Assessment of global megatrends — an update

Global megatrend 4: Accelerating technological change

European Environment Agency

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Europe is bound to the rest of the world through an enormous number of systems — environmental, economic, social, political and others. Such networks enable complex flows of materials and ideas across the globe, producing uncertain feedbacks and knock-on effects over time. Greenhouse gas emissions in Europe today can affect the climate in distant locations and far into the future. Land management choices on the other side of the world can influence food and energy prices in Europe. Global communication and trade networks fuel innovation — sometimes boosting efficiency, sometimes creating new environmental pressures.

Most of these interactions are intimately linked and set to unfold over decades. All are likely to have important implications for living standards and well-being.

The European environment's status, trends and prospects have always depended in part on events outside its borders. Yet the growing importance of global networks and flows has augmented this interdependence, creating complex challenges for traditional governance systems framed within national or regional territories. To design effective ways to manage the environmental changes ahead, societies and governments need to understand the global drivers at work and their potential implications.

With this challenge in mind, the European Environment Agency in 2010 produced its first assessment of emerging global trends as part of its five-yearly flagship report on the European environment's state and outlook (SOER 2010). The exploratory analysis summarised 11 global megatrends grouped into five clusters — social, technological, economic, environmental and governance. Introducing the issues succinctly, it sought to trigger a discussion about how Europe should monitor and assess future changes in order to better inform environmental policymaking.

In preparation for its next report on the European environment's state and outlook (SOER 2015), the EEA has initiated an update of the assessment of global megatrends, analysing each of these drivers in a little more detail than previously in terms of their impacts on the European environment and well-being. During the second half of 2013 and 2014, the EEA is reassessing the 11 megatrends and publishing the updates separately on its website. The chapters provide the basis for the analysis of megatrends included in SOER 2015 and will be consolidated into a single EEA technical report in 2015. The present chapter addresses megatrend 4: 'Accelerating technological change'.

Again, it needs to be emphasised that the complexity of highly interconnected human and natural systems introduces considerable uncertainty into projections and forecasts. As much as anything, the assessment of megatrends aims to encourage readers to acknowledge this interdependence and uncertainty. In so doing, it may help point the way towards systems of planning and governance better adapted to meeting the challenges ahead.

Global megatrend 4 Accelerating technological change

The pace of technological change is accelerating. The shifts in technological paradigms that once were separated by centuries or millennia — such as the development of agriculture or the industrial revolutions based on steam and then electric power — are now occurring within a single lifetime. Indeed, the pace at which new technologies are being adopted by the market and used in society has rocketed over the past century and a half. In the early 1900s, it took more than 30 years for a quarter of the US population to adopt telephones and radios — but more recently, the World Wide Web reached this level in only seven years.

Today, research and development around the world are accelerating — in particular for nanotechnologies, biotechnology and information and computer technology. Moreover, the integration of techniques and knowledge across these three areas as well as closely related ones is speeding up the pace of discovery. The new products and innovations emerging from this 'NBIC cluster' can increase resource efficiency and support the shift to low-carbon economies. In this process, technological change may transform energy, manufacturing, health care and many other sectors over the coming decades.

Along with the opportunities, accelerating change will also create new risks for society, for health and for the environment. Institutional and policy innovations will be needed to minimise the emerging risks and promote technological change that supports public goals.

4.1 Drivers

Economic and social megatrends are driving the ever-faster pace of technological development and market adoption. Ongoing economic growth, in particular in Asia and other developing regions, will support greater research and development around the world. The growing middle class in the emerging economies of an increasingly multipolar world will bring new and larger markets for innovative products (GMT 5 and GMT 6). These economies are expected to see rising levels of education, boosting the human capital for research and innovation (GMT 1). The Organisation for Economic Co-operation and Development (OECD) projects that, in coming decades, the number of young people with a tertiary education will be higher and grow fastest in such non-OECD G20 countries such as Brazil, China and India (OECD, 2013). Already, the numbers of engineering graduates in these countries has grown rapidly in recent years (Loyalka et al., 2013).

The growing urban areas of the developing world, including megacities from Kuala Lumpur to Sao Paolo, are expected to further drive innovation, as they create a critical mass of education, research, markets and social needs to sustain it. Cities will, however, need effective planning and strong investment in infrastructure in order to achieve and maintain innovation, for example by attracting and keeping skilled workers (GMT 2).

Economic growth is thus driving technological development — and at the same time, policies support research and innovation as a driver for economic growth. Policy initiatives support new technology as a key to growth in Europe (EC, 2015c) and around the world; they follow in the footsteps of research by 1987 Nobel Prize winning economist Robert Solow, who showed that technological progress is one of the three key factors for economic growth, along with capital and labour — and in the long run, it becomes the dominant factor.

The growing global population and economy will lead to intensified competition for resources, from fossil fuels to critical raw materials: many of these non-renewable resources are scarce (particularly in Europe), costly to extract or unevenly distributed globally, creating risks of supply disruptions (GMT 7). This is a driver for technological development, as competition spurs research into alternative energy sources, substitutes for scarce materials and new extraction methods as well as more efficient ways of using these resources. Ecosystem degradation is threatening renewable resources such as timber (GMT 8): this may drive innovation to improve the efficiency of extraction and use and also to strengthen ecosystem protection and management. The growing threats of climate change (GMT 9) and environmental pollution (GMT 10) can also spur research and innovation for low-carbon and less pollution technologies.

Finally, technology itself is a driver: the Internet is facilitating new forms of communication, collaboration and access to information — factors that in accelerate scientific collaboration and innovation. At the same time, many inventions build on previous ones, and this means that technological changes are often 'path dependent' (Biois, 2013). Even with the changes from typewriters to tablet computers, the pattern of letters on keyboards — set over a century ago — remains in use. On a broader scale, over a century of research and infrastructure have the internal combustion engine a persistent feature of the modern world. As a result, it is vital to look ahead to possible technological developments and consider their benefits and risks ahead of time — rather than when they become pervasive in the economy and in our lives.

4.2 Trends

Many observers foresee that the core of the next, long-term wave of innovation and growth will be formed by links among: the rapidly emerging nanosciences and nanotechnologies, biotechnology and life-sciences, and information and computer technology (ICT) together with cognitive sciences and neurotechnologies — the 'NBIC cluster' (Nightingale et al., 2008; Silberglitt et al., 2002). Indeed, these areas of knowledge have already seen far-reaching advances, and much greater developments are foreseen in coming decades. Cycles of technology-induced social and economic change have accelerated in recent decades and are likely to move even faster: as described in the following pages, there is evidence of exponential rather than linear growth for some areas of technological progress.

