs*, Committee for the Future, Helsinki, *www.eduskunta.fi/FI/tietoaeduskunnasta/julkaisut/Documents/tuvj_11+2014.pdf* (accessed 7 May 2016).

López Peláez, A. and D. Kyriakou (2008), “Robots, genes and bytes: Technology development and social changes towards the year 2020”, *Technological Forecasting and Social Change*, Vol. 75, pp. 1176-1201, *http://dx.doi.org/10.1016/j.techfore.2008.01.002*.

Maharbiz, M.M. (2015), “Neural dust: an untethered approach to chronic brain machine interfaces”, in G. Marcus and J. Freeman (eds.), *The Future of the Brain*, Princeton University Press, Princeton and Oxford.

Mak, J.N. and J.R. Wolpaw (2009), “Clinical applications of brain-computer interfaces: Current state and future prospects”, *IEEE Reviews in Biomedical Engineering*, Vol. 2, pp. 187-199, *http://dx.doi.org/10.1109/RBME.2009.2035356*.

MarketsandMarkets (2014), *Additive Manufacturing & Material Market by Technology, by Material (Plastics, Metals, and Ceramics), by Application, and by Geography – Analysis & Forecast to 2014-20*, MarketsandMarkets, Dallas.

Mavroidis, C. and A. Ferreira (2013), *Nanorobotics: Current Approaches and Techniques*, Springer, New York.

MGI (McKinsey Global Institute) (2013), *Disruptive Technologies: Advances That Will Transform Life, Business and the Global Economy*, McKinsey & Company, *www.mckinsey.com/business-functions/business-technology/our-insights/disruptive-technologies* (accessed 7 May 2016).

MGI (2011), *Big Data: The Next Frontier for Innovation, Competition and Productivity*, McKinsey & Company, *www.mckinsey.com/business-functions/business-technology/our-insights/big-data-the-next-frontier-for-innovation* (accessed 7 May 2016).

Motavalli, J. (2015), “Technology: A solid future”, *Nature*, Vol. 526/7575, pp. 96-97, *http://dx.doi.org/10.1038/526S96a*.

Nanowerk (2015), *Nanotechnology in cosmetics*, *www.nanowerk.com/nanotechnology-in-cosmetics.php* (accessed 7 May 2016).

Nanowerk (2014), *Nanotechnology start-up develops a first-of-its-kind multifunction water filtration membrane*, *www.nanowerk.com/nanotechnology-news/newsid=37320.php* (accessed7 May 2016).

Nash, K.S. (2016), “Blockchain: Catalyst for massive change across industries”, *The Wall Street Journal*, 2 February, *http://blogs.wsj.com/cio/2016/02/02/blockchain-catalyst-for-massive-change-across-industries/* (accessed 7 May 2016).

Nijboer, F. et al. (2013), “The Asilomar survey: Stakeholders’ opinions on ethical issues related to brain-computer interfacing”, *Neuroethics*, Vol. 6, pp. 541-578, *http://dx.doi.org/10.1007/s12152-011-9132-6*.

Nuffield Council on Bioethics (2013), *Novel Neurotechnologies: Intervening in the Brain*, Nuffield Council on Bioethics, London, *http://nuffieldbioethics.org/wp-content/uploads/2013/06/Novel_neurotechnologies_report_PDF_web_0.pdf* (accessed 7 May 2016).

OECD (Organisation for Economic Co-operation and Development) (2016a), “The Internet of Things: Seizing the Benefits and Addressing the Challenges”, *OECD Digital Economy Papers*, No. 252, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jlwvzz8td0n-en*.

OECD (2016b), *STI Micro-data Lab: Intellectual Property Database*, *http://oe.cd/ipstats*.

OECD (2015a), *OECD Digital Economy Outlook 2015*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264232440-en*.

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

OECD (2015c), “Enabling the Next Production Revolution”, *Issues Paper*, OECD, Paris, *www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=DSTI/IND(2015)2&docLanguage=En* (accessed 7 May 2016).

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

OECD (2015e), "Testing Programme of Manufactured Nanomaterials web page", OECD Publishing, Paris, *www.oecd.org/chemicalsafety/nanosafety/testing-programme-manufactured-nanomaterials.htm* (accessed 7 May 2016).

OECD (2015f), "Refining regulation to enable major innovations in financial markets", *Issues Paper from the OECD Competition Division*, OECD Publishing, Paris, *www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=DAF/COMP/WP2(2015)9&doclanguage=en* (accessed 7 May 2016).

OECD (2014a), *OECD Science, Technology and Industry Outlook 2014*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/sti_outlook-2014-en*.

OECD (2014b), *The Space Economy at a Glance 2014*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264217294-en*.

OECD (2014c), *Emerging Policy Issues in Synthetic Biology*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264208421-en*.

