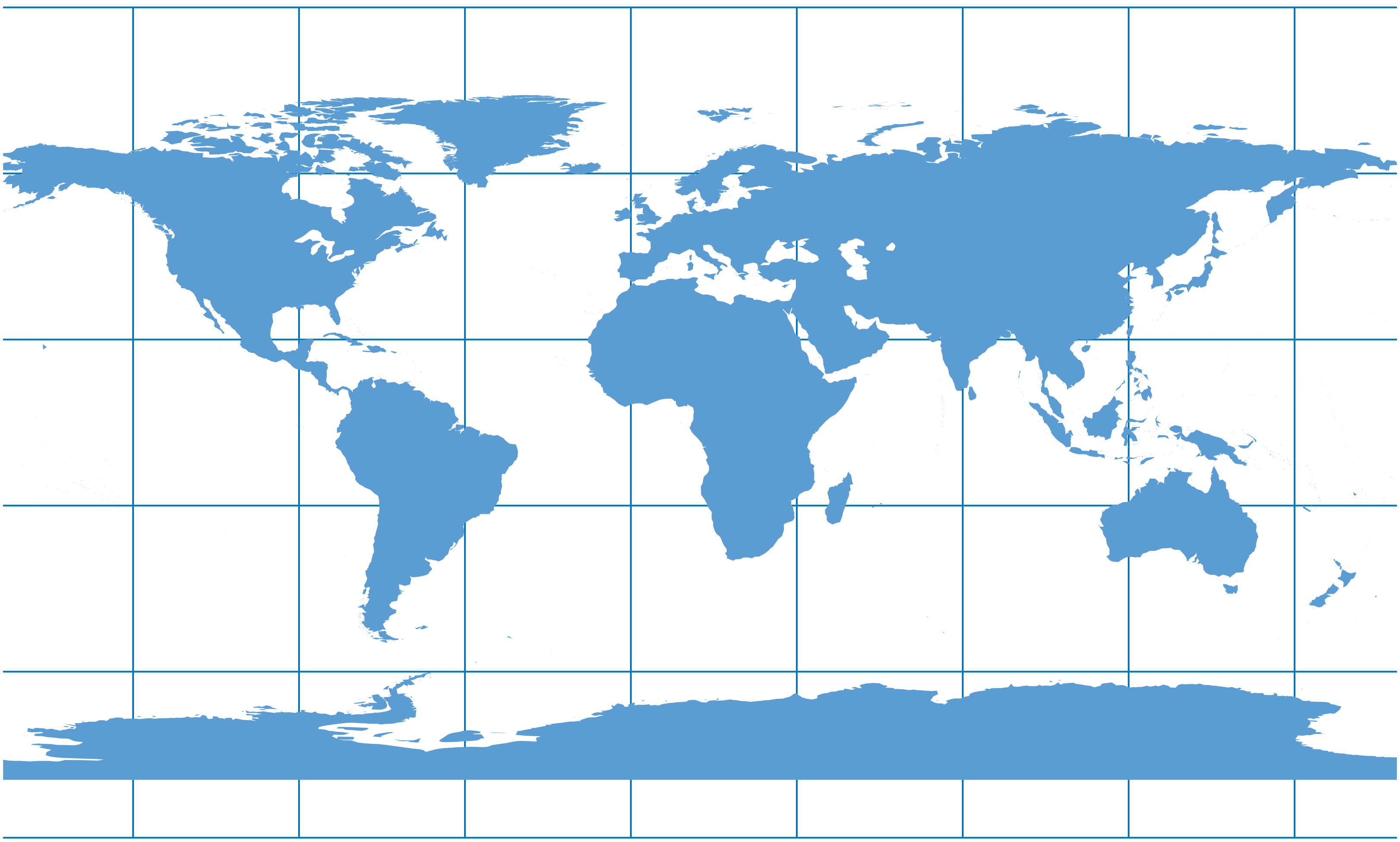
E/2018/50/Rev.1
ST/ESA/370

Department of Economic and Social Affairs

World Economic and Social Survey 2018

Frontier technologies for sustainable development



United Nations
New York, 2018

Chapter I

Frontier technologies for a sustainable future

Introduction

The 2030 Agenda for Sustainable Development[1] unites humanity around a new, common aspiration and charts a path of action towards achieving the 17 universal and mutually reinforcing Sustainable Development Goals (SDGs). Those Goals are necessarily ambitious and reflect the challenges of addressing hunger, poverty, mortality, decent jobs, inequality and environmental sustainability, among others.

Achieving these ambitious goals—while leaving no one behind—will require new development strategies and innovative resource mobilization, as well as the creative use of both existing and emerging technologies. *World Economic and Social Survey 2018* focuses on the promise of those emerging technologies and examines how policy measures can expand their potential benefits and mitigate their potential adverse effects. It should be noted that the *Survey* is less concerned with any technology per se, but rather on how the SDGs can be impacted by rapid technological change. To the extent it discusses individual technologies, it does so to illustrate the depth and breadth of the impact possible.

Innovative and fast-growing technologies are frontier technologies that have the potential to transform societies, economies and promote environmental sustainability

The *Survey* regards as frontier technologies those technologies that are innovative and fast-growing and have the potential to exert a significant impact on societies, economies and the environment (Rotolo, Hicks and Martin, 2015).[2] The scope of frontier technologies includes advanced materials such as graphene and biodegradable plastics, scientific breakthroughs in biology and genetics, and advancements in 3D printing, robotics and artificial intelligence (AI). They are deeply interconnected and interdependent, as advances in one are likely to impact many others; and just as rapid improvements in transistor capacities enabled faster and smaller devices, advances in AI will help advance other emerging technologies. They are also interconnected through their generation of, and need for, large data sets.

Technological breakthroughs offer us the best hope for a sustainable future…

The excitement generated by many technological breakthroughs is justified as they offer us the best hope for a sustainable future. These technologies promise to help overcome some of the more intractable among existing challenges, ranging from attaining natural resource and climate sustainability to combating diseases and hunger and ensuring that education is accessible to all.

1 General Assembly resolution 70/1.

2 The terms “new technologies”, “emerging technologies”, “frontier technologies” and “technological breakthroughs” are used interchangeably throughout the *Survey*.

…but technological change is seldom neutral and cost-free, presenting new equity, ethical and moral challenges

But technological change is seldom neutral and cost-free. Previous industrial revolutions, while enhancing efficiency and increasing prosperity, came with huge environmental costs and also contributed to greater income inequality across countries and regions. History shows us that advances in a technology—automation, for example—can benefit capital owners and workers as well. Automation can free workers from inhumane toil, but in many cases it can also dislocate them, squeeze their wages and exacerbate already existing inequalities in income distribution. Clearly, then, the emergence of new transformative technologies creates major opportunities and challenges for societies. Indeed, for many developing countries, their level of access to these new and existing technologies will determine their development trajectory.

Frontier technologies also present new and unique ethical, moral and equity-related challenges, which can potentially undermine trust, cohesion, tolerance, peace and stability. The *Survey* makes a compelling case for upholding ethical standards and effective and accountable institutions as a means of guiding progress in the development and application of many frontier technologies and promoting peaceful and inclusive societies. Because frontier technologies are associated with externalities which are often global, stronger and more effective international coordination is needed to maximize the positive impacts of new technologies for sustainable development outcomes.

The present chapter examines how the shared vision of sustainable development can be realized by harnessing frontier technologies, while at the same time minimizing their adverse and disruptive effects. It highlights a few of the remaining challenges for the planet, people and prosperity as humanity strives to achieve sustainable development and then reviews the relevance of and the challenges presented by a select set of frontier technologies within the context of the SDGs.

Regarding the planet, the chapter emphasizes the need to improve the management of natural resources and the environment, which has been made urgent by the threat of climate change, the environmental impact of human activities, and the additional demand for natural resources generated by a growing and ageing population. In this regard, advances in the extraction, conversion and storage of electricity may reduce emissions and improve the environmental outlook. Regarding people, the chapter argues that, to improve health outcomes and longevity, progress in improving access to sanitation and water must continue. Technology will help enhance access to health care, and lead to better, cheaper and more innovative services and medicines, and improved health outcomes. To promote prosperity, we must achieve equitable and robust growth. The chapter discusses the economic challenges posed by low productivity growth and rising inequality in many countries. If their progress is managed appropriately with sustainable development in mind, frontier technologies like artificial intelligence, advanced automation and 3D manufacturing techniques, digital finance and blockchain technologies can create new economic opportunities and prosperity.

As the emerging technologies also raise important ethical and moral issues (as noted above), as well as issues related to equity and data ownership, the chapter discusses the need to balance the benefits of technology against the impacts of such issues. The trade-offs become particularly important within the context of the 2030 Agenda for Sustainable Development, which aims towards leaving no one behind.

Key development challenges for the planet, people and prosperity

On 25 September 2015, by its resolution 70/1, the General Assembly adopted, without a vote, the 2030 Agenda for Sustainable Development. In that resolution, Heads of State and Government and High Representatives announced the 17 Sustainable Development Goals (SDGs), galvanizing global efforts along the three dimensions of sustainable development: economic development, social inclusion and environmental sustainability. Pursuant to its universal vision of a common future based on global solidarity, the 2030 Agenda affirms the commitment to prevent degradation of natural resources and climate change; to ensure prosperous and fulfilling lives for all and that progress occurs in harmony with nature; to eradicate poverty and hunger; and to foster peaceful, just and inclusive societies free from fear and violence.

Frontier technologies can accelerate the achievement of the goals set in the 2030 Agenda

The world has seen tremendous progress in confronting many of these issues. Countries are making headway in limiting—or reversing—the human impact on climate and on natural resources. There has been progress in combating diseases and in providing access to health services and medications, with commensurate reductions in child mortality, for example. The decline of poverty by half since 2000 has helped to reduce hunger and malnutrition (United Nations, 2017c). Despite such progress, achievement of the goals set in the 2030 Agenda is still a long way off. The discussion of a few of the persisting global challenges illustrates the transformative potential of frontier technologies.

In the present section, the discussion on climate change and natural resource depletion highlights the link between progress achieved in addressing socioeconomic issues and greater environmental degradation and demonstrates how the pressure on natural resources and environment is intensified by the needs of a growing and ageing population. The discussion on people's health and well-being examines the progress achieved and the remaining challenges to combatting diseases and improving health and sanitation. The section concludes with an examination of the economic challenges of low productivity growth and rising inequality which are of concern to many countries and present a formidable challenge to achieving prosperity and sustainable development.

Combating climate change and depletion of natural resources

Climate change is perhaps the most critical existential threat facing humanity. In 2017 and 2018, the *Global Risks Report*, issued annually, ranked climate change-related events as the most likely risk facing the world and in 2017 as the second most impactful (World Economic Forum, 2017; 2018). The 2030 Agenda for Sustainable Development recognizes that climate change, whose adverse impacts undermine the ability of all countries to achieve sustainable development, constitutes one of the greatest challenges of our time.

Human activities and demographic changes continue to affect all aspects of our environment

As reported in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), total greenhouse gas (GHG) emissions from human activity have continued to increase since 1970. Average annual growth of global emissions during the period 2000–2010 was 2.2 per cent, significantly higher than the 1.3 per cent annual growth rate observed in the period from 1970 to 2000 (IPCC, 2014b, p. 6). As continued GHG emissions will cause further warming and changes in all components of the climate system, limiting climate change will therefore require substantial and sustained reductions of those emissions.