Research is becoming more global, including for the NBIC cluster. New centres of innovation are taking seed in the developing world, heightening competition and shortening product innovation cycles. Europe trails the US and Japan in terms of global innovation performance, but remains ahead of others, although South Korea and China are developing rapidly (EC, 2014b). North America and Europe are expected to remain important centres of R&D, but there is a shift in the technological centre of gravity to fast-growing countries of Asia and Latin America (NIC, 2012). India, South Korea and particularly China are already increasing their share of patent filings, simultaneously providing markets for new products (WIPO, 2014). Asian economies, Latin America and other rising technology centres are expected to grow in importance in coming decades.

Although the acceleration of innovation and technological change is stable, its direction is uncertain. Many NBIC technologies are still in the laboratory, and future discoveries cannot be predicted — nor which innovations will be commercially viable. Besides technological constraints, key uncertainties relate to future levels of research funding and also to the role of public policy. Intellectual property regimes and the way they may shape development are also a major concern across new technologies (Biois, 2013).

4.2.1 Nanotechnology

Nanotechnology involves the manipulation of materials at minute scale: the United States National Nanotechnology Initiative defines nanotechnology as the 'understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications' (NNI, 2013). In 2011, the European Commission published a definition of nanomaterials (EC, 2011a) for European legislation and policy on nanotechnology:

- 'Nanomaterial' means a material containing particles where for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm.
- Includes aggregates and agglomerates.
- In specific cases and where warranted by concerns for the environment, health, safety or competitiveness the number size distribution threshold of 50% may be replaced by a threshold between 1 and 50%.

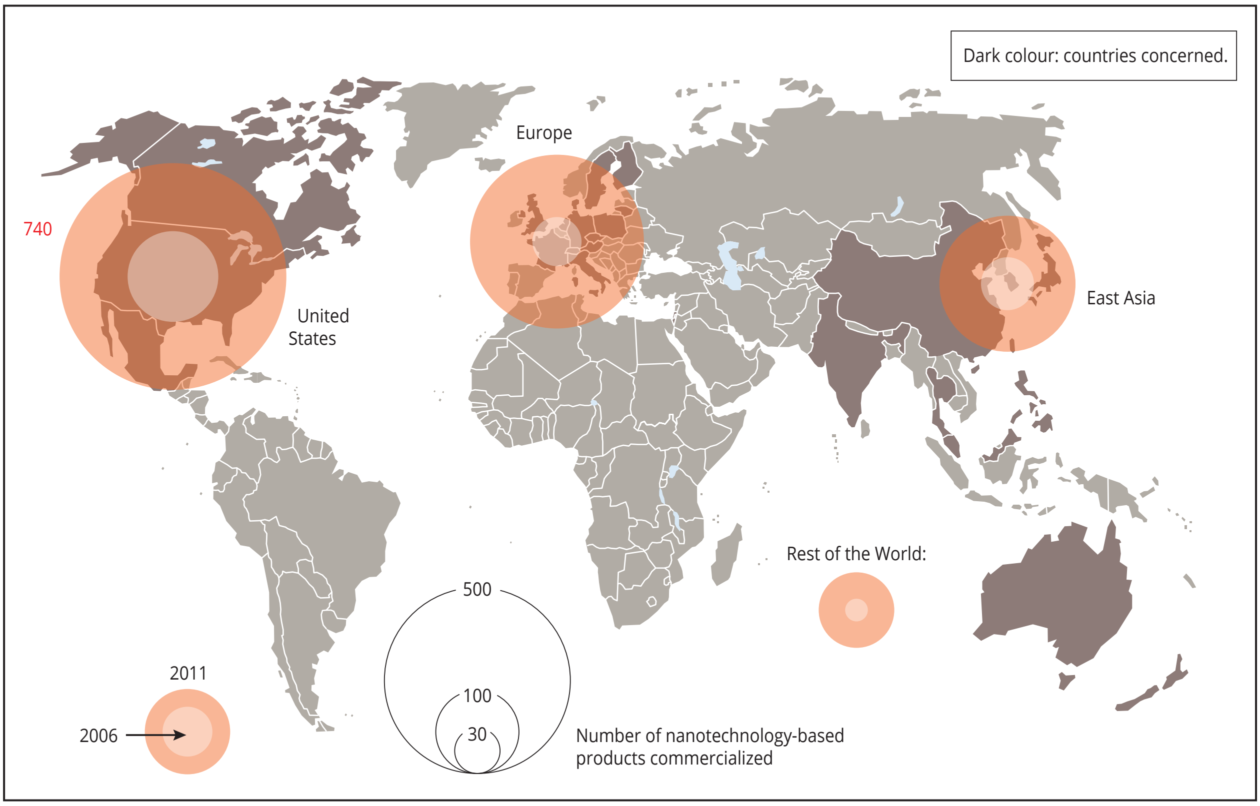
This burgeoning field includes many different techniques, materials, applications and products. Nanomaterials are sought after for their special properties, such as greater reactivity, unusual electrical properties or enormous strength per unit of weight compared to normal materials.

Although nanotechnology is only a couple of decades old, it already plays a major role in at least eight major industries: aerospace, automotive, construction, electronics, energy and environment, manufacturing, medical and pharmaceutical, and oil and gas (Forfàs, 2010). Moreover, nanomaterials are increasingly found in consumer products such as cosmetics, personal care products and clothing: in 2013, the Wilson Canter's Project on Emerging Nanomaterials identified 1628 consumer products containing nanomaterials in 30 different countries (Figure 4.1), almost four times as many products compared to 2006.

Among the applications, researchers are seeking to use nanomaterials to create substitutes for critical raw materials, minerals that are at a high risk of supply shortage (GMT 7). Some of these materials are used for key products such as advanced batteries and solar cells (Box 4.1).

Advances in the control of matter at the nanoscale continue, often with synergies from other emerging technologies. In 2010, for example, scientists succeeded in creating a DNA assembly line with the potential to create novel materials efficiently on the nanoscale (Gu et al., 2010). In 2013, researchers achieved the self-assembly of nanochains for the first time (Liu et al., 2013), a technique that could open a path for the creation of still new materials and products (Travesset, 2011).

