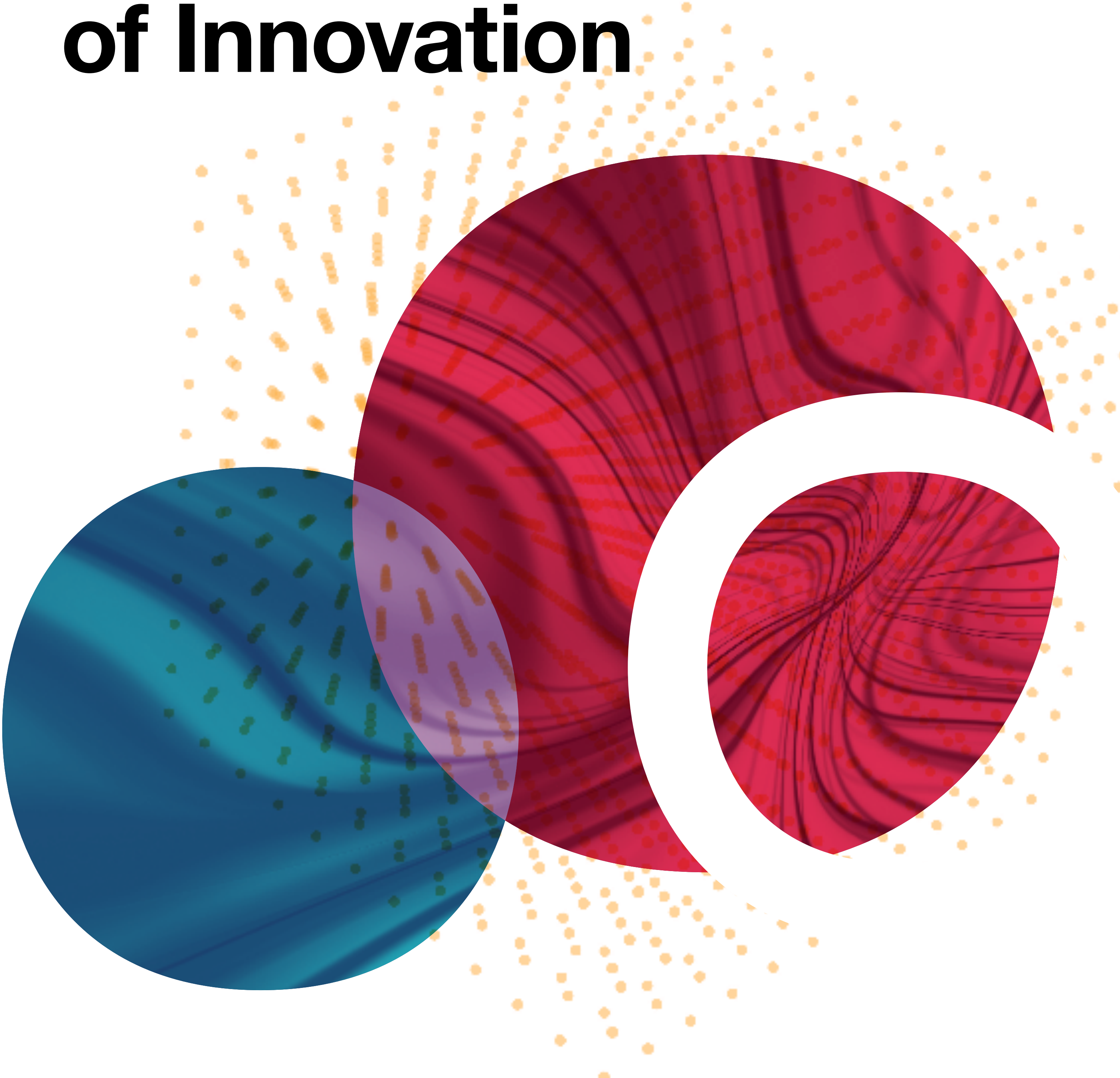
World Intellectual Property Report 2022

The Direction of Innovation



WIPO

World Intellectual Property
Report 2022

The Direction of Innovation

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For more than a century innovation activity has grown substantially around the world. Driven by a series of technological breakthroughs from the internal combustion engine, to information and communication technologies, innovation has become one of the most powerful tools at our disposal for advancing overall welfare and wellbeing.

Photo: WIPO / © Berrod

Today, we are at the start of a promising new chapter in global innovation. Digital technologies such as artificial intelligence, big data, cloud computing and the Internet of Things are booming. These rapidly emerging technologies have the potential to transform large swathes of the global economy, spark new growth opportunities for startups and businesses and empower people and communities in all regions of the world.

But while the positive impact of new ideas, products and services is well understood, the broader decision-making environment behind innovation is subject to far less analysis.

To a large extent, this is a reflection of the wide variety of factors at play. Decisions on innovation are often complex and involve a cross-section of different stakeholders and interests. For instance, while new scientific and technological opportunities are endless, resources – both human and financial – are not. Likewise, new technologies need to be weighed up against each other, and existing models, before investment decisions are made. And then there are the variables that cannot be anticipated, the shocks, emergencies and other events that can alter society's demand for innovation in a blink of an eye.

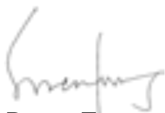
This process is the theme of the *World Intellectual Property Report 2022*. Our aim is to shine a light on how the decisions of various actors within innovation ecosystems, including policymakers, researchers, enterprises, entrepreneurs and consumers, come together to shape the future trajectory not only of innovation, but of economies and societies around the world.

The report begins with a discussion of the main factors that govern the direction of innovation, including the relationship between social and private returns. While public and private motivations are not always aligned, the report shows that they can be leveraged effectively for the common good.

In keeping with previous editions of this report, we supplement this conceptual discussion with a series of historical case studies. Through the prisms of medical innovation during the Second World War, the evolution of the space race, and the rise of information technology industries in East Asia, we detail the variety of factors and stakeholders that influence the direction of innovation and offer insights relevant to both highly-industrialized and emerging economies.

The report concludes by discussing how innovation can help address the global challenges of today and tomorrow. While the long-term trajectory of innovation remains uncertain, we know that new digital technologies and solutions have a key role to play in building a greener, fairer, healthier and more resilient world. But how can we steer the direction of innovation towards productive outcomes that benefit economies, communities and our planet? What policy levers can be pulled to align private innovation incentives with societal needs? And what can be done to better support developing and the least developed countries to pursue innovation opportunities?

As the world looks to rebuild from the pandemic, innovation has a crucial role to play in opening up new growth possibilities and creating much needed solutions to the common challenges that we face. Decisions on innovation may be complex, but, as this report highlights, it is vital that they are understood.



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Chapter 1: Carsten Fink provided inputs on the social estimates of COVID-19 vaccines, and Xiaolan Fu (University of Oxford) and Liu Shi (University of Oxford) on the perspectives of developing countries.

Chapter 2: Henry Hertzfeld (George Washington University), Benjamin Staats (George Washington University) and George Leaua (George Washington University) provided background research on space; Bhaven Sampat (Columbia University) on antibiotics; and Keun Lee (Seoul National University) on information technology in East Asia.

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What economists define as the "direction of innovation" – the theme of this report – is the combination or sum of all the decisions individuals, firms, universities and governments make on which technological opportunities to pursue at any one time.

It is not only a question of how much economies invest in new ideas. The allocation of human and financial resources to different innovation activities can set the direction of innovation of communities, countries and even the world for decades to come.

The short-term direction of innovation and its implications are relatively easy to anticipate and coordinate. For example, to face the COVID-19 pandemic, governments and companies successfully redirected innovation investment towards the discovery, approval and mass-production of vaccines, achieving the objective in record time. Vaccines drastically reduced the number of deaths and helped the global economy to recover from the pandemic-provoked slump of 2020.

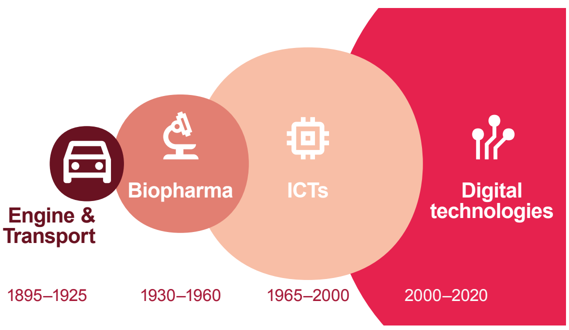
The long-term impact of the direction of innovation – in terms of both the returns or profits to companies and the benefits, or lack of them, to society – is less predictable. For example, it is difficult to predict which of the technological innovations limiting climate change will prove most effective.

Innovation has increased exponentially over the past 100 years, with very different technological catalysts

Over the last century, innovation decisions have cumulated in shifting technological trajectories. Technologies related to combustion engines, transport and other mechanical machines dominated the innovation landscape in the early decades of the past century. Biopharma technologies boomed thanks to pharmaceuticals in the 1930s and to biotechnologies since the 1990s. And in the final decades of the 20th century, there was a big shift towards information and communication technologies (ICTs) and semiconductors, which accounted for a quarter of all patents in the 30 years between 1990 and 2010. This increase in ICT patent share was mostly at the expense of "traditional," mechanical machine technologies.

Diverse technologies have driven innovation growth over the past 100 years

Figure 1 Top growing technological fields in patent filings, 1895-2020



Today, the direction of innovation is at a crossroads where promising new technologies are booming

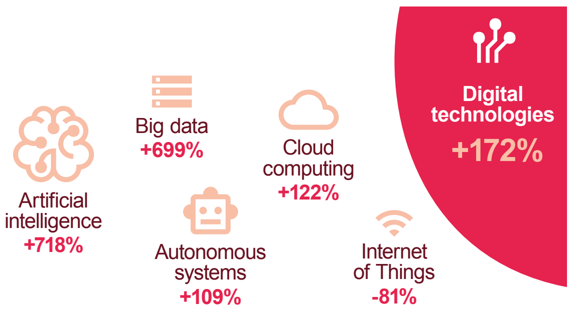
As we enter the third decade of the 21st century, new and powerful forces are driving the direction of innovation in fields such as science, technology and medicine.

Digitalization is changing the world. A wave of digitalized general-purpose technologies includes artificial intelligence (AI), predictive technologies, highly sophisticated automation and big data. Digital general-purpose technologies are transforming industries by bringing in new innovators, structures, practices and values. These technologies give rise to new industries, such as the Internet of Things.

Digitalization has the potential to spur economic growth, but risks exacerbating inequalities. AI, automation and other digital general-purpose technologies can spur economic growth when they generate innovation that complements and enhances human productivity. But they risk worsening economic inequality when innovation simply replaces people. They will make certain occupations obsolete and give rise to new ones that require different sets of skills. While they may create leapfrogging opportunities for some less-developed economies, others may miss out due to a lack of large capital investments and the high-skilled labor force necessary for these technologies to thrive.

Digital-related innovation has grown 172% faster than all patents in the past five years

Figure 2 Growth of technologies as percent of total patents average growth, 2016-2020



The COVID-19 vaccine success is an innovation model to build on. The COVID-19 pandemic generated and, in part, accelerated demand for new technologies to combat it. The COVID-19 crisis prompted responses to find solutions urgently from all actors in the innovation ecosystem – governments, the private sector, research institutions and universities, international communities, non-governmental organizations (NGOs), including philanthropic foundations.

The scale of the pandemic and the fact that it affected a large share of the global population created an important incentive for the private sector. In addition, several governments gave significant financial support to the private sector, including for clinical trials and for vaccine developers with promising vaccine candidates to build large-scale manufacturing capacity.

Moreover, the special emergency authorization and coordination efforts provided by relevant national and international government agencies allowed for a faster deployment of the vaccines worldwide.

The successful public–private collaboration in quickly identifying and developing COVID-19 vaccine candidates shows how policies can be useful in redirecting innovation efforts toward a common goal.

COVID-19 vaccine development has had an impact on medical research and practice. The success of the mRNA vaccine platform for COVID-19 has provided strong evidence that the technology works well and could have applications for other diseases. This could also signal the beginning a new golden era for vaccine development, similar to the one during the Second World War.

The COVID-19 crisis has also changed medical practice by accelerating the adoption of digital technologies. Many changes were already underway, but the pandemic highlighted the urgency to "go digital" and created opportunities to introduce operational improvements, such as virtual medical consultations.