Yet, it is not just the atmosphere that is being affected by human activity. The rise in the quantity of marine and land plastics waste is closely connected with economic growth, particularly with the rise in the use of packaging for global trade and marketing of products. Annual global plastic production increased from 1.7 million to 322 million tons between 1950 and 2015. The same period witnessed an accumulation of 6.8 billion tons of mostly non-biodegradable plastic waste. Nearly 8 per cent of this waste has been deposited in landfills or water bodies, including seas and oceans (see box I.1). Plastic waste not only continues to impact many wildlife species but also hosts microbial communities, and by transporting non-native species provides new habitats for microbes. Land-based plastic waste also creates human health problems.

Box I.1

Plastics and ocean pollution: sustainable polymers[a], bioplastics and bio-benign materials

Plastic is the major component of marine debris. Most plastic does not biodegrade, but only fragments into smaller and smaller particles. The growth of the plastics industry has been driven by the growth of the packaging industry and increasing globalization. As goods, particularly food, are transported globally, the packaging industry has embraced plastic, especially, as a useful material. Through its durability, plastic protects goods and food, and its lightness has enabled a reduction in transportation costs and carbon emissions.

Because of the popularity and durability of plastic products and, most important, the lack of proper waste management systems, microplastics (defined as being smaller than 5 millimetres (mm) in diameter) are now found in the environment—floating in lakes, rivers and oceans, and along coastlines all over the world. Impacts from plastic marine debris are wide ranging. Not only have a multitude of different species of wildlife been affected but the debris also represents a physical hazard to shipping, boating, fishing and the industrial system. Coastal tourism as well is adversely affected by marine debris and other litter. Plastic can host diverse microbial communities, referred to as plastispheres (Zettler, Mincer and Amaral-Zettler, 2013); transport non-native species; and provide a habitat for microbes that might not otherwise thrive.

New material development and product design would help eliminate the adverse impact of plastic in oceans. In 2014, however, sustainable polymers—defined as plastic materials that address "the needs of consumers without damaging our environment, health and economy" (University of Minnesota, Center for Sustainable Polymers, 2018)—made up less than 10 per cent of the total plastics market (Peplow, 2016). Further, the global production capacity of bioplastics—plastics derived from renewable biomass sources, such as vegetable fats and oils, corn starch and microbiota—was only at 1.3 per cent of total polymer production capacity. However, bioplastics and biodegradable plastics are expected to maintain high growth rates in the near future, as bioplastics are being used increasingly in several industries, such as consumer goods, automotive and transport, and construction and building.[b]

Yet, despite these positive trends, production capacities will remain marginal relative to total plastic production. The pace at which new alternative materials are replacing the current types of toxic plastics is too slow to decelerate annual flows of plastic debris into the ocean. Thus, there is a considerable need for complementary investment aimed at changing the way in which plastic products are produced, consumed and disposed of. At the same time, so-called bio-benign materials—that is, non-toxic materials that are biodegradable and recyclable—need to be promoted in the context of both production and consumption.

Source: Jambeck (2017).

a Polymers are the constituents of the plastics that we encounter in our daily lives. They are commonly used in packaging and durable goods, such as toys, cars, construction materials and furniture, as well as in textiles.

b See "Demand for bio-based plastic continues to rise despite falling oil costs", Bio-Based World News, 6 December 2016. Available at www.biobasedworldnews.com/bio-based-plastics-market-to-grow.

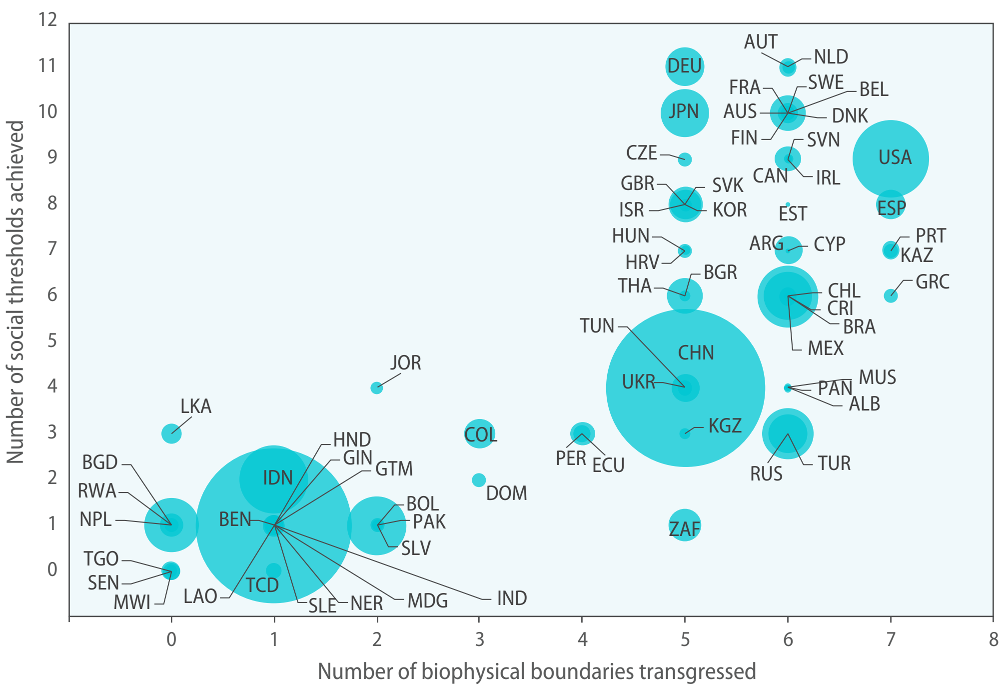
Human activities continue to drive an increasing demand for natural resources, as manifested in technology choices and consumption and production patterns. This trend is exacerbated by a growing and ageing population. It is expected that the world population, currently at 7.6 billion, will have reached 9.8 billion by 2050. During the same period, populations of 26 African countries are projected to double. According to the United Nations Environment Programme International Resource Panel (2017, p. 8), material resource use, which was expected to reach 89 billion tons in 2017, may more than double between 2015 and 2050. At the same time, the world's population is ageing, with the number of persons aged 80 or over expected to triple by 2050, to 425 million (United Nations, Department of Economic and Social Affairs, Population Division, 2017). Countries with ageing populations will require economic growth and higher productivity from younger workers to support the growing number of older people as they exit the workforce. For those countries, achieving this goal without raising the need for natural resources will remain an uphill battle.

Progress in social and economic goals in the past generally came at the expense of environmental sustainability

Figure I.1 illustrates the link between socioeconomic progress and environmental sustainability. Several countries have made significant progress in achieving many socioeconomic goals (e.g., sanitation, access to energy, educational attainment, poverty reduction, economic prosperity and higher standards of living). At the same time, a price has been paid for such progress, namely, the crossing of biophysical boundaries related, inter alia, to CO_2 emissions, the phosphorus and nitrogen footprints, water use, the ecological and material footprints and forests.

Figure I.1

Social thresholds achieved versus biophysical boundaries transgressed for different countries, results weighted by each country's population



Source: UN/DESA, based on O'Neill and others (2018), figure 2.

Note: The figure includes only the 70 countries for which there are complete data on all indicators.

Achieving good health and well-being

Ensuring healthy lives and promoting well-being for all constitute a cardinal objective of the 2030 Agenda. The major health challenges facing the world, according to the World Health Organization (WHO), include reducing maternal and child mortality, improving nutrition, and combating communicable diseases such as hepatitis, HIV/AIDS, malaria, tuberculosis and neglected tropical diseases. Non-communicable diseases, mental health problems, road traffic-related injuries and environmental health are also areas of priority (WHO, 2017).

There has been significant progress in combating communicable diseases and reducing child and maternal mortality...

Despite the significant achievements in combating communicable diseases and child and maternal mortality, further efforts are needed to eradicate a wide range of diseases and to address many persistent and emerging health issues. The treatment of communicable diseases which disproportionately affect the developing world will be made more difficult by growing antibiotic resistance. Non-communicable and neurological diseases are projected to increase sharply as the population ages and as more people maintain unhealthy lifestyles. In ageing societies, infectious and parasitic diseases will continue to give way to non-communicable diseases such as heart disease, cancer and diabetes as the members of the population change their lifestyle and diet, and grow older (National Institute on Aging, National Institutes of Health and World Health Organization, 2011).

…but millions remain vulnerable to persistent health risks due to poor water and sanitation facilities

Millions of people remain vulnerable to persistent health and sanitation risks. In 2015, only 66 per cent of the population in low-income countries had access to an improved water source. In those countries, only 28 per cent use improved sanitation facilities and 12 per cent of the global population still practise open defecation. The lack of basic water and sanitation facilities has serious health risk implications, resulting in the spread of disease and affecting the physical and intellectual growth of children. The future of our planet and the future of people are inextricably interlinked. Climate change and environmental degradation also adversely affect public health. Improper disposal of plastic waste—on land, for example—can contribute to the spread of diseases such as chikungunya, dengue, malaria and Zika.

Promoting economic growth and reducing inequality

Despite the reduction of extreme poverty rates by more than half since 1990 for the world as a whole, 42 per cent of the population in sub-Saharan Africa still lived on less than $1.90 a day in 2013 (United Nations, Economic and Social Council, 2017, para. 5).[3] Achieving the goal of eradicating poverty in all its forms everywhere will require economic growth that is equitable, inclusive and sustained. Societies will need to create the conditions that enable people to secure quality jobs and benefit from opportunities that stimulate the economy without inflicting harm on the environment.

Slowing productivity growth is a risk to sustained economic growth

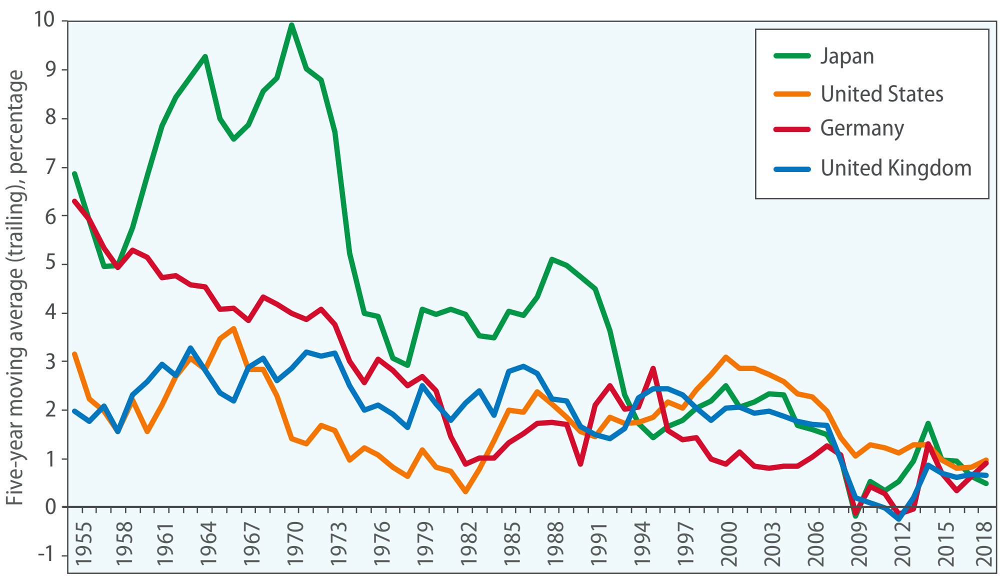
The slowdown in productivity growth—i.e., output per worker or per hour worked—represents a key structural weakness in the context of the medium-term growth outlook

3 Poverty is evidenced not only by the lack of income and resources to ensure a sustainable livelihood, but also by hunger and malnutrition, limited access to education and other basic services, and social discrimination and exclusion, as well as the lack of participation in decision-making.