OECD (2013a), "Protection of privacy in the collection and use of personal health data", in *Strengthening Health Information Infrastructure for Health Care Quality Governance: Good Practices, New Opportunities and Data Privacy Protection Challenges*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264193505-9-en*.

OECD (2013b), "Policies for bioplastics in the context of a bioeconomy", *OECD Science, Technology and Industry Policy Papers*, No. 10, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5k3xpf9rrw6d-en*.

OECD (2011), *Nanosafety at the OECD: The First Five Years 2006-2010*, OECD Publishing, Paris, *www.oecd.org/env/ehs/nanosafety/47104296.pdf*.

Olson, R. (2013), "3-D printing: A boon or a bane?", *The Environmental Forum*, Vol. 30/6, p. 34, *www.wilsoncenter.org/sites/default/files/OLSON_FORUM_NOV-DEC_2013-1.pdf (accessed* 7 May 2016).

Pagliery, J. (2015), "Record $1 billion invested in Bitcoin firms so far", CNN Money, 3 November, *http://money.cnn.com/2015/11/02/technology/bitcoin-1-billion-invested/* (accessed 7 May 2016).

Perera, C. et al. (2015), "Big Data Privacy in the Internet of Things Era", *IT Professional*, Vol. 17/3, *http://doi.ieeecomputersociety.org/10.1109/MITP.2015.34* (accessed 7 May 2016).

Piniewski, B., C. Codagnone and D. Osimo (2011), *Nudging Lifestyles for Better Health Outcomes, Crowdsourced Data and Persuasive Technologies for Behavioural Change*, European Union, Luxembourg, *http://ftp.jrc.es/EURdoc/JRC64206.pdf* (accessed 7 May 2016).

Policy Horizons Canada (2013), *METASCAN3 – Emerging Technologies: A Foresight Study Exploring How Emerging Technologies Will Shape the Economy and Society and the Challenges and Opportunities They Will Create*, Government of Canada, Ottawa, *www.horizons.gc.ca/sites/default/files/Publication-alt-format/pdf_version_0239_6698kb-45pages.pdf* (accessed 7 May 2016).

Potomac Institute (2015), *Trends in Neurotechnology*, Potomac Institute for Policy Studies, Arlington, Virginia, *www.potomacinstitute.org/images/stories/publications/NeuroTrendsAug2015.pdf* (accessed 7 May 2016).

Roland Berger (2014), "Les classes moyennes face à la transformation digitale: Comment anticiper? Comment accompagner?", *Think Act*, October, *www.rolandberger.fr/media/pdf/Roland_Berger_TAB_Transformation_Digitale-20141030.pdf* (accessed 7 May 2016).

Royal Academy of Engineering (2009), *Synthetic Biology: Scope, Applications and Implications*, Royal Academy of Engineering, London, *www.raeng.org.uk/publications/reports/synthetic-biology-report* (accessed 7 May 2016).

Sample, I. (2015), "Genome editing: How to modify genetic faults – and the human germline", *The Guardian*, 2 September, *www.theguardian.com/science/2015/sep/02/genome-editing-how-to-modify-genetic-faults-and-the-human-germline* (accessed 7 May 2016).

Santander Innoventures, Oliver Wyman and the Anthemis Group (2015), "The Fintech 2.0 paper: rebooting financial services" (website), *http://santanderinnoventures.com/wp-content/uploads/2015/06/The-Fintech-2-0-Paper.pdf* (accessed 7 May 2016).

SCENIHR (European Commission Scientific Committee on Emerging and Newly Identified Health Risks) (2009), *Risk Assessment of Products of Nanotechnologies*, European Commission Directorate-General for Health & Consumers, Brussels, *http://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_023.pdf* (accessed 7 May 2016).

SCHER, SCENIHR and SCCS (EC Scientific Committees on: Health and Environmental Risks, Emerging and Newly Identified Health Risks, Consumer Safety) (2015), *Opinion on Synthetic Biology II: Risk Assessment Methodologies and Safety Aspects*, European Union, Luxembourg, *http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_048.pdf* (accessed 7 May 2016).

Schermer, M. (2009), “The mind and the machine. On the conceptual and moral implications of brain-machine interaction”, *Nanoethics*, Vol. 3/3, pp. 217-230, *http://dx.doi.org/10.1007/s11569-009-0076-9*.

Shih, J.J., D.J. Krusienski and J.R. Wolpaw (2012), “Brain-computer interfaces in medicine”, *Mayo Clinic Proceedings*, Vol. 87/3, pp. 268-279, *http://doi.org/10.1016/j.mayocp.2011.12.008*.