But the fast deployment of COVID-19 vaccines and the wide adoption of underlying biotechnology tools are not without challenges in the short term. Creating and rolling out the vaccines using the new technology required a highly skilled labor force and well-equipped research labs. Moreover, the speed of COVID-19 vaccine development and medical trials came at the expense of delaying the approval of other medicines in the pipeline. In addition, the focus on vaccines and treatments to fight COVID-19 pandemic may hurt other lines of medical research for a number of years.

Societies' demands for innovation can change in the blink of an eye, especially when confronted by crises

Sometimes, large and unexpected systemic changes – such as new breakthrough technologies, epidemiological crises or wars – shake the preferences and priorities of the ecosystems' stakeholders. Governments and policymakers are usually called on to act in the face of priority-changing shocks.

For instance, as a direct result of the Second World War, the U.S. Government mobilized civilian science to address wartime needs by creating and funding public research organizations, for example, the U.S. National Institute of Health (NIH). More than seven decades later, many of the medical innovations developed during that period are now part of standard hospital practice.

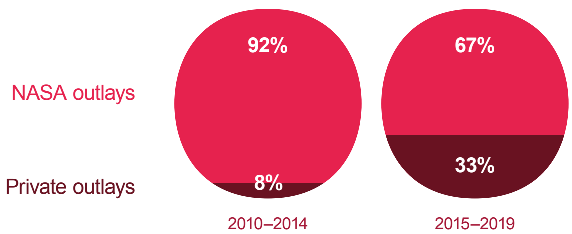
The Second World War created the demand for new technological solutions to problems such as treating wounded soldiers and reducing mortality rates. During the war, the U.S. Government allocated a large sum of money to its research and development (R&D) budget, almost 100 times what it had been investing in science in prior years. This concerted surge in public effort aided and supported the mass production of penicillin, the development of blood substitutes and the creation and production of vaccines, along with research on hormones and numerous other medical breakthroughs. This opened avenues for further research and medical improvements that reached far into the future. Penicillin research efforts were the precursor of antibiotics' development by pharmaceutical companies during the post-war decades.

Similarly, the Cold War led to an expansion in U.S. federally funded R&D into new domains, such as its mission to the Moon. In 1957, the Soviet Union became the first country to launch a satellite into low-Earth orbit. The U.S. responded in 1961 with a program to put a man on the Moon within a decade. Great political commitment, a large budget and scientific and engineering technical ability saw the goal achieved in October 1969.

By the end of the 20th century, U.S. "mission-oriented" R&D funding into space programs had led to the development of telecommunications satellite technologies and eventually fueled commercial involvement in space activities. Advanced industrial economies have become increasingly dependent on space systems for their information technology, remote sensing imagery, PNT (position, navigation and timing) data and other applications. A new space race between the U.S. and China may trigger innovative – and unpredictable – technologies in the decades to come.

Space innovation: government funding paved the way for new technologies and industries

Figure 3 Space funding by NASA and U.S. private investors, 2010–2019



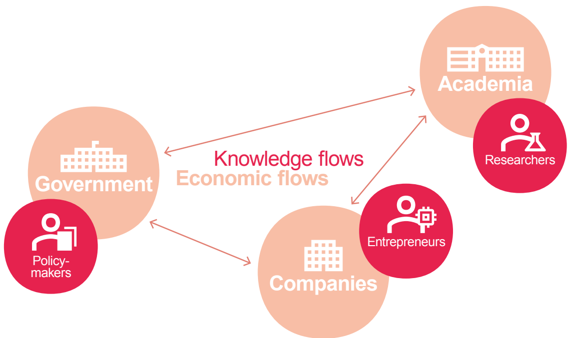
The direction of innovation is not decided single-handedly; it is the result of the dynamic interaction of multiple decisions by entrepreneurs, researchers, consumers and policy makers

The direction of innovation is constantly changing. It is influenced by the choices and interactions of public and private stakeholders looking to benefit from innovation. It is this innovation ecosystem that sets the direction of innovation. Curiosity guides researchers to explore new scientific fields and engineers to experiment with new technologies. Companies, entrepreneurs and governments alike identify innovation opportunities based on predictions of potential private and social returns.

Private stakeholders seize innovation opportunities more quickly when the expected returns are both foreseeable and easy to capture in monetary terms. They are also drawn to short-term innovation projects where the risks of failure are lower. But longer-term, riskier opportunities frequently hold the greatest potential for positive social returns.

Innovation ecosystems set the direction of innovation for decades to come

Figure 4 Conceptual summary of interactions between innovation ecosystem stakeholders



Governments must promote both the social and private returns of innovation. They often do this by centralizing activities and resources for innovations which affect the public good – goods or services freely available to all, such as national defense or pandemic prevention. They can also be the main source of demand for innovative technologies. Governments will design policies to influence the provision of public goods related to health, security or education.

Much of the direction of innovation is set by the knowledge gained by industries through their operating experience or their supply chains. Knowledge and innovation flows across fields and industries provide scientists, engineers and entrepreneurs with strong incentives to move to new fields and industries, applying the technologies they already master, rearranging the allocation of resources and ultimately affecting the direction of innovation.

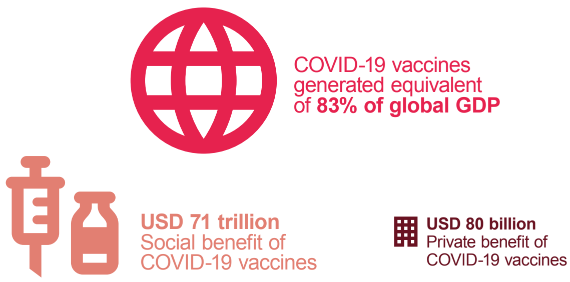
Public and private motivations to innovate are not necessarily aligned, but they can be leveraged for the common good

Social and private returns of technologies steer innovation. Innovations can have a transformative effect – for better or for worse – on the environment, public health, local communities, or on specific demographics, to name just a few examples. These are the social returns of innovation. If a technology is environmentally friendly, it will bring socioeconomic benefits to the wider community; conversely, a cheaper but more polluting new technology may have a negative socioeconomic impact.

The social returns of innovation can differ substantially from the private returns reaped by commercially-driven innovators, as manifested by the development of COVID-19 vaccines. Our research estimates that the social benefit of vaccine innovation amounts to USD 70.5 trillion globally, exceeding its private benefit by a factor of 887. This large social benefit reflects the value of saved lives, avoided health impairments and the lifting of lockdown measures, which far outweighs the revenues generated by vaccine manufacturers.

Public–private innovation is vital to leverage the common good

Figure 5 Estimates of social and private benefits of COVID-19 vaccine development



Innovation needs differ around the world

The ability of developing economies to either generate new technological solutions or absorb existing solutions in order to address their specific socioeconomic needs depends on their local innovation ecosystems and how connected they are to global innovation networks.

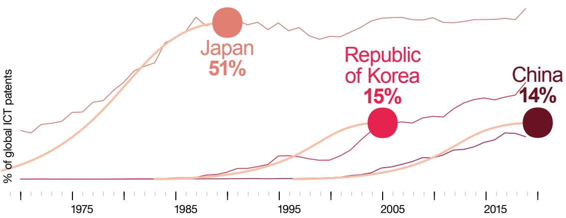
In some cases, usually those economies in the middle-income bracket, innovation ecosystems may unblock unprecedented innovative ability by leveraging scientific capacity, technological capital and skilled labor to narrow the technological gap between them and the most advanced economies.

In the case of the IT industry in East Asia, for example, Japan, the Republic of Korea and China managed to fully integrate into the global economy as core and active participants in international value chains. Their respective industrial policies facilitated their jump into cutting edge IT in just a few decades. The 1980s saw the East Asians enter the markets for PCs (personal computers), VCRs (videocassette recorders), audio cassette players and telecom equipment. In the 1990s came memory chips and wireless cell phones, and the 2000s brought various digital products, including digital TVs, wireless telecommunication systems and smart phones.

The development of all East Asian economies has common elements. These include economic catch-up, the fast technological progress of private firms and industries, and government policies to reduce the risks involved for firms in entering new industries.

New technological opportunities can spur economic development

Figure 6 Share of global ICT patent technologies, selected East Asian economies, 1950-2020



In other cases, market and non-market participants may have insufficient local innovative capacity either to identify, assimilate and learn from new technologies developed elsewhere, or else generate the innovations themselves. Low purchasing power may make it difficult to access global innovation to serve their needs. Basic infrastructure, such as roads, electricity or medical care, and important institutions, such as an effective financial sector, may be poor or non-existent, rendering some foreign technologies less suitable. Innovation may then need to be low-skilled, generally small in scale and targeted at specific communities or regions.

In all cases, the needs of the country come first, as innovation happens differently in different parts of the world. Innovation imported from abroad has to be usable in the importing country. Leapfrogging can only happen when this is taken into account. More importantly, innovation does not have to be cutting-edge to be socially valuable.

Technologies to address major challenges, such as climate change, are greatly needed

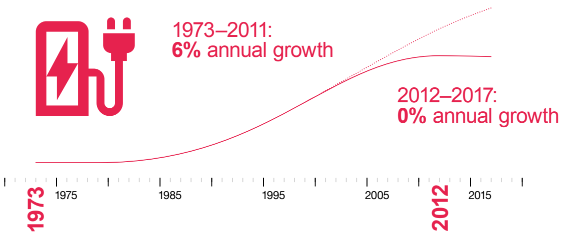
The future direction of innovation will depend on international and multilateral policies to address "grand challenges," such as access to education and health and climate-change mitigation.

The successful public–private collaboration in quickly identifying COVID-19 vaccine candidates shows how mission-oriented policies can be useful in generating important changes. Similar to the wartime efforts during the 1940s, these collaborations relied on existing science and technologies, proving that they work and ensuring the swift and large-scale production and deployment of vaccines.

Can "mission-oriented" policies be used to address the major and complex social, environmental and economic challenges that face the world? Policies based on centralized decision-making and the concentration of resources on one specific goal were very useful in the case of NASA's space program to reach the Moon and of COVID-19 vaccine development. But even mission-oriented policies may not be enough. Some observers see government policies as just one element of any solution, which will also require the efforts of all stakeholders of the innovation ecosystem, including consumers.

Clean technologies boomed after oil price shock, but it might not be enough...

Figure 7 Growth of global environmental related technologies, 1973-2017



Deepening commitments to sustainability at public, private and even consumer levels is changing how businesses conduct activities such as shifting to renewable energy or adopting climate-change mitigation technologies to reduce their carbon footprint. By using subsidies, regulations and standards to promote environmental technologies, governments are helping mitigate some of the risks and uncertainties associated with investing in new, relatively untested alternative energy technologies.

Innovation in low-carbon emission technologies, especially in the energy sector, has grown in the first two decades of the 21st century and seen with a sharp increase in related patenting. This is also the case of enabling technologies, such as batteries, hydrogen and smart grids.

However, technologies that are at the early stages of development – basic or applied research stages – tend to be riskier and so require public funding to mitigate these risks. Carbon-removal technologies, for example, are expensive to build and maintain.

In addition, perception of the risks associated with global warming changes gradually. The incentive for private stakeholders to invest in developing clean technologies relies on such predicted demand.

Can policy help in shaping the direction of innovation?

Public policy can shape the direction of innovation in several ways:

Scientific and technological discovery-stimulating policies are most needed when innovation uncertainty and risk are greatest. For instance, governments use direct purchases regularly to assist the development of defense and aerospace technologies.

Risk-mitigating policies are likely to be most effective in the early phases of development after an initial discovery. R&D subsidies, soft loans and R&D tax incentives are typical risk-mitigating policy instruments.