(United Nations, Department of Economic and Social Affairs, Economic Analysis and Policy Division, 2017). In developed countries, labour productivity growth has been on a downward trend since the 1960s, briefly interrupted by the positive contributions often associated with the digital and information technology revolution. In the aftermath of the global financial crisis of 2008–2009, productivity growth declined further, and gross domestic product (GDP) per person employed has barely grown in recent years. This persistent weakness in productivity growth, as illustrated in figure I.2, has continued despite rapid advances in technology and has given rise to what is often referred to as the "productivity paradox" (LaFleur and Pitterle, 2017; Bruckner, LaFleur and Pitterle, 2017).

Figure I.2

Trends in labour productivity growth, Germany, Japan, United Kingdom of Great Britain and Northern Ireland and United States of America, 1955–2018



Sources: Conference Board Total Economy Database (2018); Feenstra, Inklaar and Timmer (2015), Penn World Table 9.0.

Achieving prosperity for all — and leaving no one behind — will require bridging the technology divide between and within countries

In developing countries, productivity trends are mixed. Productivity growth in East and South Asia has been on an upward trend since 1975 as countries such as China and the Republic of Korea transition from agrarian to industry-based economies. Rapid growth in productivity and income levels in some developing countries, notably China and India, has been made possible by greater manufacturing growth and trade enabled by technological progress. In contrast, productivity growth in the other developing regions has been relatively subdued. In Latin America, average labour productivity growth slowed between the 1960s and the mid-1980s and has remained weak since then. A similar trend is observed in Western Asia and sub-Saharan Africa. It will be difficult, if not impossible, to achieve prosperity for all—and leave no one behind—without boosting productivity growth, particularly in low-income, developing countries. Bridging the technology divide, as discussed in chapter III, will remain key to stimulating productivity growth in those countries.

Trends in income inequality[4]

The differences in productivity growth noted above are reflected in the distribution of income within and across countries. As noted by Milanović (2016), global inequality[5] levels remain very high but underwent some stabilization in the 1980s and began a sharp decline in 2003. This trend is attributed largely to rapid growth in productivity and income levels in China and India as these economies, supported by technological progress and trade, integrated with the global economy. As a result, the poorest half of the global population experienced strong income growth. At the same time, the top 0.1 per cent saw huge growth in their income. Those caught between the bottom 50 per cent and the top 1 per cent have seen no gain since 1980 (Alvaredo and others, 2018).

While global inequality may have declined to some extent, within-country inequality has increased in many regions of the world. Many East Asian countries, including Indonesia, the Philippines, the Republic of Korea and Viet Nam, have seen a relatively steady increase in wage inequality since the 1990s; and China, India and the Russian Federation witnessed steep increases in income inequality following the liberalization of their economies. While inequality has also increased sharply in developed countries, countries in Latin America and the Caribbean, in the Middle East and in sub-Saharan Africa have seen some improvement but still have some of the world's highest income inequality levels. In Brazil, the Middle East and South Africa, the top 10 per cent of the income distribution captures between 55 and 65 per cent of national income. The declining labour share in national income in many developed countries largely explains the growing income inequality in both developed and developing countries (figure I.3).

Globalization and automation have contributed to widening income inequality in some countries

In developed countries, offshoring of production, decline in manufacturing, the process of automation and replacement of manufacturing jobs by lower-paying service sector jobs, and the decline in negotiating power of workers have played a role in exacerbating income inequality (see chap. II). Automation—which is also spreading to large emerging economies, notably China, in response to rising labour costs—further increases the returns to capital. There has also been a more unequal distribution of labour income itself, driven by polarization of skills. Middle-skill jobs have been particularly affected by automation and AI, with wide-ranging distributional effects. Since 1970, the real wages of high-skilled workers have risen faster than those of both medium- and low-skilled workers.[6] There is therefore a need to ensure that further advances in technological progress do not worsen income inequality, especially if the overarching goal of leaving no one behind is to be achieved.

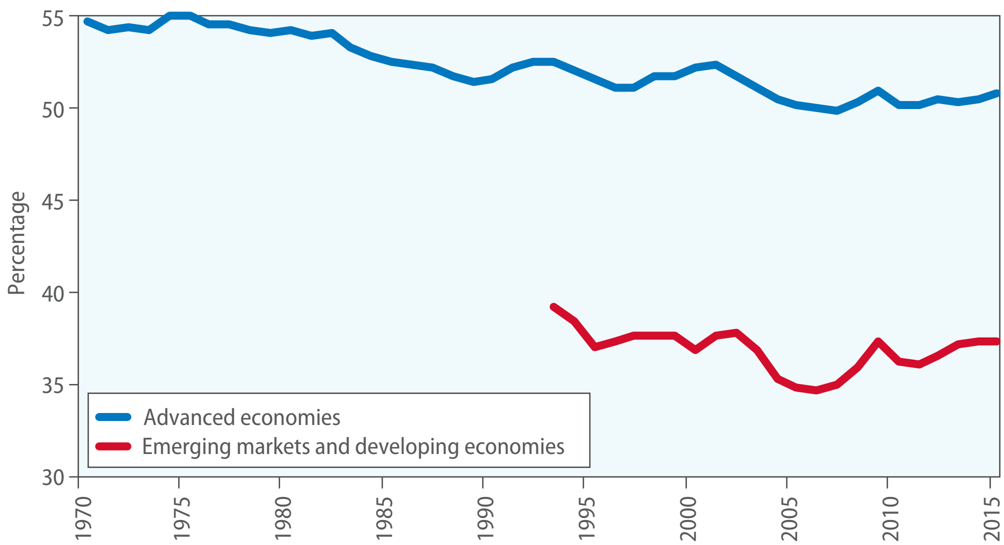
---

4 The focus of the present section is on productivity and economic growth. Therefore, the discussion is focused on income-related forms of inequality, particularly on how they are affected by wages. The *Survey* recognizes that inequality is a broader concept, as reflected in the SDGs, which encompass other important types of inequality, such as in economic opportunities, access to education, health and other basic services; and in political representation. However, those types are not examined here. See the 2016 edition of the *Survey* (United Nations, 2016b) for a discussion of the importance of addressing structural inequalities, including chap. II which considers how technology can worsen existing inequalities. Additional discussions on inequalities can be found in the *Report on the World Social Situation 2013* (United Nations, 2013) and the *Report on the World Social Situation 2016* (United Nations, 2016a).

5 The term "global inequality" refers to the inequalities of the income of individuals regardless of country. It contrasts with inequalities in per capita income of countries and with population-weighted international inequality (i.e., between-country inequality).

6 See chap. II and Bruckner, LaFleur and Pitterle (2017) for a fuller discussion of how automation impacts labour and income inequality.

Figure I.3
Trends of labour share of income, 1970–2015



Source: IMF (2017), figure 3.1.

Potential of frontier technologies to help foster sustainable development

Technology invites us to imagine a future without poverty and hunger, with fewer diseases and higher life expectancy, greater equality of economic opportunities and universal financial inclusion. Ushering in such a future, however, will require more intensive and extensive use of natural resources, unless there are significant improvements in and use of relevant technologies. By one estimate, achieving many development goals would require a level of resource use that is 2–6 times the sustainable level (O'Neill and others, 2018).

Frontier technologies have a central role in protecting our planet and people and promoting prosperity

The present section uses challenges discussed in the previous section as the basis for illustrating the central role that frontier technologies could play in protecting our planet and people and in promoting prosperity. Specifically:

- For our planet, new advances in the extraction, conversion and storage of electricity may hold the key to making renewable energy sources competitive with fossil fuels and improving environmental sustainability.
- For improving people's lives, new technologies will continue to improve health outcomes, leading to better, cheaper and newer services, medicines and goods. Those technologies are making new methods of diagnosis and new forms of treatment possible and improving the administration and management of health care with better data and analysis.
- For prosperity, new technologies mean new products and services for a greater number of people. For example; AI is being used in a widening range of fields, from image recognition to financial analysis and scientific research; advances in automation are enabling new forms of manufacturing and self-driving drones and vehicles; and financial innovation in the form of digital payments is bringing financial services to millions.

This section is not intended to provide an exhaustive treatment of the ways in which each frontier technology can impact sustainable development in all its aspects and dimensions. The discussion does not, for example, examine the role of new technologies in reducing vulnerabilities to climate hazards or in improving educational outcomes. Instead, building on the assumption that every sustainable development challenge faced by societies at local, national and global levels can benefit from some combination of existing and new technologies, the discussion focuses on three areas where frontier technologies can be transformative for the planet, people and prosperity.

Furthermore, while much of the discussion connects certain technologies with specific challenges, this *Survey* recognizes that the technologies and their applications discussed are often interconnected and interdependent. Technological advances in such areas as AI, machine learning, robotics, nanotechnology, additive manufacturing (3D printing), genetics, biotechnology and smart systems build on and amplify one another.[7]

Promoting environmental sustainability

The production of energy is the largest contributor to global GHG emissions, being responsible for approximately 35 per cent of total anthropogenic GHG emissions in 2010 (IPCC, 2014a, p. 46). As the economic growth necessary for higher standards of living requires more energy, and hence more carbon emissions, limiting climate change requires a fundamental transformation of the energy supply system entailing a shift towards low GHG emissions.

Cleaner renewable energy technologies have opened the door to a sustainable future

The challenge posed by energy scarcity and climate change has spurred the development of new, cleaner energy technologies and opened the door to a possibly sustainable future. The threat of climate change and the demand for new energy sources have changed the economics of existing energy systems and spurred a new wave of green technology-based manufacturing and trade.

Rapid technological advancements are driving this transformation by improving low-emission energy technologies such as renewable energy and nuclear power, and carbon dioxide capture and storage. Only a small proportion of the potential for renewable energy has been exploited with current technology, but this proportion has been increasing as the performance of many renewable energy technologies advances and their costs decrease. (Bruckner and others, 2014; World Energy Council, 2016). These developments are expanding the access of renewable energy technologies in poorer and remote locations, making off-grid installations scalable and economically feasible.

The pursuit of renewable energy generation goes hand in hand with the need for advances in energy storage to prevent energy from being wasted. The supply of renewable energy from wind, solar and other sources fluctuates depending, e.g., on the time of the day and weather conditions. The ability to secure the supply of a steady, large quantity of electricity generated from renewable sources, and to transmit it as needed to meet demand, calls for advances in storage technology.