SpaceWorks (2015), *2015 Small Satellite Market Observations*, SpaceWorks Enterprises Inc. (SEI), Atlanta (GA), *www.spaceworksforecast.com/docs/SpaceWorks_Small_Satellite_Market_Observations_2015.pdf* (accessed 7 May 2016).

SpaceWorks (2014), *2014 Nano/Microsatellite Market Assessment*, SpaceWorks Enterprises Inc. (SEI), Atlanta (GA), *www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf* (accessed 7 May 2016).

Sriraman, N. and A. Fernandez (2015), *Good News: Pervasive Neurotechnology – The Digital Revolution Meets the Human Brain*, *http://sharpbrains.com/blog/2015/06/09/good-news-the-digital-revolution-meets-the-human-brain-as-evidence-by-the-explosion-of-neurotech-patent-filings/* (accessed 7 May 2016).

Stephens, B. et al. (2013), “Ultrafine particle emissions from desktop 3D printers”, *Atmospheric Environment*, Vol. 79, pp. 334-339, *http://dx.doi.org/10.1016/j.atmosenv.2013.06.050*.

Suran, M. (2014), “A little hard to swallow?”, *EMBO Reports*, Vol. 15/6, pp. 638-641, *http://dx.doi.org/10.15252/embr.201438925*.

The Economist (2015), “The great chain of being sure about things”, *The Economist*, 31 October, *www.economist.com/news/briefing/21677228-technology-behind-bitcoin-lets-people-who-do-not-know-or-trust-each-other-build-dependable* (accessed 7 May 2016).

Thomson, A. (2015), “Using the blockchain to fight crime and save lives”, *TechCrunch*, 27 September, *http://techcrunch.com/2015/09/27/using-the-blockchain-to-the-fight-crime-and-save-lives/* (accessed 7 May 2016).

Travis, J. (2015), “Germline editing dominates DNA summit”, *Science Magazine,* Vol. 350/6266, pp. 1299-1300, *http://dx.doi.org/10.1126/science.350.6266.1299*.

Tsuzuki, T. (2009), “Commercial scale production of inorganic nanoparticles”, *International Journal of Nanotechnology*, Vol. 6/5-6, pp. 567-578, *http://dx.doi.org/10.1504/IJNT.2009.024647*.

Ubaldi, B. (2013), “Open government data: Towards empirical analysis of open government data initiatives”, *OECD Working Papers on Public Governance*, No. 22, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5k46bj4f03s7-en*.

UK GOS (Government Office for Science) (2016), “Distributed Ledger Technology: beyond block chain”, UK GOS, 19 January, *www.gov.uk/government/uploads/system/uploads/attachment_data/file/492972/gs-16-1-distributed-ledger-technology.pdf* (accessed 7 May 2016).

UK GOS (2012), *Technology and Innovation Futures: UK Growth Opportunities for the 2020s – 2012 Refresh*, Department for Business, Innovation and Skills, London, *www.gov.uk/government/uploads/system/uploads/attachment_data/file/288562/12-1157-technology-innovation-futures-uk-growth-opportunities-2012-refresh.pdf* (accessed 7 May 2016).

UK IPO (Intellectual Property Office) (2014), *Eight Great Technologies: the Patent Landscapes*, United Kingdom, *www.gov.uk/government/uploads/system/uploads/attachment_data/file/360986/Eight_Great_Technologies.pdf* (accessed 7 May 2016).

University of Massachusetts Amherst (2014), “Promising new method found for rapidly screening cancer drugs” (news release), *www.umass.edu/newsoffice/article/promising-new-method-found-rapidly* (accessed 7 May 2016).

US Department of Energy (2014), *Energy Storage Safety Strategic Plan*, Office of Electricity Delivery and Energy Reliability, Washington, DC, *http://energy.gov/sites/prod/files/2014/12/f19/OE%20Safety%20Strategic%20Plan%20December%202014.pdf* (accessed 7 May 2016).

US FAA (Federal Aviation Agency) (2015), *2015 Commercial Space Transportation Forecasts*, FAA Commercial Space Transportation (AST) and the Commercial Space Transportation Advisory Committee (COMSTAC), Washington DC, *www.faa.gov/about/office_org/headquarters_offices/ast/media/Commercial_Space_Transportation_Forecasts_2015.pdf* (accessed 7 May 2016).

US NASA (National Aeronautics and Space Administration) (2014), *Small Spacecraft Technology: State of the Art*, NASA/TP–2014–216648, NASA Ames Research Center, Moffett Field, California, *http://cmapspublic3.ihmc.us/rid=1NG0S479X-29HLYMF-18L7/Small_Spacecraft_Technology_State_of_the_Art_2014.pdf* (accessed 7 May 2016).