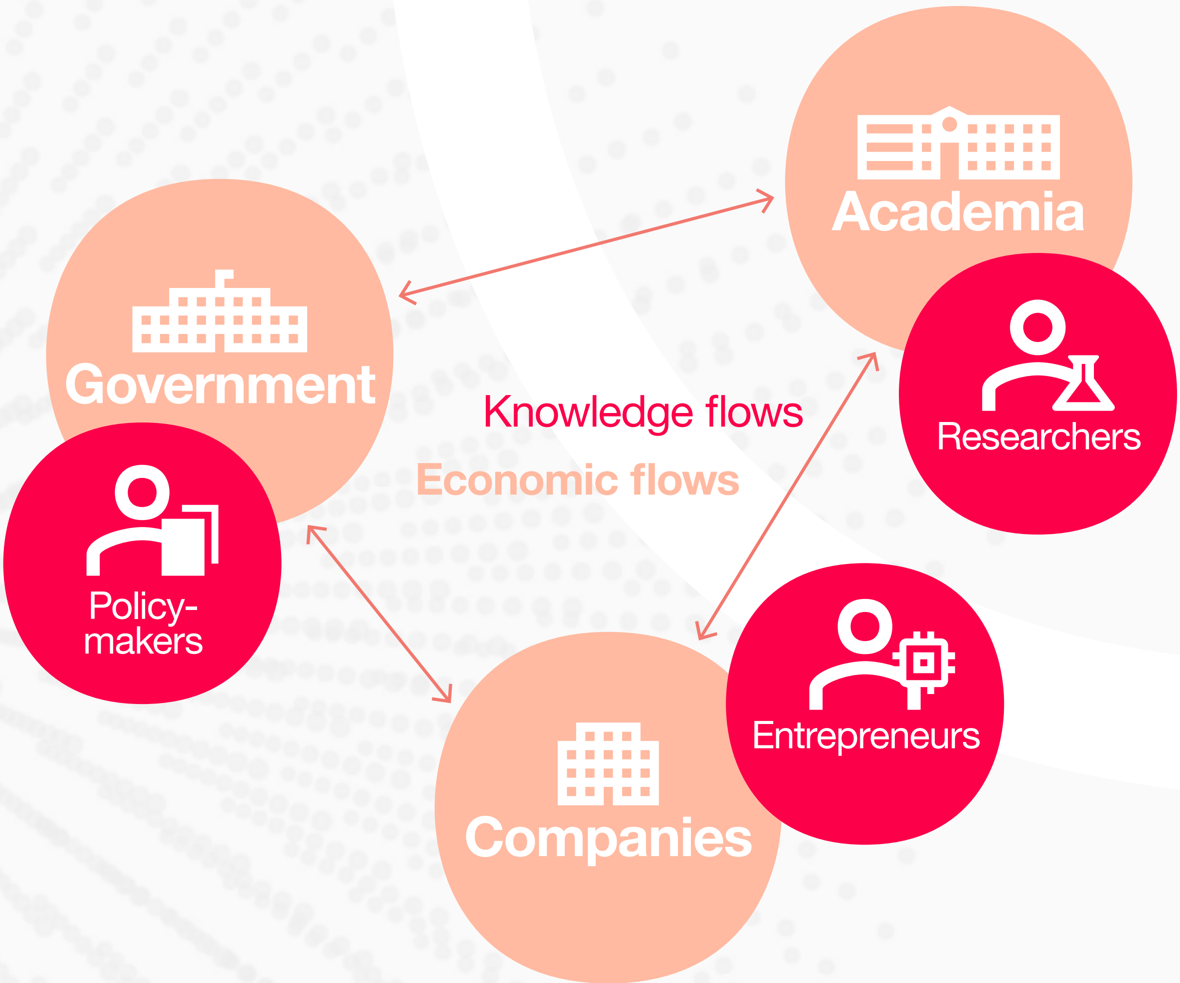
Early-adoption policies aim not only at reducing innovation risk but also at increasing the number of companies using a given technology. Governments can step in to boost production of a given technology and by so doing ensure sufficient scale is achieved for it to be profitable.

Governments can also reduce risk or incentivize adoption indirectly by inducing consumption of goods and services containing a desired innovation. They can provide subsidies to producers to keep prices down or to consumers to encourage them to buy. They can influence adoption through publicly-funded education programs to cut the cost and increase the availability of skilled labor and to promote entrepreneurship in selected fields.

Regulation of digital technologies – including how access to data is governed – plays an important role in sustaining a competitive marketplace that promotes and rewards innovation. As digital technologies evolve at a fast pace, many governments around the world are currently considering adapting their regulatory toolbox.

The world's grand challenges – addressing climate change, reducing inequality, ensuring food security, preventing pandemics – are public goods, and the private sector on its own is unlikely to allocate enough innovation resources to resolve them. Nor can climate change be addressed by private and public-sector efforts within individual economies. It is only through a multi-stakeholder, internationally coordinated effort that we will be able to solve these global challenges.

Innovation ecosystems set the direction of innovation



What is the direction of innovation?

Since Scottish engineer James Watt (1736–1819) built the first workable steam engine over 250 years ago, thereby effectively launching the First Industrial Revolution, rapid technological advances have driven ever more widespread economic growth, benefitting countries and economic stakeholders around the globe. Today, the world is at the outset of a new industrial revolution – the Fourth – based on digital technologies, such as robotics, artificial intelligence and big data.

How much and how fast countries, industries and companies invest in transforming research and development (R&D) resources, both human and financial, into new technologies will in large part determine future economic growth, standards of living and overall global welfare.

However, not all decisions on innovation – understood as commercialized new products and processes – are simple to make. At any given moment, existing technologies compete with promising new ones in terms of potential returns. The steam engine, electricity and the Internet all had viable alternatives that could have replaced them or blocked their development. In the 1800s, the "Stirling" heat engine was considered a serious rival technology to the steam engine, but not so well suited to the available raw materials and the industrial needs of the time. At the turn of the 20th century, urban lighting was mostly powered by gas. Only once electricity became generally available in the years that followed did cities start replacing gas streetlights with safer, cheaper and brighter electric lighting. In the 1980s, over a decade before email and the Internet boom, an interactive online content service known as *Minitel* was already being widely used in France to communicate or buy goods via a screen, keyboard and modem linked to the telephone network. Ironically, such was the commitment to what was then groundbreaking technology, but which ultimately proved a dead end, that it slowed the Internet's adoption in France compared to neighboring economies which had developed no similar innovative system.

Deciding which technological path to follow is not, then, a simple task. Whereas technological opportunities may be in abundance at any point in time, the economic resources to invest in innovation are not. The number of talented people – engineers, scientists or entrepreneurs – and financial resources that can be assigned to innovation activities is limited. To obtain the best returns to R&D investments, private companies and entrepreneurs always weigh the technological prospects and consumer preferences of one or other technology before making innovation decisions. For instance, petrol and electric-powered automobiles coexisted at the start of the 20th century; however, little in the way of electrical grid infrastructure existed outside of urban areas, while the infrastructure to support petrol-powered cars was less costly to develop. As a result, consumers preferred the autonomy that petrol cars provided.

The more successful an innovation decision is, the more revolutionary – or "disruptive" – it may be: mobile phones, for instance, have transformed the telephony market. New companies and industries are created to produce the successful innovations, replacing producers of the less successful ones. Governments and policymakers face the challenge of trying to pick winners when deciding how best to use taxpayers' money and designing policies to support innovation.

What economists call the "direction of innovation" – the theme of this latest *World Intellectual Property Report* – is the combination, or sum, of all the decisions individuals, firms, universities and governments make on which technological opportunities to pursue. The short-term economic implications of the direction of innovation are relatively easy to anticipate and coordinate. To confront the COVID-19 pandemic, governments and companies successfully redirected innovation investment toward the discovery, approval and mass-production of vaccines (see Chapter 3), achieving the objective in record time. Vaccines dramatically cut the number of deaths from the disease and helped the global economy bounce back from the pandemic-provoked slump of 2020, with the private companies involved in vaccine production earning significant revenues.

What economists call the “direction of innovation” is the combination, or sum, of all the decisions individuals, firms, universities and governments make on which technological opportunities to pursue

In contrast, the *long-term* economic returns to the direction of innovation are much less predictable and harder to coordinate. It is difficult, for example, to foresee what the effects of COVID-19 will be further into the future. Similarly, current efforts to produce “clean” technologies to curb CO_2 emission, the most common greenhouse gas, have so far yielded uncertain results. It is unclear whether the resources devoted are sufficient or whether the technological paths explored are complementary enough to successfully address the crisis of global warming (see Chapter 3). Technological choices can open up unpredicted commercial opportunities, sometimes far into the future. As illustrated in Chapter 2, solar panels were initially deployed as part of the U.S. space program in the late 1950s, but it took many years for their commercial use to take off.

Moreover, there is the question of not only how much to invest, but also how to allocate this investment among the different technological options. The allocation of human and financial resources to given innovation activities can set the direction of innovation of communities, countries and even the world for decades to come.

What is the role of government policy in setting the direction of innovation? In many ways, national governments already attempt to direct innovation through the funding of higher education and research-related activities. Most economies have academic institutions, such as universities and other higher education establishments, which run publicly-funded training and research programs. These are part of long-term policies attempting to address the uncertainties and wide horizons of basic science. Governments also fund mission-oriented science and technology programs, such as the U.S. National Aeronautics and Space Administration (NASA) or the European Space Agency, which frequently commission technological developments from the private sector.

Government policies and the innovation decisions made by private companies coexist in a complex innovation ecosystem that includes individuals – such as scientists – government agencies and multinational companies, among others. Government and private companies can complement each other or otherwise compete for the limited resources devoted to innovation. In either case, they are continuously influencing one another. It was government demand, for instance, that created the U.S. space program, NASA and the U.S. aerospace industry (see Chapter 2). Understanding innovation ecosystems is crucial for the design of innovation policies that efficiently allocate resources to induce and direct innovation toward the concrete needs of the world.

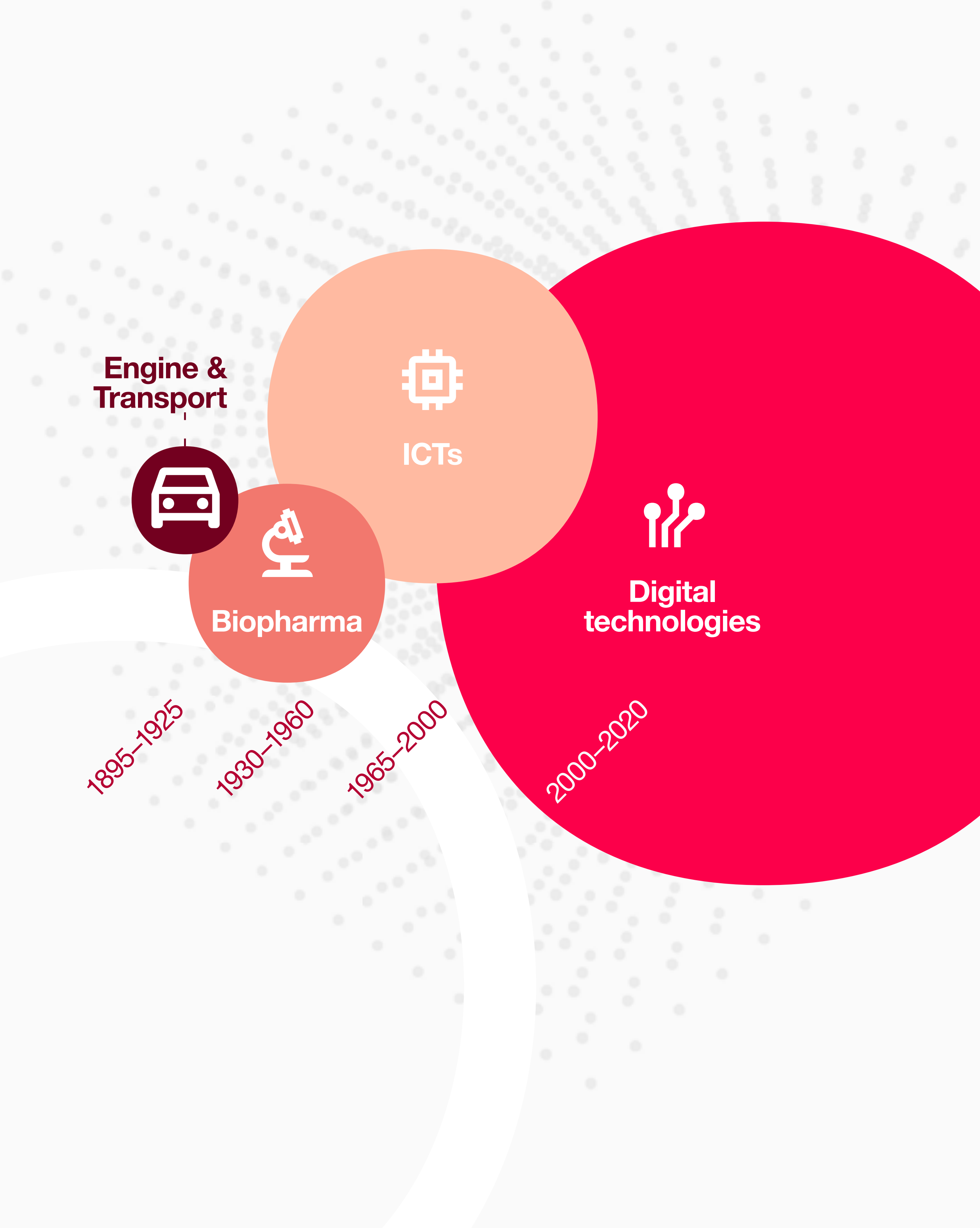
Past scientific discoveries contribute to tomorrow’s new innovative products. The basic research done over the years, and the advances achieved in biology and genetics made it possible to develop COVID-19 vaccines so quickly (see Chapter 3). Government and private consumer choices inform engineers and entrepreneurs on what new products to develop.