Figure 4.1 Number of consumer products on the market containing nano-materials, by major world region



Note: Europe data include United Kingdom, France, Germany, Finland, Switzerland, Italy, Sweden, Denmark, the Netherlands.

East Asia data include China, Taiwan, Korea, Japan.

Other data include Australia, Canada, Mexico, Israel, New Zealand, Malaysia, Thailand, Singapore, The Philippines, Malaysia.

Source: Wilson Center, 2013.

Box 4.1 Nanotechnology and critical raw materials

Indium, a critical raw material, is used in indium tin oxide (ITO) to make the organic light emitting diodes (OLEDs) for displays and touch screens and as a conductor in solar cells. Silver nanowires offer an alternative to ITO in touch screen displays, whereby genetically modified viruses are used to create transparent coatings made of silver nanowires. Another possible alternative is the use of nano graphene. While applications of both nano graphene and silver nanowires in products remain at the research stage, 2013 saw the commercialisation and mass production of a nanoparticle coating to produce transparent conductive films. These nanoscale substitutes could reduce the demand for indium and enable the continued growth of technologies dependent on transparent conductors (Johnson, 2013). Regarding the use of indium in solar cells, researchers in the Netherlands have created a possible synthetic replacement in the form of a composite of carbon nanotubes and plastic nanoparticles that could have the potential for high levels of electrical conductivity. Commercially, this could reduce the costs of solar cells (Kyrylyuk et al., 2011).

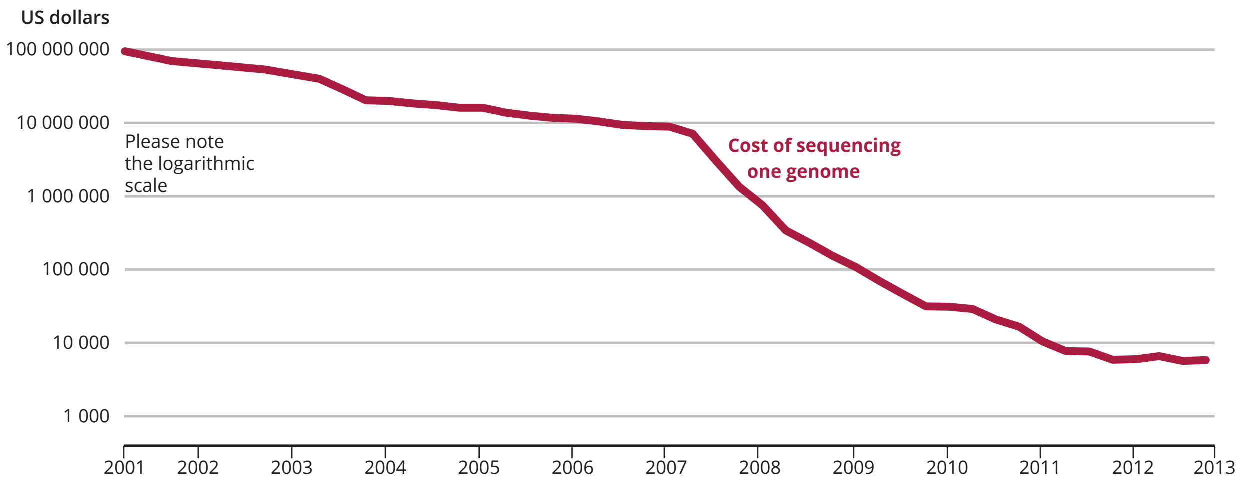
Research is also seeking to develop methods to synthesise nanomaterials using critical raw materials, in order to reduce the amounts needed. For example researchers have made progress in engineering gallium nitride nanotubes from gallium oxide powder, with potential application in photocatalysis, nanoelectronics, optoelectronics and biochemical sensors (Osborne, 2013, Jiang et al., 2013). Scientists have also succeeded in synthesising germanium nanomaterials, which could have applications in flash memories and lithium-ion batteries (Vaughn and Schaak, 2013). Semiconductor nanowires using indium phosphide and gallium arsenide have been developed, these may reduce the amounts of these materials needed to make solar cells by a factor of 1000 (Heiss et al., 2013).

4.2.2 *Biotechnology*

Biotechnology refers, broadly, to the 'application of science and technology to living organisms' (OECD, 2005), in particular their genomes. Biotechnology has contributed to a broad range of existing applications, including: the development of new medicines, health diagnostics and treatments for treatments such as dementia (Biois, 2013); testing methods for animal disease and food safety more generally; enzymes for chemical production, pulp and paper manufacturing, textile production and other industrial applications; (and also enzymes in consumer products, such as detergents); and microbes for the bioremediation of contaminated sites (JRC/IPTS, 2007).

Over the past decade, the costs of genomic sequencing, a key tool in biotechnology, have fallen exponentially: by 2013, a human genome could be sequenced in a few hours and for a few thousand dollars, a task that just over a decade ago took $2.7 billion and 13 years to accomplish during the Human Genome Project (Figure 4.2). This drop in

Figure 4.2 The falling cost of DNA sequencing



Source: NHGRI, 2013.

price is expected to be a catalyst for biotechnology research and innovation.

With these advances, biotechnology is profoundly changing healthcare. For example, genetic sequencing, already used for diagnosing health problems and developing therapies, could become a common element in healthcare: it could, for example, create more effective, personalised treatments for many types of disease, including cancer. Genetic research is looking to regrow organs and even improve them (Subramanian, 2009). The synergies between bio and nanotechnologies and ICT could drive further innovations: for example, drugs for cancer could be embedded in nanoparticles for targeted release when they reach tumours (Manyika et al., 2013).