Vance, M.E. et al. (2015), “Nanotechnology in the real world: Redeveloping the nanomaterial consumer products inventory”, *Beilstein Journal of Nanotechnology*, Vol. 6, Beilstein-Institut, Frankfurt am Main, pp. 1769-1780, *http://dx.doi.org/10.3762/bjnano.6.181*.

VDI (Verein Deutscher Ingenieure) Technologiezentrum GmbH, Innovationsbegleitung und Innovationsberatung (2015), *Forschungs- und Technologieperspektiven 2030, Ergebnisband 2 zur Suchphase von BMBF-Foresight Zyklus II*, Düsseldorf, *www.bmbf.de/files/VDI_Band_101_C1.pdf* (accessed 7 May 2016).

Vogel, J.B. (2013), *IP: 3D printing and potential patent infringement*, Inside Counsel, 29 October, *www.insidecounsel.com/2013/10/29/ip-3d-printing-and-potential-patent-infringement* (accessed 7 May 2016).

von Hippel, E. (2005), *Democratizing Innovation*, MIT Press, Cambridge, Massachusetts.

Wade, N. (2015), “Scientists seek moratorium on edits to human genome that could be inherited”, *The New York Times*, *www.nytimes.com/2015/12/04/science/crispr-cas9-human-genome-editing-moratorium.html* (accessed 7 May 2016).

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

Wolinsky, H. (2009), “Kitchen biology. The rise of do-it-yourself biology democratizes science, but is it dangerous to public health and the environment?”, *EMBO Reports*, Vol. 10/7, pp. 683-685, *www.ncbi.nlm.nih.gov/pmc/articles/PMC2727445/* (accessed 7 May 2016).

Wolpaw, J.R. (2010), “Brain-computer interface research comes of age: Traditional assumptions meet emerging realities”, *Journal of Motor Behaviour*, Vol. 42/6, pp. 351-353, *http://dx.doi.org/10.1080/00222895.2010.526471*.

Further reading

Autor, D.H. (2015), “Why are there still so many jobs? The history and future of workplace automation”, *Journal of Economic Perspectives*, Vol. 29/3, pp. 3-30, *http://dx.doi.org/10.1257/jep.29.3.3*.

Donoghue, J. (2015), “Neurotechnology”, in G. Marcus and J. Freeman (eds.), The Future of the Brain, Princeton University Press, Princeton and Oxford.

Gokhberg, L. (ed.) (2014), *Russia 2030: Science and Technology Foresight*, Ministry of Education and Science of the Russian Federation, National Research University Higher School of Economics.

Goldin, I. and A. Pitt (2014), “Future opportunities, future shocks: Key trends shaping the global economy and society”, *Citi GPS: Global Perspectives & Solutions*, Oxford Martin School, *www.oxfordmartin.ox.ac.uk/downloads/reports/Opportunities_Shocks_Citi_GPS.pdf* (accessed May 2016).

IEA-ETSAP and IRENA (International Renewable Energy Agency) (2012), “Electricity storage”, *Technology Policy Brief E18*, Bonn, Germany, *www.irena.org/DocumentDownloads/Publications/Electricity%20Storage%20-%20Technology%20Brief.pdf* (accessed 7 May 2016).

IFR (International Federation of Robotics) (2015), *World Robotics 2015 Industrial Robots*, *www.ifr.org/industrial-robots/statistics/* (accessed 7 May 2016).

Mervis, J. (2016), *Updated: Budget Agreement Boosts U.S. Science*, American Association for the Advancement of Science, *www.sciencemag.org/news/2015/12/updated-budget-agreement-boosts-us-science?_ga=1.94259668.816241758.1454942844#table* (accessed 7 May 2016).

NIC (National Intelligence Council) (2012), *Global Trends 2030: Alternative Worlds*, US NIC, Washington, DC, *https://globaltrends2030.files.wordpress.com/2012/11/global-trends-2030-november2012.pdf* (accessed 7 May 2016).

OECD (2008), *Inventory of National Science, Technology and Innovation Policies for Nanotechnology 2008*, OECD Publishing, Paris, *www.oecd.org/sti/nano/43348394.pdf* (accessed 7 May 2016).

SCHER, SCENIHR and SCCS (2014), *Opinion on Synthetic Biology I: Definition*, European Union, Luxembourg, *http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_044.pdf* (accessed 7 May 2016).

Wolpaw, J.R. and E.W. Wolpaw (2012), “Brain-computer interfaces: Something new under the sun”, in *Brain-Computer Interfaces: Principles and Practice*, pp. 3-12, Oxford University Press, New York, *http://dx.doi.org/10.1093/acprof:oso/9780195388855.001.0001*.

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

OECD Science, Technology and Innovation Outlook 2016

Please cite this chapter as:

OECD (2016), “Future technology trends”, in *OECD Science, Technology and Innovation Outlook 2016*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/sti_in_outlook-2016-5-en