Today there are several technologies on the verge of producing great transformations: renewable energies, gene editing and nanotechnologies, for example. A new industrial revolution based on digital technologies is already bringing profound changes to the global economy, reshaping international and local value (supply) chains and recasting the role of labor in service industries. Some industries will shine, others grow dim.

These new digital technologies can help meet the world’s “grand challenges,” such as global warming and future pandemics (see Chapter 3). But how can policymakers ensure that the necessary innovation continues to take place? How can they encourage innovation in social welfare-enhancing fields such as sustainable and socially responsible technologies?

This report attempts to provide a discussion on these crucial topics. Chapter 1 explores the main conceptual elements governing the direction of innovation, presenting the economic forces at work and setting the direction of innovation in the context of innovation ecosystems. Chapter 2 examines these concepts in the light of three historical case studies: innovation during the Second World War, the formation of a space industry and the rise of Asia's information and technology industry. Chapter 3 looks forward to what innovation can do to meet three specific grand challenges – creating clean technologies to contain global warming; applying the lessons learned from the COVID-19 crisis; and successfully riding the wave of disruptive new digital technologies.

Technologies
driving innovation growth



Chapter 1

Setting a course for the direction of innovation

What is meant by the direction of innovation? It is the sum at any one time of the decisions made by all individuals, firms, universities and governments – in whatever field of activity – about what lines of innovation to pursue. Although the technological and scientific opportunities to innovate may abound, the resources – both financial and human – to invest in innovation are limited. Some decisions on where to pursue innovation end in spectacular success, as has recently been the case with the new messenger Ribonucleic acid (mRNA) vaccines developed to combat the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) virus discussed below and in Chapter 3. Others lead to a dead end.

Decisions on innovation taken by individuals and firms are likely to be driven by the prospect of financial profit. But they can also have a socioeconomic impact, whether positive or negative, that is felt beyond the immediate business context. Decisions may therefore align or juxtapose social and private expectations for the direction of innovation. Section 1.1 explores such expectations by looking at the concepts of private and social returns to innovation. The complex ecosystem of companies, universities and government interactions are the subject of Section 1.2. Section 1.3 explores the economic forces that shape the direction of innovation. Section 1.4 sets out the main policy instruments available to induce innovation and explores how they can shape the direction of innovation. Section 1.5 discusses how innovation can be brought about in less developed countries. Section 1.6 concludes the chapter with some general remarks on the future direction of innovation.

1.1 Social and private returns

Private companies and entrepreneurs constantly make decisions about the innovation they hope will benefit their business. They decide whether it is financially worthwhile incorporating new technologies into production processes or developing new technologies or products. They also decide what kind of technological opportunities to follow. For instance, companies developing coronavirus disease (COVID) vaccines opted between traditional vaccine technologies, where a weakened or inactivated disease germ is used to create a defense, or a new mRNA technology. (The latter delivers a tiny piece of genetic code from the SARS-CoV-2 virus in order to stimulate the production of antibodies as an immune response.)

The private returns – essentially profits – on these decisions are the difference between the income that companies and entrepreneurs make from successfully commercializing innovations set against all the costs – including any failed earlier attempts – of development. Governments can alleviate some of the costs through tax policies, subsidies and loans. They can also assure an income for private innovation by guaranteeing prices. Such innovation policies are discussed further in Section 1.4.

Social returns cover the impact of innovations on society at large, including on the wider economy and the environment, and not just the effect on corporate bottom lines. The concept incorporates all innovation benefits or profits accruing to private companies, together with scientific and technological innovations created in universities and public research organizations. The latter feed into private sector innovation, including through university-launched start-ups and spin-off firms.

Innovations can have a transformative socioeconomic effect – for the better or the worse – on, for example, the environment, public health, local communities, or on specific demographics. In many cases, such an effect – an aspect of social returns – would not have been taken into consideration by the private sector when pursuing a given line of innovation. Economists categorize such transformative innovations as "externalities," because they are often unintended by the stakeholders generating them.

For instance, when a firm develops a cheaper and more productive new technology, all things being equal, it should benefit from positive private returns in the form of more profit, because it has gained a competitive edge. But, if the technology should turn out to be more environmentally friendly, it will also benefit the wider community socioeconomically. The more rapidly this cleaner technology diffuses to other companies and markets, the higher the social returns will be. Conversely, a private firm that develops a cheaper and more productive – but more polluting – new technology may also make higher profits, but the socioeconomic impact will be negative.

Private stakeholders will seize innovation opportunities most quickly when the expected returns are both foreseeable and easy to capture in monetary terms. They are likely to be drawn to innovation projects where risk of failure is lower, development times shorter and the scale smaller (the smaller the size, the smaller the risk tends to be). Innovation opportunities that depart from these parameters are likely to be less straightforward to monetize.[1]

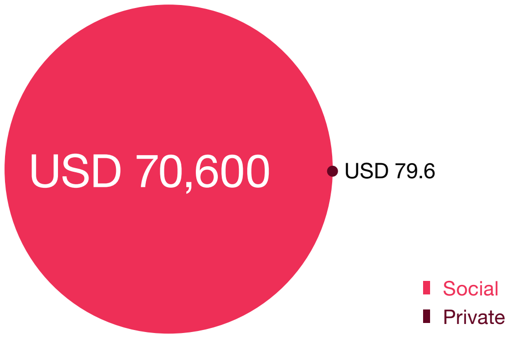
That said, innovation opportunities that are riskier, longer term and larger in scale frequently hold the greatest potential for positive social returns. For instance, some breakthrough technologies – such as the steam engine, electricity or the Internet – are later adopted widely, generating follow-on innovations across many different industries. These are what is known as "general purpose" technologies and further discussed in Section 1.3. Such a diffusion often does not happen immediately, and early investments can seem uncertain and even quite hazardous for a time.

Many innovation opportunities arise when it comes to addressing the biggest challenges confronting a society. Challenges such as global warming, pandemics or crime generate pressure to provide clean technologies, vaccines or better means of providing security. Innovation can promote the sharing or diffusion of knowledge and the accumulation of human capital. Governments may want companies to share their innovation with other firms for the greater good of the economy, including achieving a better trained and skillful workforce, even if this limits potential private returns to innovation.

Promoting both social and private returns to innovation is a difficult mission for governments. They often choose to do this by centralizing activities and resources on innovations that affect the public good, that is, goods or services made freely available to all, such as national defense or knowledge. Governments, for instance, fund public research and education in order to enhance the provision of new scientific knowledge and disseminate it more widely. They are also the main source of demand for innovative technologies in given strategic industries like defense or health.[2] A clear and recent example involves different government initiatives – for example, Operation Warp Speed in the United States of America (U.S.) – facilitating and accelerating the development, manufacturing and distribution of COVID-19 vaccines, therapeutics and diagnostics (see Chapter 3, Box 3.1).

The social benefit of COVID-19 vaccines far exceeds their private benefit

Figure 1.1 Estimated social and private benefit in USD billion



Source: Based on estimations in Fink (2022).

The direction of innovation is constantly changing due to the choices made by, and the interactions between, public and private stakeholders looking to optimize the private and social returns to innovations in different fields and industries. The next section looks at how these stakeholders interact within a complex ecosystem when setting the direction of innovation.

Box 1.1
Social versus private benefits of COVID-19 vaccine development

The COVID-19 pandemic's global scale and its far reaching economic effects meant that the private and social returns from a successful vaccine would inevitably be high. Yet, how high exactly?

Based on data on the prices of successfully commercialized vaccines and the assumption that vaccination will eventually cover 75 percent of the world's population, Fink (2022) estimates total private revenues to be USD 130.5 billion. Even if the exact research and development (R&D) costs remain uncertain, this figure represents a substantial private return to innovation.

That said, the social benefit of vaccines is many times higher. It consists of the value of lives saved and health impairments avoided, as well as the value of the economic output losses avoided by mitigating the need for measures, such as lockdowns, taken by governments to contain the pandemic. The study relies on a counterfactual epidemiological path informed by pre-vaccine infection cases and the hypothetical attainment of herd immunity. It then applies so-called value-of-a-statistical-life (VSL) estimates and global output losses from the pre-vaccine year 2020 to estimate a social benefit of USD 70.5 trillion – exceeding the private benefit by a factor of 887.

Successful COVID-19 vaccines would likely have emerged without any public R&D funding. However, the very high social return to successful vaccine innovation underlines why governments mobilized funding and helped coordinate clinical trials and the scaling up of manufacturing capacity.

Fink's study also explores how the emergence of virus variants, the need for booster jabs and different epidemiological paths affect private and social returns. These remain high relative to plausible amounts of R&D investment, and the social benefit is seen to always exceed the private benefit by a factor of at least 220.

The calculation of the social return does not take account of several socioeconomic effects that are hard to quantify and, in part, may only materialize in the long-term. These include curtailed access to health care as the pandemic overwhelmed health care systems; educational losses due to the prolonged closure of schools; workers losing their jobs and permanently leaving the labor force; and increases in public debt-to-GDP (gross domestic product) ratios questioning fiscal sustainability and crowding out other public investments.

In addition, early evidence suggests that the pandemic is associated with a 5 percent reduction in clinical trials for diseases other than COVID-19.[3] A reallocation of R&D resources may well be in a society's best interest, given the threat posed by the virus; nonetheless, it may come at the expense of diminished progress in the fight against other diseases.

1.2 Interactions within innovation ecosystems

Scientific institutions can decide to influence the direction of innovation toward given fields by, for example, developing more applied programs to train specialized engineers or by transferring technology to specific industries. Industries and companies can decide to invest more intensively in R&D and other innovation-generating activities. They do so either to create new technologies or absorb existing ones from other innovation ecosystem stakeholders, such as universities, suppliers or rival firms.[4] Governments influence the direction of innovation by allocating human and financial resources through a diverse range of public policy instruments (see Section 1.4).

An innovation ecosystem can be defined as the combination of all the stakeholders that make choices influencing innovation-related outcomes and, consequently, the direction of innovation. Stakeholders include firms, ranging from specialized suppliers to end-consumer manufacturers or retailers, and, as noted, institutions with a scientific and technological mission, such as universities or public research organizations. But ecosystems also can involve institutions without a primary scientific or technological mission, such as government agencies, financial institutions or intellectual property (IP) offices, to name a few. The degree of articulation of an innovation environment is defined not only by the degree to which its institutions are developed, but also by their interactions. The choices and interactions that occur within the ecosystem will heavily influence the direction of innovation.