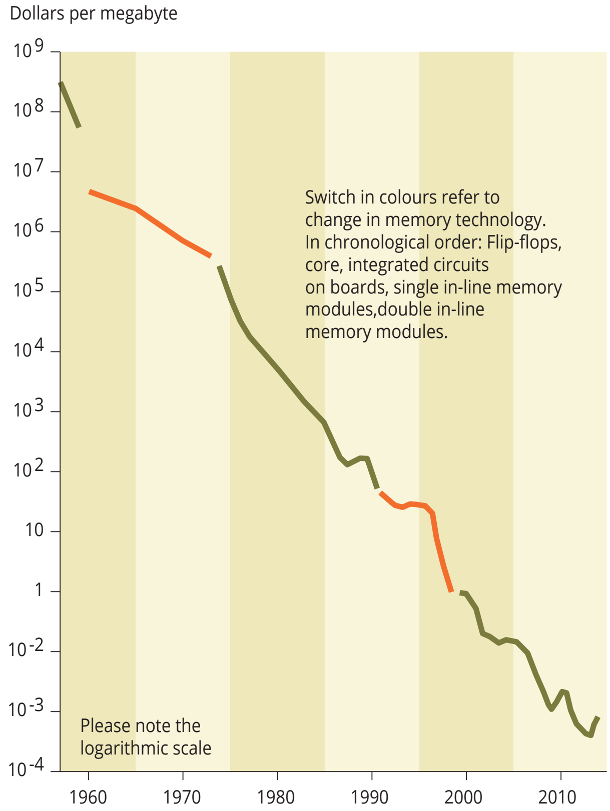
In recent years, a new field has emerged: synthetic biology, the design of new 'biological parts, devices, and systems' and the re-design of existing ones (SB, 2013). . In the laboratory, synthetic biology techniques have been used to modify bacteria to produce artemisinin, a drug used for malaria treatment; a range of modified and new organisms could be used for health care in coming years. The widespread development of organisms 'by-design' would take biotechnology to a new level and could have a profound impact on sectors from healthcare to agriculture. One step has been the compilation of a registry of 'biological parts' at MIT (UK Foresight, 2012). Another one is the creation, in 2013, of the first 'synthetic cell', with a laboratory-produced genome (Calloway, 2013). These innovations could profoundly affect a range of sectors, including agriculture — and also raise questions about environmental risks (Section 4.3.3).

4.2.3 *The ongoing information revolution*

Information and communication technology (ICT) has become pervasive around the world, as the central 'functions' of ICT — processing, storing and transferring information — have all shown dramatic increases in performance, accompanied an exponential fall in costs. For example, one megabyte of computer memory cost almost USD 1 million in 1970, but it fell to well under USD 100 in 1990 and then to about USD 0.01 in 2010 (Figure 4.3).

As a result, networked computing is now used throughout the economy, for activities from retail payments to stock market sales to guidance and control systems for high-speed trains and commercial planes. Computers, the Internet and mobile phones have permeated communities around the world. The International Telecommunications Union estimates that by 2013 there were almost 7 billion mobile phone subscriptions — almost as many as the global population; in addition, 40% of the world's households had a computer (ITU, 2013). In contrast, the UN estimates that about one-third of the world's population, about 2.3 billion, lacked access to improved sanitation in 2011; moreover, the corresponding Millennium Development Goal — to reduce this share to 25% of the global population by 2015 — will not be met (UN, 2013). In other words, more people around the world have access to mobile phones than to improved sanitation.

Figure 4.3 The declining cost of computer memory



Source: McCallum, 2014.

The rapid pace of ICT developments is expected to continue in coming decades, fuelled in part by applications from nanotechnology. For example, an integrated circuit based on graphene — a substance first produced artificially in 2004 — was developed in 2011 (Yu-Ming et al., 2011). Nanotechnologies may lead to the construction of smaller circuits and computers that run faster and have longer lives, reducing resource requirements in the production of computer hardware. Likewise, nano-based supercapacitors offer the possibility of advances in battery capacity which could deliver comprehensive mobile internet access to areas lacking reliable electricity supplies. The development of nano-electromechanical machines, novel devices which are able to generate, process and transmit multimedia content at the nanoscale, could lead to a range of mobile Internet devices (Jornet and Akyildiz, 2012).

The information revolution is spawning several new areas whose products and services are entering global markets. One of the key emerging fields for ICT is the '*Internet of Things*': the use of tiny identification tags with internet-linked sensors and actuators embedded in machines and products throughout the economy. Already, radio-frequency identification is used to track packages and products. The 'Internet of Things' would allow much greater automation and control of factories as well as more precise agricultural irrigation and pesticide application (Manyika et al., 2013).

Another major area of ICT development is '*big data*'. Computers are now able to store and process massive amounts of data: by one estimate, 2.5 trillion gigabytes of data were created every day around the world in 2012, a level that is doubling approximately every two years. Through machine learning techniques, computers have evolved in recent years from fixed algorithms that govern their actions to machine learning techniques, in which they analyse the 'big data' to alter their algorithms, (Manyika et al., 2013) giving them greater capacity for machine learning and 'intelligence'. The economic shift in global regions is an integral part of this growth: while developing countries accounted for about one-third of all data created in 2012, their share is forecast to reach nearly two-thirds of the worldwide total in 2020, with the strongest growth in Asia (IDC, 2012).

ICT is also spurring the development of *additive manufacturing*, also called 3D printing: this process makes three-dimensional solid objects from digital models. Additive technology allows more rapid prototyping of parts and complete products, offering greater room for experimentation and a shorter design-production cycle. It can also produce shapes that would be otherwise impossible or impractical to produce, and has already been used in the production of jet engines, resulting in novel designs that reduce weight and therefore fuel consumption. Future advances in layering techniques and materials are expected to enable increasingly complex goods to be printed at lower costs (UK Foresight, 2013).

Additive manufacturing can be applied to a broad range of materials: although most work now involves components and products made out of plastic and metals, researchers have successfully 'printed' simple prototypes of human organs using an inkjet printing technique to layer human stem cells with a supporting structure, and new 'bio-materials' could be created (UK Foresight, 2013). The use of additive methods for nano-materials is another area for research (Campbell et al., 2011).

Robotics is also benefitting from advances in ICT. Already, over 1.2 million industrial robots are in daily operation around the world (NIC, 2012); with lower ICT costs and more advanced programming and machine learning techniques, industrial robots are expanding their usefulness beyond the physically difficult, dangerous, or dirty jobs that they have occupied for the last few decades, and into less demanding tasks that were previously the realm of people — and thus, robots are taking over more manufacturing jobs (Biois, 2013).

Robots have entered the consumer market, in particular for cleaning. They are being tested for new and dangerous activities, such as emergency response. Robots include autonomous vehicles: already, vehicles remotely controlled by humans are used in industries such as mining and deep sea oil extraction; the use of autonomous vehicles in these sectors is forecast to grow in coming years in dangerous and remote situations. Other applications can include the inspection of remote power lines and oil pipelines. In developed countries, autonomous tractors may play a role in agriculture (NIC, 2012).