7 The appendix to this chap. provides a more detailed discussion of how specific technologies work. While the discussions here and in the appendix do not encompass every technology that may be categorized as a frontier technology, they do illustrate the potential of frontier technologies to help resolve some of humanity's biggest challenges.

Improvements in the energy density and recharging speed of batteries are making electric vehicles (EVs) viable alternatives to traditional vehicles that use internal combustion engines. As a result, a wider variety of EVs have become available at more affordable prices. The stock of EVs is forecast to reach between 40 million and 70 million by 2025 and new types of batteries are being developed which will continue to tip the scale in favour of EVs. For example, Toyota has plans to develop all-solid-state batteries by 2022. The aim of Samsung Electronics, a major producer of auto batteries, in working on lithium-air cells is to double the capacity of today's mainstream lithium-ion batteries.

Since EVs require electricity, the key to their reduction of energy consumption and emissions over the entire lifetime of the vehicle (i.e., from the generation of electricity to the use of electricity by EVs while running) lies with the energy sources that charge the EV batteries. Replacing internal combustion engine-based vehicles with EVs will not be of much help if the electricity used by those EVs is produced from fossil fuels, emitting high volumes of GHG emissions.[8] EVs have the potential not only to reduce lifetime emissions but to transform the entire auto manufacturing industry, as new companies and new production chains are created around frontier technologies.[9]

Improving health outcomes[10]

Humanity has reason to be tremendously hopeful regarding the ability of emerging technologies to help save lives, improve health outcomes and extend life expectancy. The present section focuses on health outcomes, highlighting digital technologies, genetic technologies, and drug and vaccine delivery—frontier technologies that are exerting a transformative impact on health care. These technologies will prove especially important for developing countries, helping them to expand the reach of existing and new health services to those most at risk. Another set of frontier technologies (a few of which are examined in chapter III) can be equally impactful with regard to educational outcomes.

Digital technologies: artificial intelligence, communications and robotics

Artificial intelligence presents an immense potential for improving health care

Artificial intelligence (AI)—encompassing machine learning and deployment of algorithms for data processing and pattern recognition—possesses an immense potential for improving health care. AI can help to achieve the goal of turning personalized medicine and outcome-based public health into a clinical reality (*The Lancet*, 2017). Together with other technologies, AI will make it possible to better calculate and manage risk and to better evaluate policies and intervene with those that are appropriate. Innovative means of detecting public-health risks employing cell phone and other consumer data and machine learning are already being used. They can, for example, help WHO identify and respond

8 EVs embody technologies that are very different from those employed in vehicles with internal combustion engines. The main components of electric vehicles are motors, batteries, power inverters and the controlling software. The parts are connected via electrical wires within a structure that is much simpler than the complex mechanical system required by internal combustion engine-based vehicles.

9 See chap. II and Kawamura (2017) for further discussions on the importance of electrical vehicles for economies and societies.

10 This section is based on a presentation by Henry Wei (Google's Medical Director for Benefits) made at the Expert Group Meeting on Emerging Technologies and Sustainable Development, held in New York on 14 and 15 December 2017, at which the background, objectives and outline of the 2018 *Survey* were discussed.

to health emergencies by facilitating better prediction, scenario modelling, resilience-hardening, and response planning.

Algorithms can improve medical diagnoses and extend the capabilities of medical professionals

Image analysis algorithms can help identify skin malignancies, breast cancer, pneumonia and other diseases. AI-enabled continuous speech recognition can improve medical record-keeping, a time-consuming task which in the United States of America currently consumes over half of a physician's time. Better medical records can be used to assist AI systems in predicting readmission rates, infection risks and other treatment complications. This tool complements human judgment and thus helps minimize preventable errors.

Improvements in digital technologies and human interfaces combined with machine learning can extend the capabilities of community health workers, thereby helping to mitigate the shortage of expert workers. For example, those workers can be given live instructions through augmented reality techniques on how to administer wound care under the remote supervision of a more experienced medical professional. Conversational AI systems can alleviate the shortage of psychiatrists and provide limited help to those sufferers from depression or anxiety who cannot access trained professionals (ibid.).

Advances in communications technology can further improve knowledge dissemination among health providers and patients and improve behavioural interventions for the prevention of diseases, including chronic conditions such as obesity, cardiovascular disease and cancer. For example, SMS text-based health education and treatment compliance, medical appointment reminders, and health surveys and surveillance can improve access to and effectiveness of health-care services, particularly for those in remote areas (Schwebel and Larimer, 2018). Further, social networks and mobile connectivity, coupled with data analytics, can help to strengthen public-health campaigns designed to increase awareness, influence cultural norms and improve sanitation practices.

Frontier technologies can facilitate improvements in the hardware needed for health care. New manufacturing methods like 3D printing can lower the cost of precision medicine and medical devices. Technologies available in widely used consumer devices, such as modern smartphones, can serve as low-cost substitutes for expensive medical devices, such as portable ultrasounds. Smartphones, tablets, cameras and audio sensors, among other devices, are becoming consistently more powerful and cheaper. Robots are already performing certain routine but highly technical surgical procedures, which is reducing risks of human error and infection. Autonomous surgical robots are already able to perform better than human surgeons in stitching together segments of the intestine. Assistive robots, which include exoskeletons, permit those who are paralyzed or disabled to walk.

Genetic technologies

New genetic technologies can address some of our greatest medical challenges

The development of powerful gene-editing tools and a growing capability with respect to altering biological systems, including those of humans, unveil huge possibilities for meeting some of the greatest medical challenges, including how to produce new treatments for many of the diseases which humankind has been combating for decades.

New or "next-generation" DNA sequencing technologies have drastically reduced the cost and time needed for sequencing DNA. Between 2007 and 2017, the cost of sequencing a genome declined from nearly \$9 million to just \$1,100 per genome.[11] The drastic reduction in cost has led to a "genomics race" between countries looking to establish themselves as

11 See https://www.genome.gov/sequencingcostsdata/.

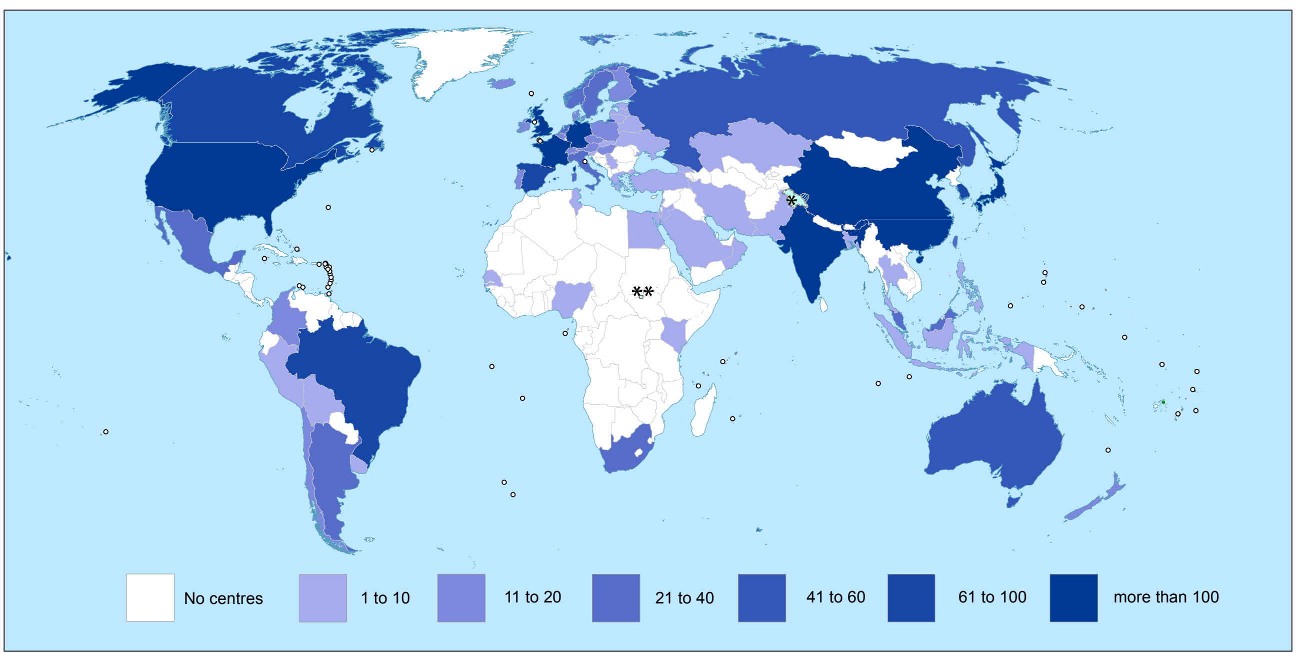
leaders in the field of precision medicine. For example, following the announcement of a precision medicine initiative in the United States, China followed suit in 2016 with its own 15-year initiative.

High costs limit the access to genetic technologies and may lead to a growing inequality in health outcomes

This is an area, however, where the technological divide may lead to a growing inequality in terms of access to precision medicine. Despite the decline in costs, next-generation sequencing remains quite costly for developing countries. As next-generation sequencing facilities require capital investments in the range of \$100,000−\$700,000 in developed countries and even greater investments in the developing world, such facilities are rare worldwide (see figure I.4). Limited availability of skilled personnel and training and limited access to the scientific community and data are other factors that prevent many countries from reaping the benefits of next-generation sequencing technologies.

Participants in the Human Heredity and Health in Africa (H3Africa) initiative, which represents an attempt to overcome the constraints on the development of knowledge and technical capacity in the continent, work to establish research infrastructure and expertise, to foster pan-continental collaboration, to nurture research and, in general, to support African scientists. The initiative directs funding from the National Institutes of Health and the Wellcome Trust to research sites across Africa, where genomics, environmental determinants of common diseases, disease susceptibility and drug responses in African populations are being studied.

Figure I.4
Genome sequencing centres per country



Source: Helmy, Awad and Mosa (2016), figure 1.C.

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

* Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

** Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

As the cost of DNA sequencing declines, the advances in gene editing and genetic therapies are accelerating. New genetic treatments for, e.g., HIV, beta thalassemia and cancer, are showing promise. Immunotherapy is another area of technology that shows promise—immense promise—for health outcomes, particularly in combating cancer. Still another promising technology—chimeric antigen receptor (CAR) T cell therapy—entails extracting a patient's own T cells and exposing them to a disarmed virus. Through exposure they are engineered to locate and attach themselves to tumor cells and subsequently destroy them.[12] The cost of the treatment, about $475,000 per year with current methods, remains prohibitive, however.

New technologies for drug delivery and vaccines

Technologies are improving access and delivery to medicines, improving the wellbeing of the most vulnerable

Drug delivery is another area where the new technologies can positively impact health outcomes. The polypill, which combines multiple drug products in a single pill, has been used successfully to decrease the incidence of cardiovascular events. Similar advances were seen in the treatment of HIV patients with the "quad pill", which has simplified treatment regimens and improved adherence. New advances in the manufacturing of pills will involve 3D printing, with medication and dosage appropriate for each individual patient.