Ecosystems assemble geographically and thematically

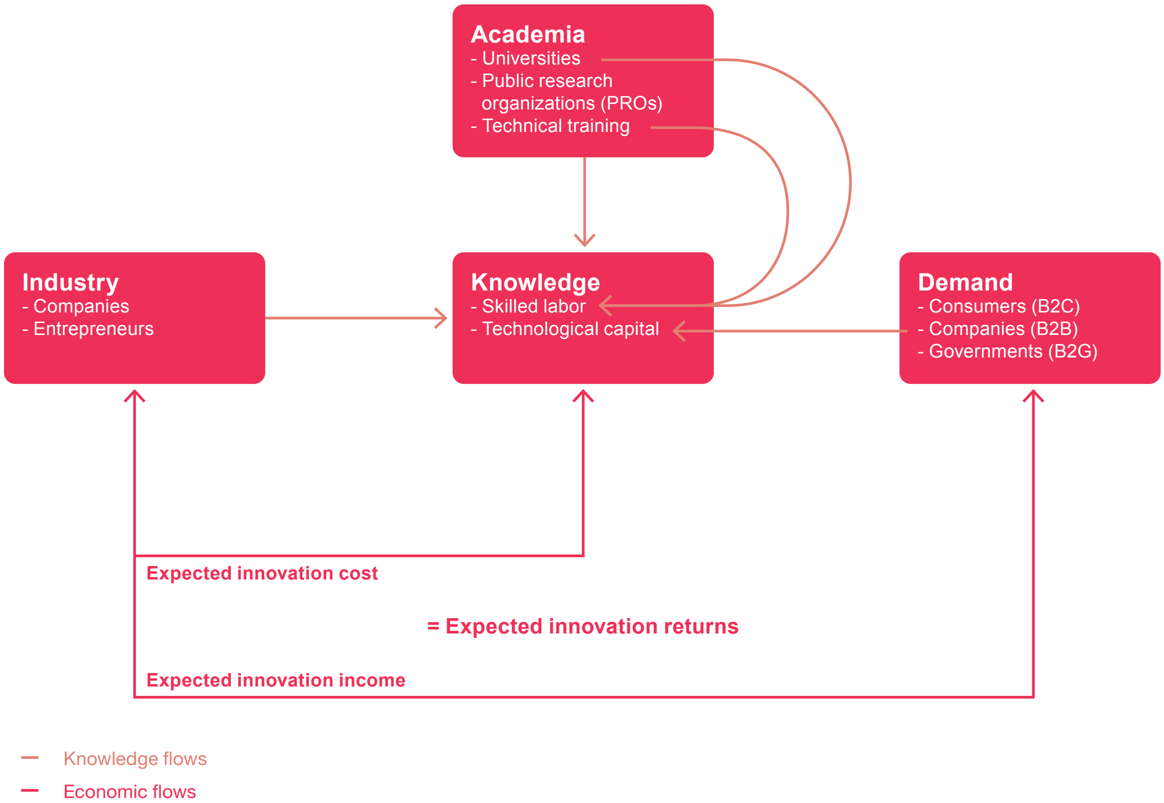
Several strands of the economic and social sciences literature have addressed the notion of innovation ecosystems.[5] Ecosystem stakeholders engage in non-linear and strongly interdependent flows of knowledge and ideas that ultimately result in innovation.

Innovation and knowledge are found to flow most easily within certain geographical or thematic boundaries.[6] Individuals and institutions in the same city or region will multiply their interactions – formal or informal – generating more opportunities for knowledge to flow and innovation to ignite. The same rule applies to an innovation ecosystem sharing common technologies or commercial links, such as in a specific global value chain. Individuals and institutions sharing a similar scientific, technological or industrial background will also most easily communicate and, hence, exchange knowledge.[7] The area around San Francisco known as Silicon Valley, with its vibrant information and communications technology (ICT) innovation ecosystem, is an example of both geographical and thematic concentration. On the other hand, the global value chains of carmakers are examples of thematic but not geographical concentration; that is, highly specific innovation flows in all directions between auto parts suppliers and automobile assemblers in various parts of the world.

Note that geographical and thematic proximity is predicated on the mobility of skilled individuals, who are the best conduits of knowledge flows, especially those with implicit knowledge. Talented individuals hop in and out of jobs within the same ecosystem, transmitting information and knowledge as they go. However, the absence of geographical or thematic proximity does not necessarily preclude innovation ecosystems from linking with outside stakeholders or other scientific and technological themes.[8]

Innovation ecosystem stakeholders interact to achieve innovation

Figure 1.2 Conceptual summary of innovation stakeholders' interactions



Source: Adapted from (Schmookler, 1962a) and (Kline and Rosenberg, 1986).
Note: B2C, business-to-consumer; B2B, business-to-business; B2G, business-to-government.

How an ecosystem sets a direction

The interaction between innovation ecosystem stakeholders is based on knowledge flows. These knowledge flows accumulate within an innovation ecosystem and determine the potential innovation opportunities available to stakeholders, which in turn sets the direction of innovation. Figure 1.2 summarizes these interactions, which are further discussed as follows.

In innovation ecosystems, every stakeholder contributes to and makes use of a knowledge set.[9] Professors train future scientists, technologists and entrepreneurs using this knowledge in university or technical educational programs, while researchers contribute new basic and applied scientific knowledge to the set. Engineers and technologists apply this knowledge when working in a company, university or government agency, and their use of it contributes to an increase in the experimental and technical base. Entrepreneurs make use of this knowledge when creating new companies and add to it when devising a new product or process.

What sets the direction of innovation chosen by stakeholders? There are several interactions happening at the same time. To begin with, there is curiosity. Curiosity leads researchers into exploring a new scientific field and engineers into experimenting with a novel technique or new technology. Curiosity is not confined to university and public institution research programs. More and more companies have engineering or formal R&D units, where scientific and technological curiosity abounds. Individuals outside of a university or company lab can get curious too. Thomas Edison (b. 1847–d. 1931), the self-taught inventor of the electric light bulb, among other things; actress and inventor Hedy Lamarr (b. 1914–d. 2000) and Steve Jobs (b. 1955–d. 2011), co-founder of Apple Inc, all had their curiosity sparked outside of any kind of formal organizational framework.[10]

Companies, entrepreneurs and governments identify innovation opportunities based on predictions as to potential private and social returns – that is, the potential profit to a company or society.

A company that has an innovative new product in mind will assess what kind of skilled labor and technological capital is required to develop and produce it. The necessary labor and equipment may already be available in the market or the company may need to train workers or create the equipment from scratch. Because of the risks and costs involved, it is likely that innovations will come about faster in areas where there is talent and equipment already available. For instance, the more proficient computer scientists and engineers and advanced computing hardware there are in an innovation ecosystem, the more likely it is that entrepreneurs and companies will pursue ICT-related innovation.

Conversely, a lack of capital or labor can also serve to motivate innovation opportunities. A shortage of advanced computing-related hardware can itself create innovation opportunities for specialized suppliers in the ICT industry like those offering shared computing and storage capacity services. The cost of specialized labor too can motivate equipment entrepreneurs to produce a labor-replacing innovation. Several scholars indicate that labor scarcity in the United States during the 19th century served to redirect innovation efforts toward labor-saving technologies faster than in Britain, which had until then been the world's industrial leader.[11] Scarcity of skilled labor can also motivate universities and government agencies into creating new training programs to provide the type of specific skilled workforce needed by specific industries.

Innovation is responsive to profit-making opportunities, which are in turn linked to the size of an actual or potential market.[12] The prospects of higher demand will induce entrepreneurs and companies to invest, as they will be more certain of recovering their innovation costs and making a profit. Economies of scale also apply to the process of innovating. The more people there are with a problem, the more likely it is that an innovative solution will be found. By the same token, the more people there are thinking about a problem, the easier it will be to find the inventive talent needed to solve it. The same logic applies to specific inputs and tools.

Market size and preferences go a long way toward explaining the rate at which firms innovate in any given direction, as evidenced by today's computer and mobile phone markets. The boom in automobile consumption (and the intertwined innovation) during the early part of the 20th century had more to do with economic and social changes in certain regions of the world than it did with technological opportunities. The scientific knowledge and the technology of combustion engines and other automobile parts pre-dated the supply and demand boom. Indeed, some scholars argue that automobile innovation only took off with the emergence of a relatively affluent middle class in the United States able to afford the price of cars.[13]

The market does not only include private end-consumers; it also includes other companies in a supply chain, as well as governments and institutions. A scarcity and cost of skilled labor or technological capital can, as mentioned, generate potential markets for companies supplying new equipment or offering specialized training. These "business-to-business" markets also help set the direction of innovation. The cost of labor can stimulate specialized suppliers of machinery and equipment to develop innovation in the fields of robotics and automation for other industries. Similarly, the cost of transport can trigger innovation in containerization or three-dimensional (3D) printing technologies.

Governments' participation in innovation incorporates funding public research and education as well as being the main source of demand for innovation technologies in strategic industries. Government policies frequently induce and support changes in academic programs to increase the supply of skilled labor. This was the case for government research institutes created in the Republic of Korea in the 1960s and 1970s; for example, the Korea Institute of Science and Technology (see Chapter 2). There are also examples from China dating from the 1990s onward. In both cases, institutions fostered the training of a specialized workforce for the IT industry. Areas where governments serve as the main source of demand for innovation technologies include defense, health, education and agriculture.[14]

1.3 The economic forces at work

Decisions made by an innovation ecosystem's stakeholders constantly change the direction of innovation. This section explores how they "deepen" or "widen" it.

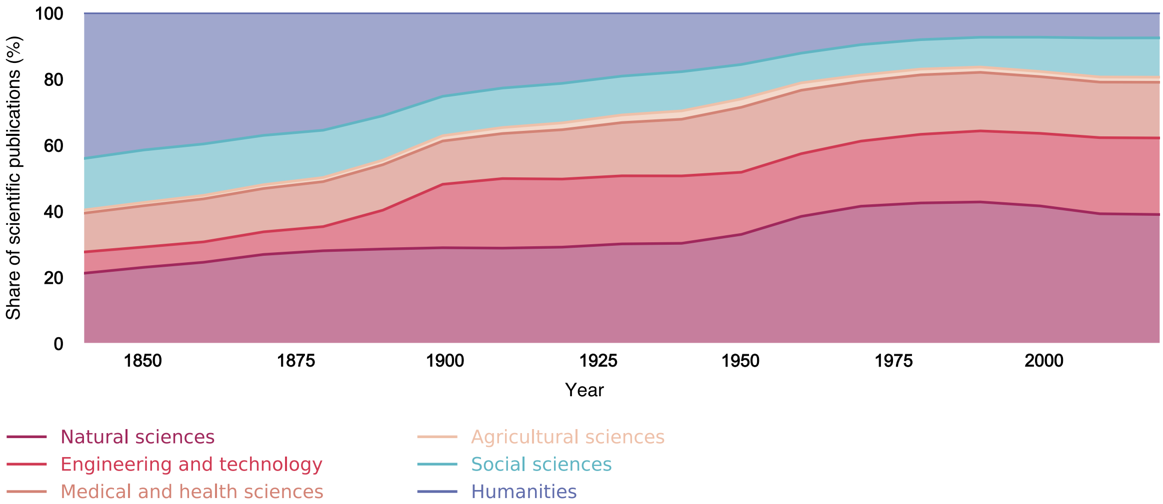
"Deepening" the direction of innovation

Economic resources gravitate to the most profitable technologies and the industries that use them. This has the effect of reinforcing past technological decisions and prioritizing the most successful innovations and industries. This reinforcing mechanism "deepens" current innovation decisions in scientific fields and industries, playing a strong role in setting the direction of innovation.

The simple allocation of more talented people and greater financial resources to a given field or industry is how companies or governments can directly influence the direction of innovation. Reallocation of more scientists and R&D equipment speeds the pace of scientific discovery and innovation in a given technology field. This was the case, for instance, in efforts to discover new antibiotics during the first half of the 20th century or, more recently, to produce COVID-19 vaccines (see Chapters 2 and 3).[15] Allocating more innovation inputs is also likely to generate more innovations relating to production processes. R&D units in companies can either develop new ideas or adapt existing ones in order to increase the production efficiency of existing products. Economic studies are consistently finding that those private companies and industries investing the most in R&D end up producing the most for every unit of capital or labor invested.[16]

Scientific output has shifted toward "hard" sciences

Figure 1.3 Shares of scientific publications by scientific field, 1840–2019



Source: Microsoft Academic Graph.
Note: Based on the scientific fields identified by the Organization for Economic Co-operation and Development (OECD).

The direction of innovation is inherently related to the allocation of resources. Fields and industries regularly investing the most in R&D will eventually outpace in terms of scientific, technological and innovative output those investing the least. For instance, a century ago, scientific interest in virology and investments in virus vaccine production were much lower than today, even in relative terms (i.e., taking into account the different level of knowledge that existed). It was not just the discoveries in the field that came later, but also the rapid reallocation of resources to them and to related industries that explain the subsequent direction of innovation and the increased activity. The multinational and complex value chains of the automobile and airplane industries of today have their origins in the almost amateurish innovations developed in independent and informal workshops over a century ago. (The Wright Brothers, credited with flying the first motor-operated airplane, began their careers working in a bicycle repair shop.) Mobile phones and Internet-connected applications – which did not even exist until relatively recently – have now become the standard for work and leisure. These are all examples of scientific and technological opportunities where governments and companies went from allocating nothing to pouring in abundant human and financial resources over the course of just a few decades.