Self-driving cars are also an application of robotics: these use a variety of sensors to navigate crowded city streets. The prospect is reduced congestion, as autonomous vehicles can space themselves more efficiently than humans; reduced emissions through optimal driving; and fewer accidents, injuries and death. Self-driving cars can also free time for former drivers, who could spend travel times in leisure or work activities. They could also be a component of car-sharing models (Biois, 2013). Autonomous vehicles could transform both passenger and freight systems — but raise a number of challenges, including legal issues as well as the impact of computer viruses on safety (Hodson, 2015).

Robots are also being created at nano-scale. Future medical nanotechnology could involve the injection of nanorobots into the patient in order to deliver targeted functions at the cellular level. A growing area for research is the brain-computer interface, such as methods for the handicapped to control artificial limbs, vehicles and computers (UK Foresight, 2012).

Among the sectors that ICT is transforming is that of science and technology development itself. Communication technologies allows scientists across the world to work together, while extensive data is now available online from sources such as GenBank, an annotated collection of all publically available DNA sequences maintained by the US National Institutes of Health (NCBI, 2013). The new 'networked science' can itself accelerate discovery; at the same time, this new 'open science' raises questions for intellectual property, including patents (Nielsen, 2012).

4.3 Implications

4.3.1 *Supporting resource efficiency and the shift to a low-carbon economy*

By 2040–2050, nano- and biotechnologies are expected to be pervasive, diverse and integrated into all aspects of life (Subramanian, 2009). The NBIC cluster will bring a range of opportunities and risks for both people and the environment (Biois, 2013). One important area of opportunity is to develop products and research that increase resource efficiency and promote the shift to a low-carbon economy (UNEP, 2011). In recent decades, environment-related applications to the European Patent Office have steadily increased, with those targeting emission mitigation and energy showing significant growth (Figure 4.4). Examples could include the use of biotechnology to develop new environmental remediation techniques. Nanomaterials are yielding advances in energy storage, stronger and lighter construction materials and new filters for water treatment and saltwater desalinisation (UBA, 2010).

Opportunities for key economic sectors

In *manufacturing*, additive manufacturing could reduce energy and materials consumption: rather than cutting away material that would then need to be recycled or discarded, this technique uses nearly the exact amount of material needed in the final part, greatly reducing (though not eliminating) waste (Biois, 2013).

For the chemical industry, *green chemistry* approaches could change the sector's environmental impacts. Green chemistry involves the 'design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances' (USEPA, 2013). It promotes the use of renewable feedstocks, including agricultural products and waste, rather than non-renewable resources from mining and oil and gas extraction. Bio-refineries, including those for bio-fuels, are currently in an early research and development phase; some studies foresee an integration of such plants with natural resource industries such as pulp and paper manufacturing, allowing them to use waste material and by-products (Hajkowicz et al., 2013). 'Bio-factories' that use modified micro-organisms to produce a range of specialty chemicals using sunlight, CO_2 and simple organic and inorganic ingredients (UK Foresight, 2012).

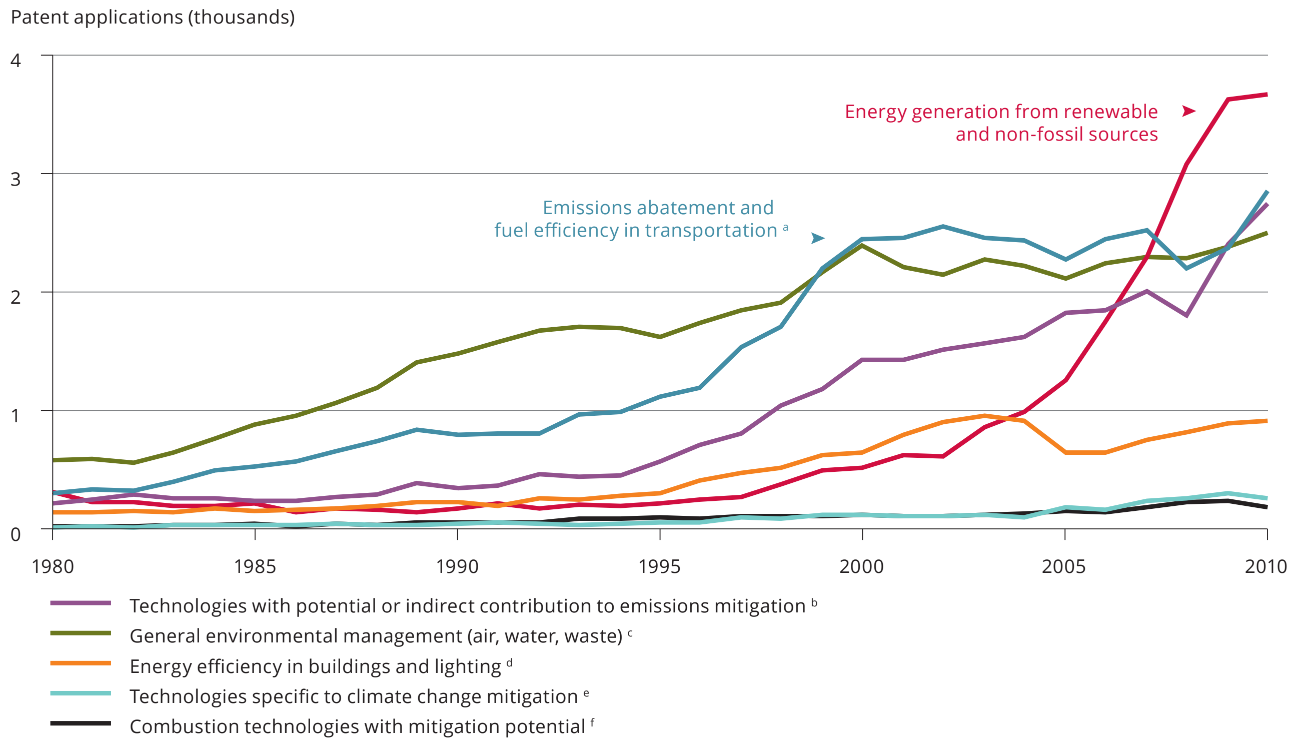
Nanotechnology can support the application of 'biomimicry': emulating natural forms, processes and systems to create more resource-efficient and sustainable products. Examples can surfaces with water-repellent nano-structures, such as those on lotus leaves, to reduce the need for cleaning; and surfaces with diffraction patterns for colouring rather than pigments (Biomimicry, 2013).