Universal access to sexual and reproductive health-care services is a basic right, as measured by SDG indicator 3.7.1, and is vital to improving lives and livelihoods. Technological advances in drug delivery will significantly improve family planning and contraception and overall health. For example, an estimated 20 per cent of all obstetric deaths could be prevented each year if all women desiring no more children used modern contraceptives (Collumbien, Gerressu and Cleland, 2004). Moreover, unplanned pregnancies are estimated to be responsible for 30 per cent of the disease burden associated with maternal conditions globally (WHO, 2009).

It has also been found that delaying pregnancy can enable women to significantly increase their incomes. This is particularly important for the approximately 225 million women in developing countries who could potentially delay or prevent pregnancy but, for various economic, social and cultural reasons, are not using any of the available methods of contraception. The development of an all-in-one injectable contraceptive simplifies contraception procedures considerably, eliminating needle and syringe and allowing women to self-inject. In 2016, 1.5 million women in 20 countries benefited from this method of contraception delivery (United Nations, Department of Economic and Social Affairs, Population Division, 2017);[13] but social and cultural norms in many parts of the world may still inhibit further uptake of the use of this contraception technology.

Typhoid is an ever present threat for millions of people in developing countries. According to WHO, between 11 million and 20 million people are afflicted by typhoid every year. Between 128,000−161,000 people die from typhoid annually (McNeil, 2018; WHO, 2018). It is also the case that, in addition to the burdens of the disease itself, the use of antibiotics to treat the symptoms of typhoid is leading to greater antibiotic resistance to the disease.

---

12 T cells are white blood cells that are important for adaptive immunity. Their unique cell surface receptors enable T cells to sense and respond to diverse forms of infection.

13 Technologicaly innovative forms of contraception may be cheaper than traditional methods, but uptake could still be hindered by the same social and cultural constraints that currently prevent many women from accessing contraception and other forms of family planning.

The control of typhoid through improved water quality and adequate sanitation has been highly effective in Northern America and Europe over the past century. In developing countries, however, the infrastructure required to break the transmission cycle of typhoid is often inadequate. While immunization programmes remain an important component of disease control, current vaccines are unfortunately not effective and cannot be administered to children under age 5.[14] However, a new type of vaccine, has recently been approved by WHO for global use. Referred to as the typhoid conjugate vaccine (TCV), it will transform typhoid vaccine delivery for children under age 5.

Achieving equitable economic growth

Frontier technologies have opened up new opportunities for economic growth, jobs and wealth creation. They continue to expand productive capacities and productivity of firms and individuals based on utilization of better machines and information, enabling new business models and creating entirely new industries. In the last 30 years, technology has been a contributing factor to the halving of the rate of global poverty since 2000; to the reduction of hunger, malnutrition and child mortality; to the combating of infectious diseases; and to progress in achieving most of the other Millennium Development Goals (United Nations, Economic and Social Council, 2017).

Developing countries have the most to gain, and also the most to lose, from the new opportunities offered by frontier technologies

Frontier technologies are rapidly changing industries and sectors, creating opportunities for competition in new markets with new production capacities (see chap. IV for a comprehensive discussion on the importance of technology for structural economic change). Countries leading the innovation of many frontier technologies will enjoy a competitive edge over those that are lagging in innovation and technology development. Closing the technological divide will remain critical for achievement by many developing countries of higher, sustained economic growth and for their reduction of economic inequalities.

On the other hand, those developing countries enjoy certain advantages during periods of rapid technological change, since they are not saddled with what are known as legacy investments in technologies, i.e., investments in technologies whose time has now passed (Gerschenkron, 1962). For example, countries may not necessarily need a twentieth century industrial base to build a twenty-first century bio-, nano- or information economy. It may be easier for a firm without large capital investments to undertake manufacturing with a 3D printer, thereby skipping all the steps needed to make the same part in the traditional way. Innovations in algorithms and data analysis, new manufacturing methods and new digital financial systems will generate new sources of growth, create new jobs and open up new opportunities for entrepreneurship.

Machine learning and artificial intelligence have wide applications

Artificial Intelligence could fundamentally reshape our economy and society

The growing ability of AI systems to solve complex problems autonomously could fundamentally reshape our economy and society, for example, through development of new forms of transportation or a revolution in health care. Whereas the steam engine was deployed in tasks that required muscle power, AI is being applied to tasks that require brainpower (Furman and others, 2016, p. 8). The World Economic Forum characterized AI as the cornerstone of the so-called fourth industrial revolution (4IR), and its growing

14 The oral typhoid vaccine, which is effective for children, is formulated in capsules that cannot be swallowed by children.

ability to mimic aspects of human intelligence as a historic development in the automation process (Schwab, 2016).

Machine learning has enabled AI to defeat the best human in a number of contests (chess and Go being the most known examples) and has proved useful in industrial automation, in better communication around the world, and in improving our ability to interpret medical data. AI capabilities have also greatly enhanced computer vision, speech recognition, motor control (of robots), language translation, and decision-making processes in science, finance and other fields.

The layers of abstraction underpinning AI—building upon deep (machine) learning of trends, patterns and scenarios—can turn it into a black box. Efforts to understand the reasoning process governing an AI system, in particular how and why it reached a particular decision point, often meet with obstacles. In health care, for example, those obstacles can make integration of AI systems into routine clinical care a difficult task. The broader use of data and algorithms also raises ethical concerns and legal issues related to data privacy, transparency and the need for an institutional framework of accountability (see chap. II).

3D printing (additive manufacturing) and digital fabrication

Advances in technologies such as additive manufacturing (the industrial version of 3D printing), which are drastically altering the way physical goods are produced, promise to transform the economics of manufacturing.[15] 3D printing offers many benefits over traditional forms of manufacturing, including the ability to generate faster design prototypes; produce complex, customized items; and change a design quickly (*The Economist*, 2017). In addition to additive manufacturing, innovations in fabrication, such as laser cutters, 3D milling machines and programmable electronics, together with advances in computer-aided design and manufacturing software, are bringing the benefits of the digital revolution to factories. Neither additive manufacturing nor digital fabrication requires economies of scale to make production profitable. With respect to metal parts, for example, 3D printing and laser cutting allow for a level of complexity in shapes which may be nearly impossible to achieve with traditional methods, and reduce the need for welding, which facilitate customized and niche applications. Additionally, 3D printing facilitates just-in-time inventories and reduces waste in manufacturing.

Currently, 3D printing is used extensively to build prototypes, but technological development continues to improve the manufacturing machinery and software and expand the range of materials that can be produced with additive manufacturing, including composites and functionally graded materials (OECD, 2016). As this technology continues to mature, it will become exploitable for new industrial, consumer and medical uses, especially when low-volume, complex and customized solutions are needed. In health care, 3D printing is used to manufacture prostheses and implants and to prototype robotic exoskeletons. Clearly, digital fabrication, offers an opportunity for developing and least developed countries (LDCs) to bridge the technological divide, kick-start manufacturing and build a new industrial base.

The environmental impact of 3D printing and digital fabrication is not yet clear. The process can decrease waste and emissions by reducing the number of steps and the energy

15 Construction of an object through the process of 3D printing entails addition of material one layer at a time based on a digital set of instructions. By contrast, construction of an object through the process of traditional (subtractive) manufacturing entails either moulding or removing material by cutting, drilling or milling.

needed to produce, transport, assemble and distribute products. Often, raw materials used in additive manufacturing are recyclable or biodegradable, as is the case for some commonly used plastics. On the other hand, certain 3D printing processes use ultrafine particles which may pose health risks. Consequently, the energy and carbon footprints of 3D manufacturing need to be studied more thoroughly (ibid.).

Digital finance technologies

Many households and small businesses, often operating in the informal sector, have no access to formal financial services and therefore rely on cash. The lack of physical availability of financial service centres means that many of those affected must travel long distances to access financial services. Globally, about 2 billion people lack a formal financial services account, of whom 1.4 billion reside in low- or lower middle income countries (Jensen, 2018).

Mobile technologies and innovations in digital finance have made financial services accessible to millions in developing countries

Mobile technologies have opened the door for a growing number of people in developing countries to access digital financial services. According to estimates by McKinsey Global Institute (2016), 80 per cent of adults in emerging markets have a subscription with mobile phone providers. This enables mobile operators to facilitate financial transactions for mobile customers for as little as $10 per year, 90 per cent lower than the fee charged by conventional banks. In 2015, there were 271 mobile money services in 93 countries, managing an average of 33 million transactions per day, including payments, deposits, microloans, insurance and pension-related transactions—and even investments in treasury or government infrastructure bonds (Suri and Jack, 2016). People are using digital financial systems to receive wages, pay school fees and utilities bills, buy groceries, save for emergencies, and send remittances. Digital finance has also helped spur new models of service delivery and payment, such as Pay-As-You-Go solutions in the utilities sector, improving the feasibility of infrastructure and other investments.[16] In lending, digital finance is helping to facilitate access of households and small and medium-sized enterprises to credit and insurance products. With regard to the impact of services, in the recent study by Suri and Jack (2016), cited directly above, it was estimated that access to the mobile money system in Kenya increased per capita consumption levels and lifted 194,000 households (2 per cent) out of poverty, a result of more efficient allocation of labour, savings and risk.

Digital finance can help to drastically lower fees for remittances, and directly help meet target 10.c under the SDGs, which aims at the reduction of the costs of sending remittances. In 2016, the global average cost of sending remittances was 7.3 per cent, with rates in sub-Saharan Africa averaging 10 per cent (Jensen, 2018).

Cryptocurrencies represent a new frontier in digital finance and their popularity is growing.[17] The decentralized networks for cryptocurrencies, bitcoin being a well-known example, can keep track of digital transactions. They enable value to be exchanged and can give rise to new business models which would otherwise require significant regulatory and institutional commitments. For example, a value token called climatecoin is being considered as a basis for creating a global market for carbon emissions, allowing peer-to-peer exchange of carbon credits and a direct connection with the Internet of Things. It

16 Because this model is metered, it can be utilized in the utilities sector. Under such an arrangement, consumer payments are a function of careful measurement and monitoring.

17 See the appendix to this chapter for a description of how cryptocurrencies work and their relationship to the traditional financial system.

would then be possible for devices to calculate their own carbon emissions and purchase carbon credits to offset those emissions.

There are also proposals for using blockchain technology as a distributed ledger of real-world information on property registration, personal identity, and provenance of food and medicines, among many other types of data. The United Nations and the World Identity Network are exploring ways to register the identities of children on a blockchain as a means of combating child trafficking.

The path of technology development towards broad-based efficiency, equity and ethics

There is no guarantee that new technologies will serve the most pressing needs of humanity

While technological progress is fundamental for achieving the SDGs, there is no guarantee that this progress will be aligned with the most pressing needs of humanity: eradicating poverty and hunger, reducing inequality, generating shared prosperity and building resilience against climate change. The *Survey* recognizes the need for balancing efficiency and cost effectiveness against equity considerations and ethical standards to facilitate development, diffusion and adoption of appropriate technologies for sustainable development. Firms may innovate the products, services and business models that will maximize profit in the short run even if those innovations do not ensure equity and meet ethical standards. However, a narrow, short-term profit-driven commercialization of technology may not always be compatible with sustainable development outcomes (figure I.5). The process of technology development—ensuring transparency, accountability and participation—matters as much as the final outcome. Effective institutional mechanisms can ensure that the new technologies entering the market meet socially agreed efficiency, equity and ethical goals and standards.