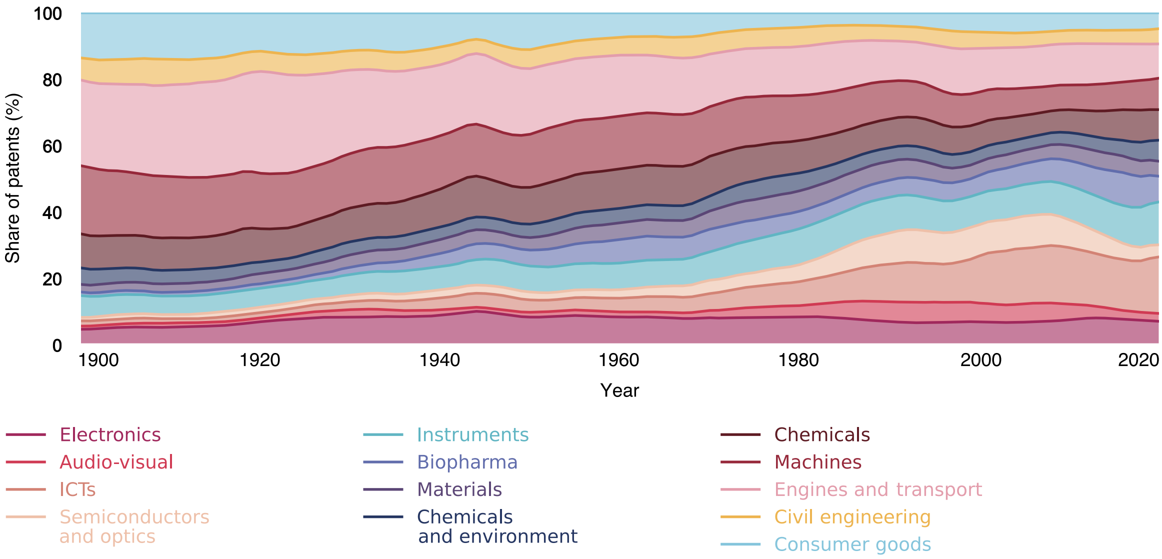
The historical data on scientific publications also point to a rapid shift in the allocation of innovation resources (see Figure 1.3). The shares of scientific publications by scientific fields can be seen to reflect the preferences of scientific stakeholders across these fields, indicating the effective direction of science and, eventually, innovation.[17] The proportion of publications across the main scientific fields changed considerably between the early 19th century and the second half of the 20th century. During this period, research relating to health sciences, engineering and natural sciences – often called the "hard" sciences – increased its overall share. From the early 1800s to the 2010s, the share of natural sciences publications, in fields such as mathematics, physics, chemistry or biology, increased from 16 percent to 36 percent of total recorded scientific publications. In the same period, the share of engineering-related publications went from 7 percent to 24 percent, while the share of health and medical sciences went from 9 percent to 16 percent.

Similarly, patent applications by technological field can be seen to reflect the direction of innovation taken by stakeholders. A rapid change in the direction of innovation is very noticeable in the distribution across technological fields of total first filing patent applications worldwide (see Figure 1.4). Unsurprisingly, during the last century, those technological fields relating to ICTs saw the biggest growth in share. Within ICT, computer technologies grew the most, accounting for over 10 percent of all patents in the decade to 2020. A similar pattern can be seen in digital communication, telecommunications and semiconductors. The larger concentration of patents in ICTs was mostly at the expense of "traditional" technologies, particularly those relating to mechanical engineering, for example, machines, tools and combustion engines.

The dynamics of success reinforce the pattern of deepening. Scientists and technologists will rationally choose careers in the most productive scientific fields and industries. Entrepreneurs and large corporations will prioritize projects, such as creating new companies or new products, in promising industries. Over time, innovation resources – both human and financial – will naturally gravitate toward the most productive fields

A century's shift from engines toward ICT innovation

Figure 1.4 Shares of patents by technological field, 1900–2020



Source: European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT, October 2021).
Notes: Based on WIPO technological fields.

and industries. This mechanism reinforces and deepens the innovation trajectories of successful scientific fields and industries.

"Widening" the direction of innovation

Industries, companies and scientific and technological institutions within an innovation ecosystem interact regularly. Their innovation activities benefit from the innovation and economic activities happening around them. Theoretical scientific fields benefit from the systematic and continuous use of technologies by applied scientists and engineers. New scientific discoveries in one field are often simply the synthesis of knowledge from different fields. Scientific discoveries in physics impact ICT industries while computing power and storage-related innovations from private companies contribute to the scientific productivity of researchers and physics institutions. Biological research labs increasingly use customized 3D printers to produce lab tools and equipment specifically for their research. At the same time, 3D printing technologists have been exploring "bioprinting" applications, such as the construction of organs for implantation, based on insights from biological science.[18]

The lines dividing science and technology have become increasingly blurred – a trend that began as far back as the mid-1800s. Today's industries both inspire and benefit from the information, techniques and methods originating in science laboratories.[19] This is especially the case in current high-tech industries, where basic science research is most influential.[20] The R&D labs of companies like Apple, Google, Huawei, Samsung or Tencent produce basic scientific outputs that contribute directly to the innovations they make.

Sometimes allocating more resources to innovation in one field translates into more output in another field. History is full of cases where an innovation in one industry spreads to others. Originally developed to pump water out of flooded mines, the steam engine became the main source of power for railroad and maritime transport is one example. Some chemical companies involved in the development of synthetic rubber, triggered by vehicle-maker demand for rubber tires, ended up switching industries to become intrinsic parts of the automotive industry and ceased to be chemical concerns altogether.

Industries relying on audiovisual, biological or management technologies have benefitted from the ICT revolution. Audiovisual industries for a long time advanced in step with innovations in lenses or analogic recording techniques. But the past three decades have witnessed an overhaul of the entire industry by digital technologies for recording and sharing content. The same applies to the increased use of digital technologies – both hardware and software – in the labs of pharmaceutical industries and the management departments of all industries. Fields such as audio-visual technologies, IT methods for management and, to a lesser extent, analysis of biological materials have increased their shares of patent applications. The underlying patent data indicate that this can be traced back to the adoption of ICT technologies, as shown in Figure 1.5.

Much of the direction of innovation is set by the knowledge gained by industries through operating experience or supply chains.[21] This is particularly pronounced in the case of the machine-tool and equipment industries developing new capital goods for other industries.[22] Incorporating innovative tools and equipment is the most straightforward route for other industries to become more innovative and productive. For instance, continuous innovations in lathe and milling tools have had a big impact on the productivity of most manufacturing industries. Likewise, innovation in pasteurization techniques and refrigeration equipment have been crucial to the food industry.

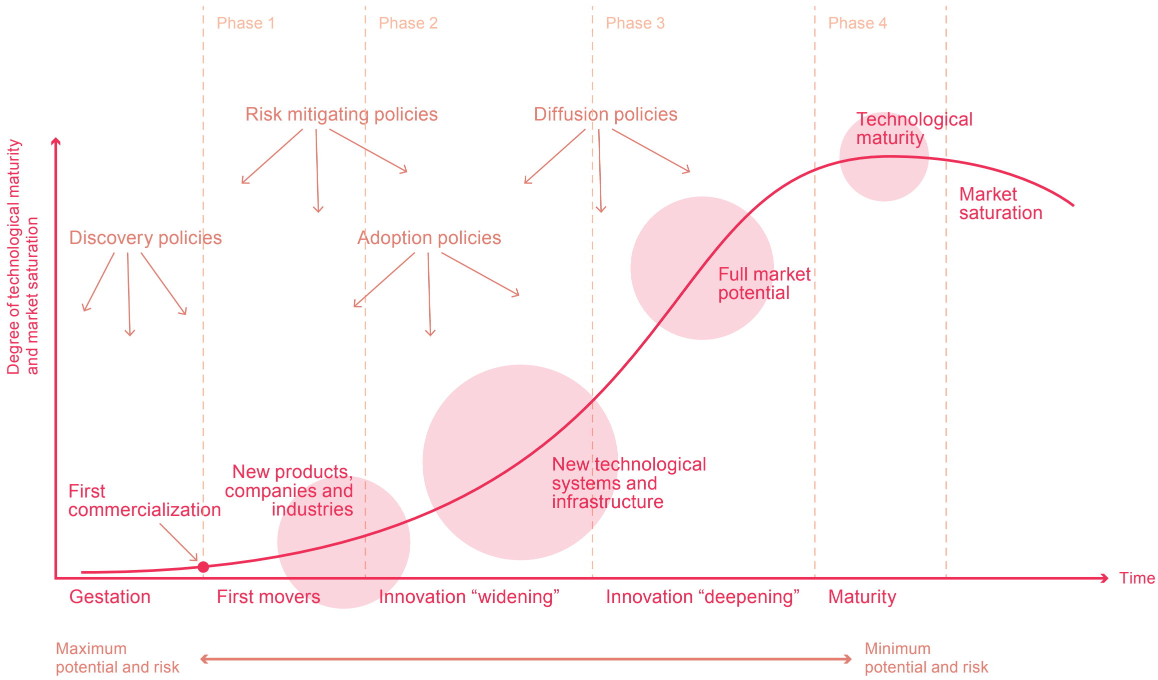
Knowledge and innovation flows across fields and industries provide scientists, engineers and entrepreneurs with a strong incentive to move to new fields and industries applying the technologies they have mastered. Contrary to "deepening", when "widening" is at work, R&D and innovation resources may be efficiently relocated to areas where there is less competition and more opportunities. This widening mechanism diffuses a given technology to other fields and industries, redistributing the allocation of financial and human resources and ultimately affecting the direction of innovation.

Differing maturity, differing returns

If successful, an innovation – a new product or new process – progresses through consecutive improvements to the underlying technology that accumulate over time. Different stakeholders nurture this accumulation of improvements. During the gestation of an innovation, only a few entrepreneurs and even fewer companies participate in the development and improvement of the technology. Slowly, the accumulation of improvements accelerates in phases, with the sequential appearance of inventors, innovators and imitators moving into the field or industry concerned (see Figure 1.5).

Innovation stakeholders and risk vary between gestation and maturity for a successful innovation

Figure 1.5 Conceptual summary of the evolving innovation ecosystem around a new technology



Source: Adapted from Perez (2003).

The entry of new entrepreneurs and innovative firms brings fresh technological know-how and ideas to established firms. This new entry produces a widening of the technological and industrial scope of those firms using the innovation. There are ever and more diverse companies thinking how to better improve the technology for a specific case. Over time, these new firms often replace many of the established ones. This is what is known as a "creative destruction," whereby the most innovative – as in more creative and commercially successful – companies take the place of old ones.[23]

The new and surviving firms set the direction of innovation in the sector concerned during this and following phases. In the later phases, there is a deepening of a by then well-established technological trajectory, mostly through incremental innovation and imitation.

The innovation ecosystem reacts differently during different phases. The maturity of a given technology is likely to affect just how incremental innovation is, and, consequently, who dictates its direction: thus, smaller and younger firms dictate the direction of innovation in the early widening phase, whereas established and market-dominant firms do so during the deepening phase.[24]

Why does this happen? There are considerable differences between private and social returns during the successive waves of technological improvement. The prospects of private returns are not only very different at each stage within a given industry or field, they are also different across industries that are at a different phase of technological maturity.

During the gestation of a new technology, private returns to innovation are typically low, due to a higher failure risk in comparison to existing competing technologies. Yet, the social returns to fully developing a gestating technology are potentially high.[25] Regardless of all the private and social costs of first-moving firms not surviving – for example, bankruptcies, jobs lost, and so on – society as a whole might still benefit in the long term from the maturing and resulting consolidation of a new technology and the establishment of more efficient firms. In the U.S., hundreds of small private carmakers produced an equivalent variety of automobile models in the first decade of the 20th century. Only a few decades later consumers could purchase fewer but more reliable models produced largely by a handful of companies. These mature versions of automobiles became standard transport equipment in many industries, benefiting society beyond just producers and consumers of automobiles.

Nobody knows exactly when, or if, a technology will spark. Sometimes, there may be an initial promise of private returns, but realizing this promise turns out to be more difficult or take longer to achieve than had been anticipated. For instance, solar panel technology was employed in the space industry way before it become a commercially viable option for household energy generation (see Chapter 3).[26]

As the prospects of private returns grow, more companies are likely to enter the specific market, thereby increasing the influence private companies have over the direction of innovation. In later phases, private returns are often high enough to provide a sufficient incentive for more companies to adopt now mature technologies and enter markets.

Systemic shocks and general-purpose technologies

Sometimes, there are large and unexpected "systemic" shocks – such as those brought about by new breakthrough technologies, epidemiological crises or wars – that shake the preferences and priorities of the innovation ecosystem's stakeholders. These shocks can generate widespread changes affecting multiple stakeholders and alter how private and social returns to innovation are perceived.