The NBIC cluster brings a range of new tools to improve resource efficiency in *agriculture*. For example, new diagnostic instruments could identify animal and plant diseases more quickly, and sensors could identify optimal moments to apply fertilisers and pesticides or irrigate fields. Some pesticides could be delivered in nanocapsules that would open when ingested by the target species (UK Foresight, 2012). These methods could reduce the amounts of agricultural chemicals released as well as their runoff and other impacts. A more speculative development is the commercialisation of 'synthetic meat' grown from tissue cultures rather than live animals (UK Foresight, 2013). So far only a laboratory product, artificial meat — if it becomes commercially viable — is expected to require a fraction of the land and water inputs of real meat (Tuomisto, 2011).

Transforming energy systems

Emerging technologies can also reduce the costs of renewable energy. In the area of power generation, technological advances have brought down the price of wind and solar renewable energy. One example is the costs of photovoltaic cells: the price of their electricity fell by over 60% from 1998 to 2008 (Jacobs, 2013). In the immediately coming years, further decreases are expected (Figure 4.5).

Figure 4.4 Environment-related patent applications to the European Patent Office, 1980–2010



Note: The graph shows the development in total patent applications (direct and patent cooperation treaty national phase entries); for the world's seven largest filing offices.

a. Technologies specific to propulsion using internal combustion engine (ICE) (e.g. conventional petrol/diesel vehicle, hybrid vehicle with ICE); technologies specific to propulsion using electric motor (e.g. electric vehicle, hybrid vehicle); technologies specific to hybrid propulsion (e.g. hybrid vehicle propelled by electric motor and internal combustion engine); fuel efficiency-improving vehicle design (e.g. streamlining).

b. Energy storage; hydrogen production (from non-carbon sources), distribution, storage; fuel cells.

c. Air pollution abatement (from stationary sources); water pollution abatement; waste management; soil remediation; environmental monitoring.

d. Insulation (including thermal insulation, double-glazing); heating (including water and space heating; air-conditioning); lighting (including compact fluorescent lamps, light-emitting diodes).

e. Capture, storage, sequestration or disposal of greenhouse gases.

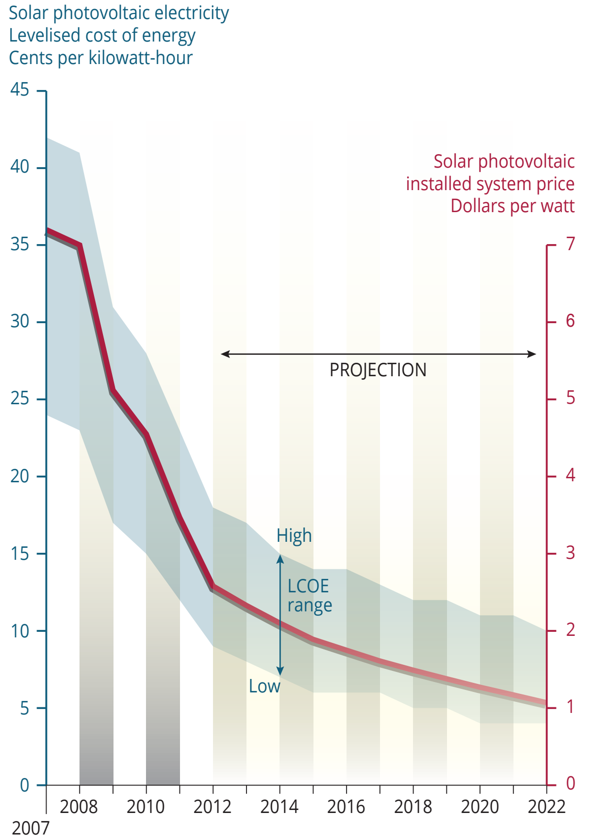
f. Technologies for improved output efficiency (combined combustion); technologies for improved input efficiency (efficient combustion or heat usage).

Source: OECD, 2014.

Biotechnology may yield new methods for biofuels, overcoming the problems seen in the current 'first generation' of biofuels: these can take land away from food crops and other uses and in some cases, land use changes have thwarted the expected reductions in greenhouse gas emissions (EEA, 2010). Research seeks to develop so-called 'second-generation' biofuels from cellulosic crops and wastes. The use of genetically modified algae to transform these materials into fuels is one of the approaches being pursued. Some advanced methods under development to produce biofuels may be carbon neutral or even carbon positive, producing carbon by-products that could be used in agriculture (Holmes, 2012). However, biofuels used in combustion would still have local air pollution impacts.

In terms of power transmission, ICT can support the introduction of 'smart grids' that use advanced monitoring and metering together with two-way communication between electricity suppliers and consumers to improve grid management and energy consumption. Smart grids are a vital tool for increasing the share of renewable energy, and their development is being supported by EU projects and

Figure 4.5 The declining price of solar photovoltaic systems



Note: Levelised cost of energy (LCOE) refers to global costs of an energy-generating system (here: solar photovoltaic) over its lifetime, including initial investment, operations, maintenance, cost of fuel and cost of capital.

Source: NREL, 2013; Pernick et al., 2013.

other investments around the world (EC, 2011b). ICT can also yield advanced sensors and computing to help industrial plants, commercial buildings and eventually private homes employ 'energy intelligence'. Manufacturing processes could be adjusted to improve their energy efficiency and scheduled to take place at times when energy prices are lower (UK Foresight, 2013).

Nanotechnology and other materials advances have brought down the price of electricity storage, and offer significant promise for further progress. For example graphene or carbon nanotube based supercapacitor batteries could dramatically decrease battery charging time and increase storage capacity, as well as increasing the speed and power of electronic devices. Further improvements are expected in the coming decade, making electric and hybrid vehicles more competitive. Energy storage improvements would support the growth of renewable energy sources by allowing them to cope more efficiently with peak loads. They can also make small-scale, off-grid renewable energy systems viable (Manyika et al., 2013).

Not all energy research, however, supports a low-carbon shift. New technologies — including new drilling materials as well as the application of ICT in prospecting and development — could increase hydrocarbon production, in particular for fossil fuels. Already, hydraulic fracturing has significantly increased natural gas production in the US and other countries (IEA, 2012). New technologies may lead to the extraction of methane from clathrates, water ice structures found under the ocean beds, further increasing global natural gas production: Japan has tested extraction methods in the Nankai Trough off its coast (Reardon, 2013).