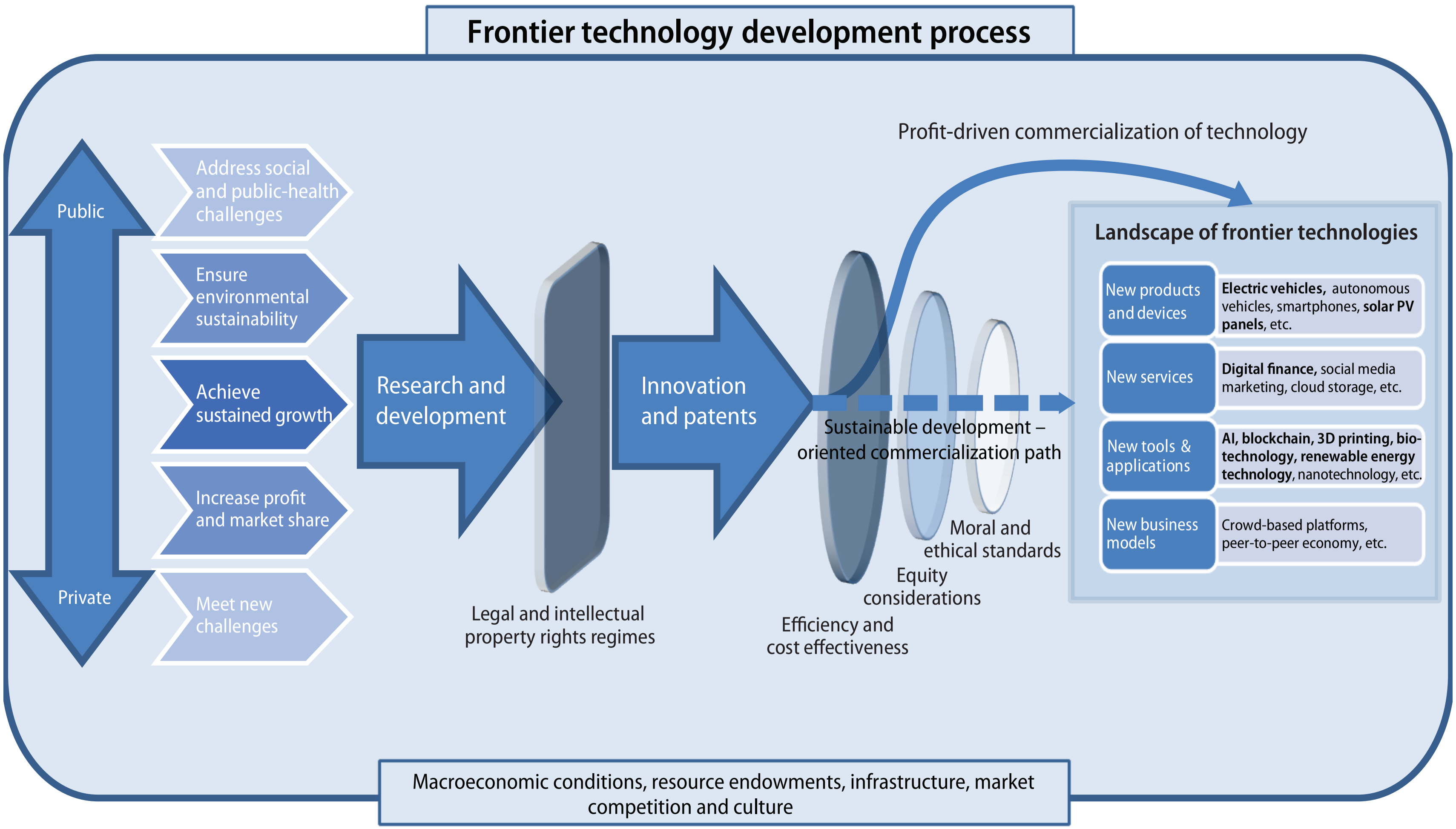
Frontier technologies also have unforeseen and unintended consequences for planet, people and prosperity

The use of AI-driven robots exemplifies how technological progress may have unintended consequences which undermine other development objectives. While this type of automation can help raise output and minimize manual and routine work, it can also cause significant job loss and thereby adversely impact the goal of achieving greater social equality. In a global context, automation may trigger a process through which manufacturing is reshored in developed countries, making it difficult for developing countries to industrialize through the expansion of labour-intensive manufacturing that has relied on the offshoring of manufacturing from developed countries.

Online social platforms—which have become an inevitable feature of modern existence, bringing individuals and communities together in the digital space—provide another example of the unintended consequences of technological progress. These networks can be used to disseminate information on environmental and sustainability options and best practices and to widen the range of consumer choices to include sustainable goods and services. However, they may also enable the spread of misinformation and become weaponized to influence political processes and undermine vulnerable institutions where governance is weakest. Along similar lines: while the Internet of Things and the use of more advanced algorithms to analyse big data can transform entire sectors (including improvement of health care, as discussed above), they can also radically reshape the concept of privacy; and while gene editing, for example, may save many lives, it may also open up a Pandora's box of dangerous pathogens.

It is therefore not sufficient for a new technology to be efficient—it must also be deployed in a way that is sufficiently equitable and ethical to support the realization of the

Figure I.5
The development process for frontier technologies



Source: UN/DESA.
Note: In the right-hand box, entitled "Landscape of frontier technologies", the names of technologies discussed in this *Survey* are in bold.

SDGs. New technologies may indeed lead to immensely significant outcomes, but they may also leave behind those who do not have access to them or who are displaced by the changes brought about by those technologies. Equity issues emerge as new technologies create winners and losers. Businesses, households and policymakers are therefore confronted with the task of establishing a delicate balance among maximizing the efficiency gains of a new technology, reducing the gap in access to those technologies within and across countries, achieving equitable distribution of the gains of technological advances and ensuring that the use of new technologies meet internationally agreed ethical, moral and human rights standards.

Countries and firms controlling access to, and use of, many of the frontier technologies stand to gain immensely

The advantages that such technologies confer on the countries and firms that can access or control them will be immense, which therefore threatens to widen the existing technological divide. Developed countries—whose research and development are led by more advanced national innovation systems and whose firms and customers will lose no time buying up and using those technologies—will be the first to reap the immediate benefits of the progress achieved through new discoveries. AI, biomedical advancements and advancements in renewal energy and storage, to name but a few of the new breakthroughs, are likely to be developed and rapidly put to use in technologically advanced countries as tools for scientists, businesses and customers. At the other end of the spectrum, many developing countries continue to struggle to provide access to electricity, Internet connectivity, water, sanitation and basic health technologies, which are necessary requirements for advancing to the new technological frontier (see chap. III).

The brightest thinkers, innovators and entrepreneurs in the field of new technologies are more likely to be based in the countries with a concentration of research universities, venture capital and innovation hubs. Indeed, this high concentration of innovation capacities is restricted to but a small set of countries. For example, data on European patent applications related to frontier technologies show that China, the European Union, Japan, the Republic of Korea and the United States account for about 90 per cent of such applications, with the United States alone accounting for an overwhelming 75 per cent of the global increase in AI patents between 2010 and 2016. The high concentration of innovation capacities in a handful of countries is likely to make it increasingly more difficult for many developing countries to bridge the technological divide and achieve the level of economic growth necessary for sustainable development.

Automation, algorithms and ever-increasing computing power have diminished the importance of human labour in production of goods and services

Within countries, technology has been diminishing the relative importance of labour compared with capital. As technology progresses, the replacement of workers by advanced automation made possible by improvements in sensors, software (including AI and machine vision) and materials will disproportionately affect workers in large advanced manufacturing firms. The replacement of labour by new forms of automation can further concentrate wealth in the hands of capital and business owners, contributing to greater income and wealth inequality (see chap. II for a fuller discussion).

New algorithms, computing power and data sets can be used to build so-called platforms which entrench the dominance of large companies, potentially undermining competition in the area of products and services and in labour markets. The result will be a growing technology gap between firms that are at the national technological frontier and those that are not. As shown in chapter IV, even as technologies make their way into new countries at a faster rate, the speed of diffusion of technologies inside a country has decreased. In the key field of AI, patent generation is also highly concentrated in a few firms, even in the most technologically advanced countries that are global leaders in the

Box I.2

Data as a common factor in frontier technologies

Data is the common thread connecting many of the frontier technologies and their applications. Data are generated every time, for example, we click on a digital device, make a phone call, swipe a credit or electromagnetic card, or use a vending machine. We leave digital footprints everywhere, often without realizing that the footprint contains a valuable piece of information. In this digital era, firms have increasingly recognized the value of data, pursuing new ways to capture the information generated by activities and contained in places and things. Digital data are now collected from, e.g., Global Positioning System (GPS) trackers in vehicles and phones, social media, commercial transactions, and medical information. The value of these data is enormous. Data generate additional data through analysis, enable network effects and platforms, and are the key input for building algorithms, improving machine learning and creating AI which already competes with human intelligence. As factor inputs for analytics and AI, data constitute valuable capital.

While the data economy transcends political and sectoral boundaries, an appropriate framework for establishing ownership rights over data are still lacking. In this economy, individuals are both producers and consumers — but are not the owners — of data,. Data have become increasingly essential as capital in the provision of many products and services (MIT Technology Review Custom and Oracle, 2016). Individuals, however, do not participate in this market as suppliers and users. Rather, as they generate data to be mined and analysed, their role is largely that of a resource to be exploited.

In the existing digital economy, the firm — which can range from anything from a social media platform to a rideshare service — that collects the data owns the data, without necessarily compensating the individuals who created those data. An asymmetric relationship therefore exists between individual creators of data and the firms that collect, compile and analyse those data. This is a relationship in which the firms amassing the data enjoy an undue advantage over the individuals that are the source or producers of the data. The fact that those firms are able to collect what are in fact huge economic rents without the explicit consent of those individuals creates a significant distortion in the marketplace.

Because of the value of data as capital and as personal information, the security, privacy and ownership of data are important considerations for ensuring the integrity of the digital economy. The rise of a data-driven economy therefore requires laws and regulations that clearly establish a basis for the ownership of data and for the recognition of data as an asset that is economically valuable. Countries and country groups have begun to set boundaries regarding how data can be collected and used. For example, in April 2016, the General Data Protection Regulation (GDPR) was agreed by the European Parliament and the Council of the European Union. The regulation, which entered into application in May 2018, brings all data of residents of the European Union that is being processed within the scope of the European Union's data protection law. GDPR specifies the rights of individuals and the obligations placed on organizations covered by the regulation, that is, those organizations must, inter alia, grant persons easier access to their data, as held by those organizations; comply, under a new fines regime, with severe penalties for infringement, of up to 4 per cent of worldwide turnover, or €20 million, whichever amount is higher; and secure the consent of individuals before collecting data on them. The European model for ensuring the rights of individuals as related to their personal data represents a step in the right direction and the start of a conversation on how the multilateral system can go about creating global standards for data privacy and rights.

Source: UN/DESA.

domain. Addressing such large and growing divides requires a broad understanding of the key dynamics driving the processes of technology innovation and diffusion.