Very occasionally, a new breakthrough technology appears that is widely adopted across a wide range of sectors, while being at the same time in continuous technical development within its originating field or industry. It becomes what the economic literature terms a general-purpose technology, able to deepen and widen its trajectory at one and the same time. It enables follow-on innovations elsewhere, while still pushing at the technological frontiers within its sector (see Figure 1.6). New companies and entrepreneurs adopt sequentially this general-purpose technology, triggering long-lasting waves of cumulative technological improvement.[27]

Different moments of history tend to be characterized by the development and diffusion of specific collections of broadly complementary technologies. These share the characteristic of permeating a wide range of industries and being used in the training of professionals in new fields of engineering and other applied sciences. The already noted historical examples of breakthrough innovations such as steam power, electricity, the internal combustion engine and, more recently, ICT technologies all generated ripple effects across scientific and technological fields, as well as in industries and markets.

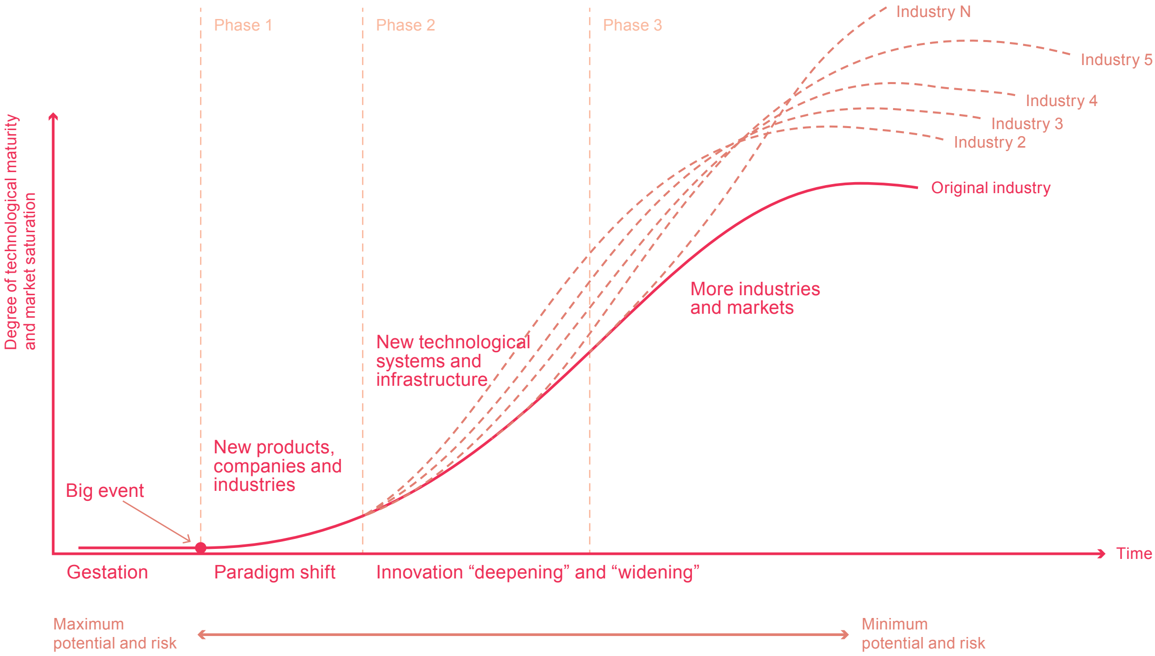
These general-purpose technologies reconfigure the main collections of technologies in a way no other technologies do.[28] Their widespread use generates competition for financial and human resources between the sector producing them and those sectors applying them. Such is the case, for example, in ICT technologies being employed in other fields like biotech. Technologies relating to IT methods for management and to the analysis of biological materials are sectors that apply ICT and which kept growing alongside the expanding patent share of the ICT-generating digital communication and computer technology sectors. The high demand for IT-skilled labor (i.e., people) and for semi-conductor inputs (e.g., ingots, wafers, integrated circuits, etc.) are two examples of the competitive tension that can arise between sectors; tension that can be resolved with new education programs and investments in new production capacity.

Systemic shocks transform the main technological base of an existing innovation ecosystem. While most such events can be traced back to a "eureka" moment – for example the discovery of penicillin, the transistor or the CRISPR-Cas9 system for gene editing[29] – it takes years of knowledge diffusion and cumulative incremental improvements until the breakthroughs come to full fruition.

Systemic shocks do not need to be scientific or technological in nature.[30] Large national investments in

General-purpose technologies both "deepen" and "widen" the direction of innovation

Figure 1.6 Conceptual summary of general-purpose technologies cycles



Source: Adapted from Perez (2003).

R&D can shift under particular conditions, such as the COVID-19 pandemic or the Second World War. This indicates that the direction of technological activity can be very responsive to both economic needs and non-economic imperatives.

There are shocks that arise out of natural disasters, such as earthquakes, tsunamis, wildfires, floods or pandemics. These natural disasters can alter preferences within a society as to the importance of any particular environmental or agricultural technology. There are shocks to a country's national interest, such as armed conflict, geopolitical upheavals or trade wars. These national interest shocks can affect how societies prioritize innovation in defense, including space exploration, for instance. Other social phenomena – such as cultural and religious beliefs – can also change the focus of innovation, affecting for example what is considered morally acceptable in medical innovation. Economic events – such as financial crises or inflation – can also shift innovation priorities by prioritizing cost-cutting technologies or innovation relating to social assistance.

Governments and policymakers are usually called upon to act after such priority-changing shocks. Governments have a long history of redirecting research into specific areas such as health, agriculture and, most certainly, defense. Wars are among the most explicit examples of a systemic shock shifting innovation preferences across an ecosystem. The U.S. Government responded to the Second World War by mobilizing the innovation ecosystem to develop technologies for military use. But it also fostered the development of communication and medical technologies, which had immediate applications in non-military markets (see Chapter 2).[31]

1.4 How can policy shape the direction of innovation?

Economic resources are finite and not allocated to every scientific field or industry in equal amount. The allocation of funds and talent governs how ecosystems shape the direction of innovation.[32] Who decides which technological opportunities are given priority in resource allocation ultimately determines the direction of innovation. Innovation policies are designed to shape these priorities.

This section explores first the broad categories of policy instruments available to induce innovation. It then turns to a discussion about innovation policy neutrality, before looking at the role played by policy tools aimed at stimulating demand for certain technologies.

Innovation policy tools

There is a whole set of policy instruments available to policymakers who want to determine the direction of innovation. This subsection reviews these in broad terms and relates them to the overall innovation cycle – from gestation to maturity – shown in Figure 1.5. The instruments in question are innovation policies

Who decides which technological opportunities are given priority in resource allocation ultimately determines the direction of innovation. Innovation policies are designed to shape these priorities

designed to induce discovery, mitigate risk and encourage early adoption and diffusion.

Discovery-inducing policies

Scientific and technological discovery-stimulating policies are most needed when innovation uncertainty and risk are at their greatest. The most typical example of such a policy is publicly-funded research carried out in academic institutions and public research organizations. Through such a policy instrument, governments can exert a great deal of influence over the potential direction of innovation, prioritizing one field over another. But governments may need to fund programs for years in order for a commercially promising discovery to arise. Before resources are allocated there needs to be a dialogue between policymakers and the scientific community about what direction to take.

A more direct approach is through government purchases. For instance, governments use regular direct purchases to stimulate the development of defense and aerospace technologies. Contracts can be awarded in different ways, so as to allow either competition or collaboration among the different innovation stakeholders. An example of the latter is when specialized companies and universities come together to create consortia to deliver the innovative good demanded. Yet, this instrument requires a government to have an in-depth technical knowledge of the specific deliverable and be able to handle not only technically complex contracts but also follow-up compliance.

Academic prizes – such as the Nobel Prizes in different scientific fields – or patents can also act indirectly as discovery-stimulating instruments. However, as prizes and patents are only awarded after a discovery or invention has been made, they have little influence on the direction of discovery.

The policy instruments discussed below can also spur discovery, although typically their impact is felt most strongly in the later phases of an innovation cycle.

Risk-mitigating and early-adoption policies

Arguably, risk-mitigating policies can be used all through the innovation cycle. But they are likely to be most effective in the early phases of development after the initial discovery. R&D subsidies, soft loans – loans with no or below-market interest rates – and R&D tax incentives are three typical risk-mitigating policy instruments. One example is the subsidies for R&D granted to companies developing COVID-19 vaccines (see Chapter 3).

Early-adoption policies aim not only at reducing innovation risk, but also at increasing the number of companies using a given technology. Even when a technology is promising enough to use – that is, it has a low adoption risk – its current cost may prevent adoption. In the early stages, new technologies are typically produced on a small scale and inefficiently, which increases costs and constrains any potential profit for adopters. Governments can step in to boost the production of a given technology and by so doing ensure sufficient scale is achieved for it to become profitable. For instance, during the Second World War, the U.S. Government provided the subsidies and soft loans necessary to scale up the penicillin-producing capacity of pharmaceutical companies hesitant to invest in what was then an innovative antibiotic medicine (see Chapter 2). Subsidies, soft loans and tax incentives are also examples of adoption policies that can be applied on the supply side to provide a direct stimulus for companies to adopt a new technology for use in R&D activities or as equipment.

On the other hand, governments can choose to reduce risk or incentivize adoption indirectly, by inducing the consumption of those goods and services that incorporate a desired innovation. Such indirect adoption policies include government subsidies to producers to keep retail prices down and subsidies to consumers encouraging them to buy. An example of the former is the aid given to solar panel producers by the German Government, while for the latter, many governments have subsidized the purchase of electric vehicles in order to make it more attractive to consumers (see Chapter 3).

Governments can also influence adoption take-up through publicly-funded educational programs in universities and technical training institutions. These programs influence the cost and availability of skilled labor and promote entrepreneurship in selected fields. IT schools in California provided the Silicon Valley industries with skilled – and cheaper – computer scientists and engineers. These schools also spurred a generation of Silicon Valley entrepreneurs into founding many of the IT giants of today.

Furthermore, IP instruments can also be part of an adoption-policy strategy. Patents allow the decoupling of the discovery of an innovation from its adoption. Inventors do not need to create a company to apply the technology – they can leave that to others. This provides a mechanism for innovation specialization, whereby inventors can keep doing what they are good at and sell their inventions to more experienced commercial entrepreneurs.

Governments have different policy instruments with which to stimulate discovery and, complementarily, induce adoption by providing licensing schemes to different potential users. For instance, public research organizations – under government contracts – can apply different licensing schemes to specific industries or companies in order to reduce the cost of adoption for the ones targeted. The U.S. space agency NASA offers different licensing terms to different contractors, including a different range of licensing fees; for example, it often grants free licenses to start-up companies spawned from NASA projects.

Trademarks and industrial designs can also act as an adoption incentive, by giving early adopters the chance to monetize their advantage.[33] This has been the case of the smartphone industry, where companies like Apple or Samsung rely on the strength of their designs and brand recognition, together with product innovation, to secure their market position.

Diffusion policies

A technology is successfully diffused when adopted by most companies as the industry standard. In the case of a general-purpose technology, several other industries start adopting it as well. Governments can influence diffusion through workforce training, subsidies, loans, tax credits and direct purchases. Typically, the diffusion of technologies that have proven successful in the originating industry should encounter less risk and lower adoption costs. For that reason, it is to be expected that private stakeholders will be more financially involved.

Can innovation policies be market neutral?

Much of the innovation policy discussion has drawn on the economic insight that the production of knowledge has the characteristics of a public good, in that it is easy and cheap to copy.[34] But this means private companies and individuals may have difficulty in reaping returns to innovations, because others can benefit from the knowledge acquired without having paid toward the cost of generating that knowledge.

Thus, innovating companies are likely to benefit the overall innovation ecosystem thanks to the knowledge they create spreading to other companies, including suppliers and competitors. But they will face greater competition from, and even risk being overtaken by, rivals that did not bear the cost of developing a new and successful technology. Economists often consider such a situation as removing the economic incentive to invest in innovation, thereby creating what is termed a "market failure" requiring policy intervention as a corrective.