The rebound effect

Notwithstanding the promise of new technologies, their efficiency gains sometimes fail to reduce environmental pressures as make products cheaper, increasing consumption: the 'rebound effect'. Energy use by ICT is one dramatic example: despite new hardware with dramatically higher efficiencies, the huge expansion of computing has made this sector a major global energy user. In 2005, ICT equipment and infrastructure consumed about 8% of the EU's electricity and emitted 1.9% of CO_2 emissions; moreover, existing trends could push ICT emissions to 4.2% of CO_2 emissions in 2020 (Biois, 2008). ICT equipment creates an important stream of solid waste as well. In 2008, an estimated 0.8 million tonnes of old computer equipment were discarded in the EU (UNU, 2007). Waste computer equipment, mobile phones and other ICT items contain a range of hazardous materials (EEA, 2012). In coming decades, additive manufacturing lead to more traffic, as the growth of small and home manufacturing systems could increase the demand for deliveries in cities, counteracting some of the technique's resource efficiencies (UK Foresight, 2013). Reducing pressures therefore requires complementary policy measures that address consumption (EEA, 2015).

4.3.2 Impacts on economy and society

Employment

The new technologies are expected to bring a range of economic and social changes. Technological advances that enable machines to perform human tasks are likely to influence inequality and unemployment. Increasing use of machines may depress wages for some, while boosting demand for highly skilled labour and low-skilled service-sector work. The resulting polarisation of job opportunities could contribute to greater earnings inequality (Autor, 2010; Goos et al., 2009).

Robots, which are already used extensively in manufacturing, may play a key role in changing employment by taking on a growing range of service sector jobs: for example, a Spanish food processing company uses robots to inspect lettuce on a conveyor belt (Manyika et al., 2013). Robots are increasingly being used for personal care of older people — an application becoming common in advanced Asian economies such as Japan and Korea (Smith, 2012) and one that may be adopted globally as the numbers of the elderly grow in Europe and around the world (GMT 1).

In coming decades, new technologies could change managerial and professional work as well. In health care, computers trawling massive data sets could supplement and in some cases replace doctors in making patient diagnoses. Computers may play a similar role in other fields — carrying out legal research for law firms, replacing teachers in some roles and perhaps even grading written exams, and taking on some of the skilled work of engineers and scientists (Manyika et al., 2013).

By reducing demand for labour relative to machinery, new technologies can mean that returns to production increasingly accrue to the owners of physical capital. In many advanced countries and industries, labour's share in national income has declined significantly since the early-1980s; the growing role of ICT has been an important factor in this shift (Karabarbounis and Neiman, 2014).

The new technologies can lead to changes in our economic systems. Electricity, mass production and steam power, for example, transformed economic systems in Europe and North American in the late 18th and early 19th centuries (Manyika et al., 2013). Many elements created then, such as centralised electricity companies, remain part of today's economic structures. Technological changes are likely to bring new financial and institutional arrangements (UNEP, 2011). Additive manufacturing, for example, could have disruptive impacts on a range of sectors, including retail, logistics and freight transport at the global and local levels (Campbell et al., 2011). It may allow for 'mass customisation' of goods, and thus change consumption patterns (EC, 2014a), possibly via small-scale production as well as home printing; in doing so, it could bring some manufacturing back to Europe from low-income, mass-production economies.

Society and politics

New technologies could also bring new dilemmas for society. The 'Internet of Things' and the development of nanotechnology sensors raise further questions about surveillance and privacy — and also about intellectual property, including counterfeiting. The World Economic Forum warns of 'digital wildfires' for companies and markets, which could start with misinformation but spin out of control, with unexpected social and financial impacts; incidents of massive data fraud or theft and rising cyber-attacks are also growing risks (WEF, 2013). The 'Internet of Things' is expected to offer a new field for cyber-attacks. Organisations may be tempted to run their own networks, separate from the Internet (UK Foresight, 2013). Additive manufacturing creates new social risks, as the small-scale and home printing of personalised goods from toys and electrical fittings to medicines or weapons can create threats to life, health and the environment (UK Foresight, 2013).

The influence of new technologies on global and national politics is a further area of uncertainty. Already, social media provide a tool for social action, including organising against autocratic regimes. Social entrepreneurs can employ new technologies to address societal problems: for example, epidemiologists have used cell phone data to help stem malaria outbreaks (Talbot, 2013). At the same time, ICT provides new ways for governments to monitor citizens; future developments, such as miniature and nano-scale sensors, could even strengthen such monitoring. Finally, new technologies could support new types of weapons, including bioweapons. Cyber-attacks against countries have already been seen; the armed forces in the USA and other countries have developed cyber defence units (NIC, 2012).

A 'post-human' future?

The NBIC cluster is investigating systems that could bring unexpected changes in how we view ourselves as humans and our relationship with our machines. One growing area of ICT research is augmented reality, the addition of virtual objects and information into real scenes: if it becomes part of our daily lives, augmented reality could also fundamentally change the way we interact with our environment, both in leisure and work (EC, 2013a). Human-machine interfaces are a focus of work for healthcare: along with wearable sensors, whose use is growing for medicine and sports, we may have increasing numbers of nano-scale machines in our bodies to monitor, support and perhaps augment our health; another area of research seeks to link our brains directly with computers.

Biotechnology is also raising profound ethical issues regarding the value of human life and the extent to which living organisms can be manipulated (Manyika et al., 2013). New drugs could enhance natural human capacities, such as intelligence and concentration, and our moods. Genetic screening could become more sophisticated, not only allowing parents to terminate pregnancies when severe handicaps are identified but also to choose 'optimal offspring'. The 'benefits' of these new technologies may, however, be restricted to the wealthy, further increasing inequalities across and within countries. A more profound question is that we may be steadily moving towards a 'post-human' future without broad public discussion (Fukuyama, 2003).

4.3.3 Environmental risks

The risks and impacts of emerging technologies are difficult to predict: already in 2001, EEA's study on *Late lessons from early warnings* cautioned that: '...the growing innovative powers of science seem to be outstripping its ability to predict the consequences of its applications...' (EEA, 2001).