Frontier technologies raise new concerns over safety and ethics

Frontier technologies present new and unique challenges to ethics and morality

Frontier technologies present new and unique ethics- and morality-related challenges, which can potentially undermine trust, cohesion, tolerance, peace and stability. These concerns arise with the emergence of new technologies, either as societies determine how to cope with those technologies' intended disruptions or as they set the boundaries of acceptable use, as in the case, e.g., of genetic engineering (see chap. II for a more detailed discussion on the ethical implications of digital technologies).

Gene editing poses a risk of off-target edits which could lead to mutations and other problems in the targeted genome. In addition to these safety risks, there are ethical concerns raised by the use of germline editing (gene editing for reproductive purposes), especially if it is applied to address the genetic diagnosis of an unborn child, a situation where off-target edits can evolve quickly. Other issues include lack of the informed consent of the future person, greater accessibility to the technology by the rich, and moral and religious objections.

The rise in importance of artificial intelligence opens up the possibility of new forms of discrimination which may be harder to identify and address (see chap. II). Machine learning algorithms by their very nature defy our ability to understand how and why a decision has been made, thereby limiting our ability to evaluate that decision within the context of ethical and other societal norms.

The growing importance of data in economic, social and political activities merits appropriate and acceptable legal and ethical boundaries that respect the fundamental rights of individuals

The rise in the importance of data as an input into economic activity raises important ownership issues; and how data are being collected and, in some cases, misused is a growing privacy concern. Breaches and leaks have occurred in the databases of financial institutions, credit-rating agencies, email providers, social networks and health facilities, among many others. Some leaks are made public, while others become the basis for criminal activities such as identity or financial fraud or for exerting political influence on a massive scale. It has recently been discovered that a research group made use—legally—of data extracted from the social media platform Facebook to help create targeted political campaigns, which has ushered in a whole new era of political campaigning.

As data become increasingly valuable to businesses for what they reveal about individuals, the world must strive to set appropriate and acceptable legal and ethical boundaries, while respecting the fundamental rights of individuals. Through work on regulation, the rights of consumers as the targets of data collection can be clearly established (see chap. V for a discussion of the policy implications in this regard).

Policies for harnessing the potentials of frontier technologies

Policies should ensure that technological breakthroughs serve the overarching goal of leaving no one behind

Considering the potential of frontier technologies to help achieve the SDGs as well as their potential to generate unintended adverse effects, proactive and forward-looking policy measures are required for managing progress in the development of many frontier technologies. There is a need to ensure that further advances in technological processes do not lead to a worsening of income inequality, especially if the overarching goal of leaving no one behind is to be achieved.

Technological breakthroughs should be embraced and promoted, while balancing efficiency, equity and ethical considerations

On the one hand, technological breakthroughs should be embraced, and continued progress should be promoted. On the other, it should be recognized that realizing the vision of the 2030 Agenda for Sustainable Development without leaving anyone behind will require a balance to be struck among efficiency, equity and ethical considerations. In this regard, countries can adopt a range of policies to ensure that frontier technologies are deployed to facilitate attainment of national and global development objectives.

Proactive and effective policies are needed to reduce the pains of adjustment to new technologies and economic structures

At the national level, policies and institutional context play a major role in determining who benefits and who loses from the adoption of new technologies. In some countries, the ushering in of new technologies will lead to changes in the demand for skills and in the nature of work. This phenomenon is already being observed in many developed economies and in the large manufacturing sectors of developing economies. Hence, policies must be proactive so as to facilitate the transition and reduce the pains of adjustment to new economic structures, ensuring that workers are employable, adaptive and competitive. Given the potential for a widening gap between winners and losers in the technological race, competitiveness and inequality effects will also require policy solutions.

Bridging the technological divide is a necessary condition for closing the development divide

The ability of developing countries to access new technologies will determine whether they will be able to keep up with and catch up to countries closer to technological frontiers. Knowledge begets knowledge and for a country and its firms to produce more and better products, that country must have the capacity to make full use of its existing resources and capabilities and develop new ones. Therefore, bridging the technological divide is an important precondition for closing the economic divide between countries. Periods of rapid technological change create opportunities for those developing or otherwise "latecomer" countries that are seeking to catch up with more advanced countries. However, seizing these opportunities to catch up can occur only with a strong national system of innovation in place to identify key challenges, direct a research agenda, provide funding requirements, and establish intellectual property and patent rights regimes (see chap. IV).

International cooperation can help facilitate access to technologies most needed for sustainable development

The immense scope of frontier technologies and the rapid pace of their diffusion across national boundaries—affecting efficiency, equity and ethical standards—demand global collective action. While national responsibilities will remain paramount, no nation alone can harness the full potential of emerging technologies and mitigate associated risks. More effective international cooperation for managing advances in frontier technologies is essential. Greater international cooperation with regard to their generation, diffusion and adoption—reflecting shared and differentiated responsibilities among all actors—can bring frontier technologies to those who lack the means to access them. This will require (a) revisiting intellectual property rights regimes that govern technology transfers among countries and firms within and across countries and (b) rethinking competition policies and creating incentives for innovation that are potent enough to ensure profitability, while at the same time fostering sustainable development. Further, international cooperation will also be needed to ensure that the advances in frontier technology meet universal ethical and moral standards and that competition in the technology sector is fair. New standards of corporate governance, corporate social responsibility and consumer protection can help ensure that frontier technologies promote equity and social justice.

A more development-oriented intellectual property rights (IPR) regime—one that balances incentives for innovation with the greater need for technology diffusion—will be critically important for sustainable development. Greater international cooperation on taxation as it relates to the digital economy can play a vital role in generating new revenues for those adversely affected by frontier technologies, although this would require a concurrent commitment to ensuring that those revenues are directed towards redressing some of the distributional impacts of frontier technologies (see chap. V).

The role of the United Nations in forging global collective action

The United Nations can facilitate a global dialogue on the risks and opportunities associated with frontier technologies

There is a need for a global dialogue, involving all stakeholders, on how to identify and manage the risks and opportunities associated with frontier technologies. The United Nations can serve as an impartial facilitator, among Governments and private sector and civil society organizations, of an objective assessment of the impact of emerging technologies on sustainable development outcomes, including on employment, wages and income distribution. One issue in this regard is how to define the rights of individuals in the context of the collection and use of their digital data. The new realities reflecting the importance of data for identification and security, and for the design of new products and services (especially in the realm of artificial intelligence) require a reconsideration of how data fit within the existing framework of principles underpinning human rights and responsibilities.

The present *Survey* constitutes one small contribution to the efforts to facilitate international cooperation and global action on frontier technologies, but many other kinds of efforts exist. The fruit of those efforts include the Technology Facilitation Mechanism, established in the 2030 Agenda for Sustainable Development under SDG 17.6, to foster collaboration and partnerships among Member States, civil society, the private sector, the scientific community, United Nations entities and other stakeholders. Other important United Nations initiatives for facilitating understanding and diffusion of relevant technologies and bridging some dimensions of the technology divide include the work of the Commission on Science and Technology for Development and the Technology Bank, first proposed in paragraph 52 ("1. Joint action") of the Programme of Action for the Least Developed Countries for the Decade 2011–2020.[18]

Given its universal membership and unwavering commitment to human values, the United Nations is also uniquely positioned to facilitate a dialogue among all stakeholders on the elaboration of a global ethical compact to guide research and development of frontier technologies, so as to ensure that they conform to universally held ethical standards. Efforts need to be directed towards forging a global consensus on the important ethical challenges. These include setting limits to bioengineering and the use of automated weapons. Indeed, the global community, and the United Nations in particular, have a unique responsibility to address these two issues (see chap. V for a more comprehensive discussion).

18 *Report of the Fourth United Nations Conference on the Least Developed Countries*, Istanbul, Turkey, 9–13 May 2011 (A/CONF.219/7), chap. II

Appendix

Frontier technologies discussed in this *Survey*

The present annex contains concise discussions on a set of technologies that are examined throughout the *Survey*, as well as technologies that are deemed important based on a review of the literature on economic and social issues, including the results of foresight exercises conducted by some Member States, identifying key or emerging technologies for policy attention (OECD, 2016).[a]

Artificial intelligence and machine learning

Since the dawn of research in artificial intelligence (AI) in the 1950s, scientists have worked to create a system capable of intelligent behaviour indistinguishable from that of a human being. Rudimentary AI systems have been used commercially since the mid-1990s to assist in a variety of decision-making tasks, such as fraud detection.

Progress in AI has accelerated rapidly since around 2010, driven by the confluence of the growing availability of large data sets from commerce, social media, science and other sources; continued improvements in computational power; and the development of better machine learning algorithms and techniques (such as "deep learning").[b] Systems are now capable of learning how to accomplish a task without having been provided with explicit steps for doing so. Once designed and deployed, the neural network that underpins modern AI can formulate its own rules for interpreting new data and designing solutions, with minimal—or no—human participation.

AI algorithms have outscored humans in identifying objects and faces in two popular tests (Aron, 2015). On the other hand, their performance is limited to certain categories, and humans can still identify a much larger number of categories and infer context and other aspects of images. The challenge in further developing AI lies in building algorithms that can draw inferences about wider contexts, including what the images convey regarding what may happen next.

It is also important to understand the limitations of this technology. AI has proved to be transformative in many areas, but deployment of the techniques currently in use result in a form of AI that is "narrow" in its applications, allowing algorithms to achieve mastery in only a single domain each time. Some visible examples of mastery include winning at a game

a Of the 10 technologies identified in the study by OECD (2016), 8 are discussed in this *Survey*: the Internet of Things; big data analytics; artificial intelligence; neuro-technologies; additive manufacturing; advanced energy storage technologies; synthetic biology; and the blockchain. The only ones not discussed are nano/microsatellites and nanomaterials. The literature review included the results of foresight exercises conducted by Canada (2013), the European Union (2014), Finland (2014), Germany (2015), the United Kingdom of Great Britain and Northern Ireland (2012) and the Russian Federation (2014), as reported in the OECD study.

b Machine learning involves algorithms whose performance improves through experience in identifying patterns from data and continuously testing and adjusting solutions. This requires large data sets and computational power.

like chess, maximizing accuracy in translating a text or understanding speech, and even the safe manoeuvring of a car. Existing techniques allow for the optimization of defined tasks, but the development of a general-purpose AI—capable of creativity, planning and other inherently human activities—remains a distant possibility. According to one expert (Lee, 2017): "[t]here are simply no known engineering algorithms for [general-purpose AI]". And he doesn't "expect to see them any time soon."[c]

There are also concerns regarding information security, as algorithms and robots insinuate themselves into our newsfeeds and election campaigns; and physical security, as lethal autonomous weapons make their way onto the battlefield and into the skies (see chap. II).

Nevertheless, applications for AI-equipped robots are being found in various fields, including manufacturing. Going forward, and in combination with 3D manufacturing, these applications may have an important impact on the current processes of offshoring and the operations of global value chains.

Renewable energy technologies

Following recent technological breakthroughs, a growing number of current and emerging technologies in the area of renewable energy generation have achieved a sufficient level of technical and economic maturity to render them ready for large-scale deployment.