Nanotechnology, for example, offers extraordinary promise but scientific understanding of the risks to both human health and the environment remains patchy, due to major limitations in available data on hazards and, in particular, on exposure. The variation of hazard profiles amongst different nanoforms even of the same basic chemistry sets requirements for a case by case assessment of hazards, whilst methods to either measure or model exposure remain in an early stage of development. As the behaviour of nanoparticles in the environment is unknown, their application is likely to raise concerns. Nanoparticles' rapid transformation could, for example, render traditional approaches to describing, measuring and monitoring air or water quality inadequate (RCAP, 2008). There is a need for both precautionary and socially and economically responsive policy strategies in the field of nanotechnology in order to ensure the responsible development of nanotechnologies (EEA, 2013).

The risks related to biotechnology are equally hard to define. Genetically modified crops are already used around the world in agriculture, and future developments of synthetic biology create new issues for the protection of our natural environment (Box 4.2).

4.3.4 Policy frameworks

As much new, potentially disruptive technology is already available, preventive and proactive responses to deal with emerging problems and changing socio-political and environmental landscapes should become a priority. This is underlined in EEA's studies on *Late lessons from early warnings*: they conclude that new and unknown risks need a new approach, involving: broader application of the precautionary, prevention and polluter pays principles; improvements in the assessment of risks associated with new and emerging technologies, both in terms of considering systemic challenges and unknowns and also drawing on lay, local and traditional knowledge; and the strengthening of institutional structures to deal with multiple, systemic threats and surprises (EEA, 2013).

When considering options, societal problems can also be viewed as opportunities. This approach is seen in moves to orient science policy and funding towards 'responsible research' that supports societal goals (von Schomberg, 2013). The EU's Horizon 2020 Programme, for example, identifies seven 'societal challenges', including 'health, demographic changes and wellbeing' to 'smart, green and integrated transport', as well as renewable energy (EC, 2015a). Horizon 2020 moreover incorporates the goal of responsible research and innovation that engages stakeholders and anticipates potential impacts of research (EC, 2015b). Other EU programmes under the Europe 2020 Strategy also address societal goals as well as economic growth (Box 4.3). In a similar vein, the US National Nanotechnology Initiative includes among its four goals the 'responsible development of nanotechnology'.

The move towards better governance nonetheless faces several challenges. For one, 'precaution' is understood differently by different stakeholders, with voices warning that it can stifle research and economic growth. EEA's *Late lessons from early warnings* concludes that 'the timely use of the precautionary principle can often stimulate rather than hamper innovation, in part by promoting a diversity of technologies and activities, which can also help to increase the resilience of societies and ecosystems to future surprises' (EEA, 2013).

Box 4.2 Biotechnology, agriculture and nature conservation

A controversial application of biotechnology is in agriculture. The global cultivation of genetically modified crops reached 150 million hectares in 2012, about 10 % of global cropland. The largest producing countries are Argentina, Canada and the United States; Brazil, China and India saw rising levels of production; GMO crops are now grown in 22 developed and developing countries around the world (FAO, 2012). At present, three types of crops account for nearly all GMO cultivation — cotton, maize (corn) and soybeans — with genetic manipulations that provide resistance to herbicides or to insects. New genetically modified crops reaching wide-scale production include potatoes, rapeseed and rice. Research is creating crops with new properties: greater drought resistance, the transfer of genes for nitrogen fixation of soils from legumes to other crops, and greater plant nutritional properties such as vitamin or protein content (UK Foresight, 2012).

The potential impacts of genetically modified crops on the environment are a topic of extensive research and debate. The fast-developing field of synthetic biology, raises new concerns. In a 2013 conference on potential interactions between synthetic biology and nature conservation, it was noted that this new field of research is often described in terms of either utopias or dystopias. In practice, the ongoing development of biotechnology and synthetic biology will pose a range of difficult questions for policy makers, stakeholders and society as a whole. The following are among the topics raised (WCS and TNC, 2013):

- Genetically modified plants and synthetic organisms that could be cultivated on marginal land could expand agriculture to protected and other high-biodiversity areas.
- New organisms are likely to interact, perhaps in unexpected ways, with existing protected species and protected ecosystems.
- In changing agriculture and other forms of resource extraction, these technologies might transform rural economies and their interactions with natural systems.
- If synthetic biology one day allows the possibility to 're-create' recently extinct species (e.g. Redford et al., 2013), should this be pursued?

Box 4.3 Innovation under the Europe 2020 Strategy

The Europe 2020 Strategy sets an objective of smart, sustainable and inclusive growth. Several of its 'flagship initiatives' support technology development, including the following (EC, 2013b):

- The Digital Agenda for Europe promotes the greater use of ICT in the economy and throughout society. Among its goals is boosting public funding for digital research and development.
- The Innovation Union seeks to increase the pace of development of new products and services, both through education as well as the removal of potential obstacles.
- A Resource Efficient Europe supports actions across a range of policy sectors to move towards a low-carbon, resource-efficient economy.

Moreover, a range of specific strategies support these goals. The European Commission unveiled in 2012 its strategy for key enabling technologies for the future, including nanotechnology, biotechnology and micro and nano-electronics: its support seeks to strengthen Europe's economic competitiveness and contribute to the move towards a low-carbon economy (EC, 2012).

The global dimension of technology development raises a key challenge. Major differences are seen in approaches to addressing new risks, for example for nanotechnology regulation. Among advanced economies, current requirements as well as discussions on future regulation differ between Europe, which takes a more precautionary approach, and the US. Several fast-growing countries — including Brazil, China and India — support nanotechnology research but have less capacity to implement regulation; moreover, these countries are concerned that regulation in developed economies could be a trade barrier for them. Although informal international discussions have been held, in particular through the OECD, a convergence among the different approaches appears to be a distant prospect (Falkner and Jaspers, 2012).

Cooperation on responsible research also needs to be considered in the global context. In 2009, an EU Expert Group on the Global Governance of Science — with members from both Europe and around the world — proposed a set of recommendations for European funding that encourages global cooperation in promoting ethical governance of science and supporting fundamental rights (EC, 2009).

These moves are vital, as vulnerabilities are created when policies do not keep up with the opportunities and threats of unfolding dynamics, conditions and realities of socio-technological systems. A key consideration for innovation governance is an ability to react, learn and adapt. New governance paradigms that emphasise reflexivity create capacities for adaptive decision-making — interventions essential for coping with emerging impacts.

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