In terms of maturity level, solar energy technologies ranges from those in the R&D stage (e.g., fuel production from solar energy), to those in the maturing stage (e.g., concentrated solar thermal power) and on to technologies that are technically mature (e.g., solar heating and photovoltaic (PV)). The result intended through achievement of technological progress in solar PV is the development of commercial-scale production technology for PV that has low capital intensity, high conversion efficiency, an exemplary relationship with the environment and long module lifetime. New materials such as organic solar cells and graphene are central to achieving these objectives. At the same time, researchers continue to improve the efficiencies of silicon solar cells through engineering breakthroughs.[d] Improvements in PV technologies and manufacturing processes, along with the change in manufacturing capacity and reduced non-hardware costs, have substantially reduced PV costs and prices (see chap. III for an examination of the use of PVs in developing countries).

Traditional land-based wind technologies are mature. As for the use of wind energy in offshore locations, it is increasing but is typically costlier than land-based wind energy. Turbines currently extract nearly 50 per cent of the energy conveyed by wind, just below the theoretical maximum of nearly 60 per cent.[e] The aim to be achieved through technological progress on materials, mechanical engineering and wind forecasting is to reduce cost and increase the availability of wind power. Individual wind turbines are increasing in size, helping to reduce the cost of wind energy, particularly for offshore wind farms.

Bioenergy technologies are diverse and span a wide range. Examples of mature technologies include conventional biomass-fuelled power plants and heating systems as well as ethanol production from sugar and starch. Technological progress has been made in

c See Artificial Intelligence Index (2017) for a complete discussion on the technical possibilities of ongoing research on AI.

d See www.nrel.gov/pv.

e https://www.worldenergy.org/wp-content/uploads/2017/03/WEResources_Wind_2016.pdf.

the area of conversion systems that use more sustainable fuel sources (advanced biomass). Performance improvements have also been effected in cropping systems, logistics and multiple conversion technologies for bioenergy. Technological advances have been witnessed in the area of geothermal energy as well.

Energy storage technologies

The technology of utility-sized energy storage has been advancing and becoming more economical. The appropriate method of storing energy depends on the resources available to the local power producer. The existing technologies for storing energy include: (a) hydropower and compressed air storage; (b) molten salt thermal storage; (c) the redox flow battery; (4) the conventional rechargeable battery; and (e) thermal storage.[f]

Storage of hydropower, e.g., through pumped storage, represents 99 per cent of the world's operational electricity storage capacity.[g] Pumped hydro-storage plants work through gravity, by pumping water up into a reservoir when electricity is in surplus, "charging" the system. When the electricity is needed, the water is allowed to flow down to another reservoir through a hydroelectric generator. As of 2015, global pumped storage capacity was 144.5 gigawatts (GW). East Asia and Europe accounted for 108 GW.

Compressed air storage works in a similar way, pumping ambient air into a storage container and releasing it through electrical turbines when needed. Special arrangements must be made for such systems to enable them to deal with the heat of the air as it compresses, which adds to the cost.

Heat generated by solar thermal plants, when not used immediately to generate electricity, can be stored in molten salt. This heat storage extends the hours of solar plants into the evening. There is ongoing research on the use of molten metal as a replacement for salt, which would further increase the efficiency of these systems.

Redox flow batteries store energy in the form of electrolytes and release energy as the different electrolyte solutions are made to interact and generate an electrical charge. These batteries require large quantities of electrolyte tanks, which is not a barrier to utility-level installations. They also have a longer service life and are less prone to fires. Increasing their capacity requires only larger storage tanks.

Conventional rechargeable batteries are making their way from personal electronics into vehicles and utility-size applications. Companies are also exploring the viability of pairing wind turbines with batteries to store excess energy. In November 2017, the State of South Australia installed the world's largest battery, with the capacity to power 30,000 homes. The installation, which was carried out in less than 100 days by Tesla, will help the State balance the supply-and-demand problems that have resulted in regular blackouts for its residents and the world's highest electricity prices (Baidawi, 2017).

A less traditional form of energy storage is thermal storage, where excess electricity is used to freeze water. The "ice battery" then provides cooling without the use of traditional air-conditioning systems when demand for electricity is high.

f See https://arstechnica.com/information-technology/2017/10/a-world-tour-of-some-of-the-biggest-energy-storage-schemes/.

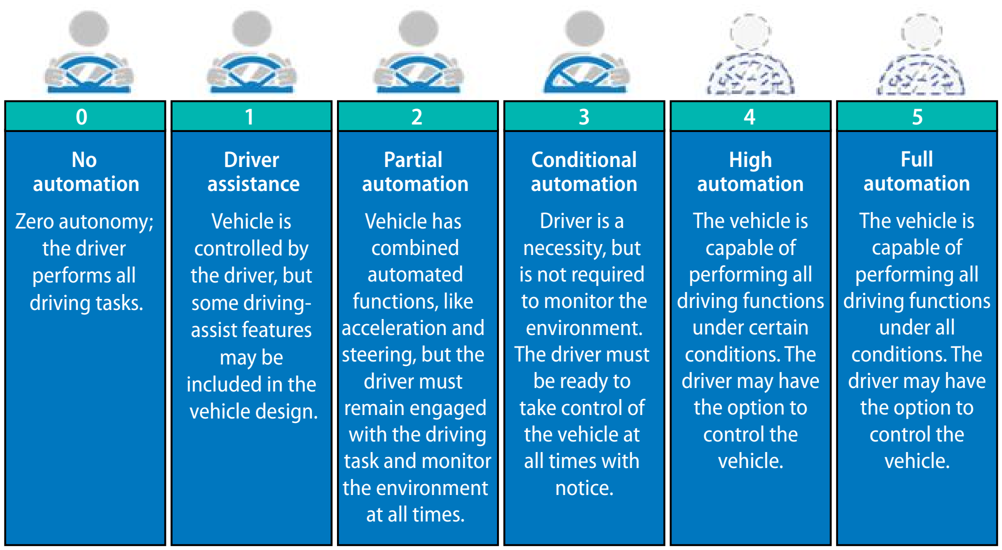
g See https://www.worldenergy.org/wp-content/uploads/2017/03/WEResources_Hydropower_2016.pdf.

Autonomous vehicles and drones

Autonomous vehicles are perhaps the most visible applications of advanced algorithms, sensors and powerful computing power. Five levels of automation exist for vehicles (excluding zero automation), ranging from basic driver assistance (level 1: "hands on") to full automation (level 5: "steering wheel optional") (see figure A.1). The most successful automation system currently available, offered by Tesla in its passenger cars, provides level 2 automation ("hands off"), where the driver can rely on the vehicle to steer and control speed but must be attentive and ready to intervene when required. A significant amount of research is being conducted whose aim is to allow vehicles to operate at level 3 ("eyes off") and higher automation levels. While some automakers are announcing plans to market level 3 automation capabilities in the next two years,[h] level 5 automation is, by some estimations, decades away.[i]

In a recent study on the potential benefits of autonomous vehicles, it was estimated

Figure A.1
Six stages of automation



Source: www.nhtsa.gov/technology-innovation/automated-vehicles-safety

that their use could reduce accident rates by 90 per cent in the United States, potentially saving 30,000 lives and $190 billion in associated health-care costs.[j]

Automation also has applications in the development of unmanned aerial systems (UAS), or drones. These systems are used for surveillance, operations, entertainment and advertising, signal emission, and the movement of people or goods (Cohn and others, 2017). The most mature use of drones involves surveillance (using photographs and video applications without analytics). Drones that can assist with labour-intensive and dangerous

h See https://www.slashgear.com/2019-audi-a8-level-3-autonomy-first-drive-chasing-the-perfect-jam-11499082/.

i See https://spectrum.ieee.org/cars-that-think/transportation/self-driving/google-selfdriving-car-will-be-ready-soon-for-some-in-decades-for-others.

j See https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/ten-ways-autonomous-driving-could-redefine-the-automotive-world.

tasks and those that can be leveraged for entertainment (e.g., advertising and light shows) are beginning to enter into commercial use. Drones are also planned to provide radio, video and Internet connectivity in remote areas. Transporting objects is another logical future use of this technology. In October 2016, a company called Zipline began using drones to deliver medical supplies (medicines and blood) to health clinics in remote locations of Rwanda. In 2017, the Government of the United Republic of Tanzania announced its partnership with Zipline to "provide emergency on-demand access to critical and life-saving medicines" in the country.[k]

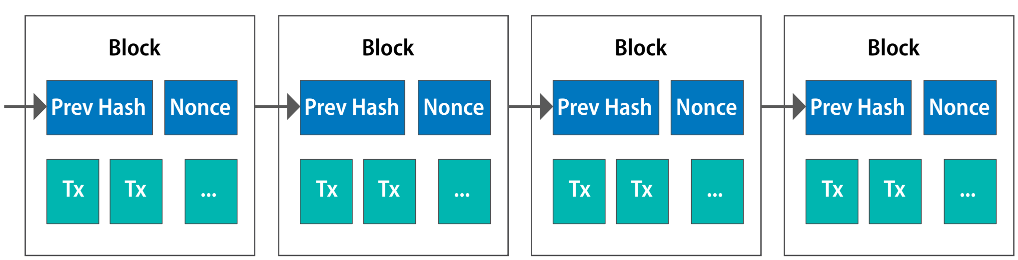
Cryptocurrencies and blockchain technology

In any monetary transaction, it is required that the buyer of a product have sufficient funds and that the funds be used only once (i.e., there is no "double spending"). Electronic transactions require special attention, since it is easy to copy and alter digital information. The traditional financial system verifies the ownership of funds and checks for any double spending by means of ledgers, or records of the balance in every account and in every bank. The transaction then modifies the appropriate ledgers to reflect the withdrawal and deposit of funds. The functioning of this system requires trust in formal institutions and regulatory systems.

In 2009, a person or persons going by the name of Satoshi Nakamoto proposed a public distributed ledger system which would rely on cryptography and self-interest to enable electronic transactions. This notable innovation, in the form of a system underpinned by incentives and mathematical proofs, would obviate the need for trust in any one actor or central institution as the basis for preventing fraud and ensuring that the ledgers were kept up to date. Within such a system, every participant therefore works to build a single public ledger of transactions and constantly verifies its validity. That ledger is known as the blockchain.

The blockchain works through a competitive process whereby the first to successfully validate a block of transactions and broadcast the solution to the network wins a monetary reward. The proposed block is quickly and independently verified by every participant. If a majority of the network agrees that the block is valid, the block and the transactions it contains become part of the consensus blockchain (see figure A.2).

Figure A.2
Anatomy of a blockchain



Source: Nakamoto (2008).
Note: A block represents data which include descriptive information such as unique identifiers (hash) and counters (nonce) as well as transactions that have been validated (Tx). The connection between blocks (the chain) is the unique identifier of the previous block. Any change in the previous data will change all subsequent identifiers.

k See http://www.flyzipline.com/uploads/Tanzania%20Announcement%20Press%20Release%20vFinal.pdf.

The innovativeness of this system lies in the way in which the various parts combine to create the trust and guarantees that the traditional financial system derives from institutions and regulation. The incentives align the interest of participants towards contributing to the system's security. In contrast, the traditional system relies on a complex armature of reporting, oversight and implicit or explicit guarantees, ultimately backed by the reputation of the central authority. As such, the blockchain technology presents the possibility—a first in the field of finance!—that trust in institutions backed by government can be replaced by trust in computer code.