The argument that innovation-related "market failures" need to be corrected has dominated much of innovation policy research and discussion. However, very little has been proposed by way of economic policy discussions as to where innovation investments should go. Other economists affirm the contrary, arguing that the direction of innovation is not the concern of public policies; for them, public policies should be market neutral.[35]

A market-neutral innovation policy seeks to stimulate the production of new knowledge and technologies without distorting the current market structure – that is, without altering the market status quo or favoring one participant over another.[36] For instance, many innovation policies attempt neutrality by supporting scientific and technological research in universities and public research organizations, while declining to do the same for private companies. Decisions on which technological opportunity to pursue are instead to be left to individual firms to make. In practice, however, it is very difficult for government policy to be entirely market neutral. Policy-induced changes to the direction of scientific and technological research may eventually lead to a change in the direction of innovation.

Moreover, there is a tacit bias in "neutral" innovation policies. Left to themselves, private companies are quite likely to select innovation projects that have safer and faster financial returns. As discussed earlier, the market is unlikely to select new, potentially disruptive technologies, which are more uncertain and riskier, ahead of well-established, mature technologies. Neutral innovation policies that let the market decide the direction of innovation are likely to reduce diversity and horizon of investments to an undesirable degree from society's point of view. This same bias favors follow-on innovation along already profitable technological paths and discourages follow-on innovation along new ones, thereby reinforcing the conservative dynamic.[37]

To conclude, innovation policy neutrality seems to be at odds with general practice. Several of the most industrialized economies – the United States, Western European countries, Japan and China, to name a few – have historically directed a large portion of public investment in R&D into either creating or stimulating specific technologies and their complementary markets in fields such as national defense, public health or agriculture.[38] Likewise, policymakers have in recent years been more inclined to provide direct financial support to those R&D-intensive sectors critical for national security, such as semiconductors.[39]

As a result, more and more, scholars agree that innovation policies have to be market-making or market-shaping, rather than just seeking to fix failures.[40] However, unreliable information – inaccurate, incomplete or mistaken data, for example – and the high degree of uncertainty surrounding innovation inevitably set limits on the extent to which governments can successfully tilt the direction of innovation in a socially desirable way.

Demand-side, mission-oriented policies

Demand-side innovation policies are often broadly referred to as "mission-oriented" policies. Their main features are centralized decision-making and the concentration of resources on one specific goal. In other words, the direction of innovation is set by the government, which acts as the main source of demand for a targeted innovation.[41]

Archetypical examples of mission-oriented programs are the medical research conducted by the U.S. Office of Scientific Research and Development (OSRD), set up to mobilize civilian science during the Second World War, and NASA's space program to land on the Moon. These case studies – discussed in further detail in Chapter 2 – show how directed, mission-oriented initiatives by governments can facilitate and direct innovation toward specific technological solutions. These initiatives had clear achievable targets, were national in scope and entailed a subset of industries. For instance, in the development of the technologies needed for the space industry, the role of the government was to overcome the extremely high cost of developing the technologies needed for space exploration. These costs were due to the large scale and longer period required to develop unprecedented technologies with a narrow and extremely specialized application.[42]

Some economics scholars suggest that demand-side policy instruments could also be used to address the major and complex social, environmental and economic challenges confronting the world, sometimes referred to as the "grand challenges."[43] These are categorized as major and complex, because they are extremely intertwined and widespread, but more importantly they require urgent and coordinated action.[44] For example, global environmental concerns cannot be solved without international, inter-industry and multidisciplinary coordination. National governments need to agree on global solutions, companies have to set standards and best practices along their entire global value chains, and scientific and technological experts from different fields – energy, biodiversity or meteorology, to name a few – need to collaborate to produce new solutions (see Chapter 3).

To some degree, addressing the grand challenges requires more than just government-directed policies.[45] Several innovation economists argue that mission-oriented policies will not be sufficient.[46] What is needed are broad, well-funded initiatives that deploy government policies as one element of the solution, while acknowledging the need for concerted efforts from the different stakeholders within the innovation ecosystem.[47] This inevitably requires the participation of private companies, universities and research institutes, civil societies, individuals and international communities in order to effect the change globally. Getting all these elements to work together requires a mechanism (or several) to help coordinate the priorities and resource allocation of individual initiatives.

Unfortunately, there is not yet a complete example of a grand challenge having been successfully addressed by innovation policies alone. Nonetheless, steps undertaken through international cooperation and agreements highlight the necessity for concerted efforts worldwide to address these challenges. For example, the United Nations Framework Convention on Climate Change (UNFCCC) or the International Civil Aviation Organization's (ICAO) sustainable aviation fuel initiatives show the international commitment to meeting the goals of reducing carbon emission and addressing climate change.

1.5 Developing economies and the direction of innovation

There are arguably two main routes for innovation in low- and middle-income developing economies, as with any economy: adapting foreign technologies or creating technologies locally. Yet developing economies, particularly the poorer states, are unlike developed ones. The problems needing to be resolved by innovation are substantially different. Developing economies' ability to absorb or generate technological solutions with which to address their specific socio-economic needs depends on their local innovation ecosystem and how connected it is to global innovation networks.[48]

In some cases, market and non-market participants may have in sufficient local innovative capacity either

> **Developing economies' ability to absorb or generate technological solutions with which to address their specific socio-economic needs depends on their local innovation ecosystem and how connected it is to global innovation networks**

to identify, assimilate and learn from new technologies developed elsewhere or else generate the innovations themselves. Low purchasing power may make it difficult to access global innovation to serve their needs. Basic infrastructure, such as roads, electricity or medical care, and important institutions, such as an effective financial sector, may be poor or non-existent, rendering some foreign technologies less suitable. Innovation may then need to be low-skilled, generally small in scale and targeted at specific communities or regions.

In other cases, innovation ecosystem stakeholders may have access to varying levels of innovative capacity. Such economies – usually those in the middle-income bracket – are able to leverage their scientific capacity, technological capital and skilled labor to narrow the technological gap between them and the most advanced economies. This was the case of the IT industry in the many East Asian economies – as further discussed in Chapter 2 – that managed to fully integrate into the global economy as core and active participants in international value chains.[49] A handful – including China and India – have become sources of innovation in several technological fields and participate actively in global innovation networks by contributing scientific knowledge, technologies and technologically-advanced goods and equipment.[50]

Adapting foreign technologies

Adapting foreign technologies to the needs of developing-economy markets tends to be incremental, with limited improvements added to the original technology. But not all foreign technologies can be easily transposed to developing economies.

Not all innovation from elsewhere is relevant to the needs of developing economies. Innovations from highly innovative economies – predominantly Western Europe, Northern America and East Asia – are conceived for economies with industries that are typically more capital-intensive due to relatively higher wages; have the skilled labor to implement and operate the innovations; have mass-production processes using high-quality infrastructure; and, have consumers with higher purchasing power.[51] By contrast, as has already been noted, developing economies tend to have relatively abundant but less skilled labor; are segmented with diverse needs; have weak or absent infrastructure; and have consumers with relatively low purchasing power. These differences often make frontier technologies less appropriate for the needs of poorer economies.[52]

The adoption of automation in South Africa's apparel industry provides an example. South African apparel firms have been shifting toward capital-intensive production, but uptake of automation technologies has been limited. Lack of access to capital, the inconsistency of order volume, lack of government support, low margins and the low profitability of the industry in general are some of the factors that explain the lack of automation.[53]

Even if appropriate for local needs, frontier innovation is often costly. Adapting frontier technologies to make them affordable requires high levels of technical knowledge. Since price is one of the main constraints, most innovation efforts are geared toward reducing costs, either through using cheaper inputs, such as local raw materials to substitute for the original ones, or stripping out features of the technology to leave just what is necessity. Economists often refer to these as "frugal," "*jugaad*" (an Indian term for non-conventional innovation) or "bottom-of-the-pyramid" innovations, as they are produced taking account of local needs and purchasing power.[54]

One example of "frugal" innovation is Transsion – a Chinese mobile phone manufacturer and service provider based in Shenzhen – which adapted mobile phones specifically for the African market. While relatively unknown in China, Transsion has captured over 40 percent of the mobile phone market in Africa, outperforming the likes of Apple, Huawei, Nokia, Samsung and Xiaomi, particularly in the lower cost segment.[55] This Chinese company understood the demand of many African consumers for low-cost mobile phones, but with a technology that addressed issues such as weak network signals and coverage and unreliable access to electricity, among others. Transsion produced price-accessible phones with an effective signal reception, long battery life and apps specifically designed for local market preferences.[56]

Developing economies are also highly heterogeneous, with a large gap between fast-growing emerging economies and the least developed ones. While technologies from developing economies may be diffused to others, successful technology transfer depends on the destination economy's needs and skills being similar to those of the source.

For instance, as an emerging economy known for its agricultural production and innovation, Brazil's agricultural technologies could be thought relevant and appropriate to other developing economies. Several African policymakers and industrial interest groups hoped to deploy Brazilian tractors, which are particularly well adapted to large-scale tilled farming areas, and simple hand-held planters known as *matracas*, which can be used on untilled land and in smaller and scattered farming areas. However, adoption of the tractors, which require significant maintenance and training, failed – but the *matracas* did relatively well. The characteristics of African agriculture partially explain these results. It is characterized by small farming areas, relying on low-skilled, abundant labor and locally-sourced materials, resources and knowledge.[57]

Solutions must consider the local perspective

The examples above have a common thread: local problems require solutions in accord with local conditions. These conditions often include a lack of access to finance; insufficient energy, transport and telecommunications' infrastructure; and a scarcity of skilled labor, to name a few. Innovation in developing economies must also involve non-market participants, such as research institutions, government agencies and non-governmental organizations (NGOs), if it is to address local needs.

An example of a successful innovation adapted to local social needs is M-PESA, a Kenyan mobile payment service for people without access to a banking system and usually operating in the informal sector.[58] It leverages short messaging services (SMS) mobile phone technology to enable secure electronic cash transfer on almost all mobile phones. The rapid uptake of M-PESA was due to the innovation being tailored to the demands of a local market eager to access a financial system.[59] This private–public partnership – including a foreign company, a local subsidiary, a local microfinance institution and an established East African bank – was developed in consultation with market and non-markets actors, such as microfinance institutions, NGOs and industry regulators. The Communications Authority of Kenya, the country's ICT regulatory body, was crucial in helping to legitimize the platform and promote its diffusion.[60]

Developing economies may also often lack institutions to facilitate and support innovation, leaving such activities to the informal sector.[61] But innovations generated within the informal sector may have limited scope to scale up. These types of innovation are often not documented in scientific articles, technical bulletins or patents – making them extremely hard to reproduce and diffuse. They often escape the attention of innovation policymakers, as they are not captured well by the usual innovation indicators, such as R&D investment, skilled labor counts or scientific publications and patents. This is why such local innovations are often referred to as "under-the-radar" innovations.[62]

Adapting to local needs should not be thought of as lower-quality innovation. Local adaptation of foreign technologies can lead to innovations that are equally valuable for industrialized economies. Such cases are often referred to as "reverse innovation." When U.S. company GE adapted its electrocardiogram and ultrasound devices for rural consumers in India and China, it relied on its Indian and Chinese subsidiaries to re-engineer the technologies to make them smaller and cheaper. The result was so successful that eventually GE started selling these adapted units to consumers in high-income economies as well.[63] Other examples are the Renault Dacia Logan automobile, conceived for lower-income markets in Eastern Europe and later successful in France; or Nestlé's Maggi low-cost, low-fat dried noodles, first developed for sale in rural areas in Pakistan and India but which also found strong markets in New Zealand and Australia.

1.6 The future direction of innovation

Innovation can certainly assist in solving or at least mitigating the world's grand challenges, be it climate change, inequality, the need for greater food production or better access to water, health and education. Nonetheless, just raising the general rate of technological change might not be enough. Several of these challenges resemble public goods, and as a result the private sector is unlikely to allocate enough innovation resources to resolving them. Some of the challenges, notably climate change, cannot be met by private and public-sector efforts within individual economies alone. All nations would benefit from climate change

- related innovation policies, but nobody will benefit if implemented by only a few. Arguably, the same logic applies to investment in innovation in any one of the grand challenges. It would appear, therefore, there is a strong case to be made for international and multilateral innovation policies that lay down key directions.[64]

Some hope comes from growing evidence that digital technologies will prove a new general-purpose technology. A Fourth Industrial Revolution based on these technologies is likely to produce all sorts of productivity gains across a wide range of industries. They may prove a springboard for private and public provision of technical solutions to the health, education and climate change challenges. They are also likely to transform how governments design innovation policies and provide public services in these areas. These questions are explored further in Chapter 3.

Notes

1 Acemoglu (2011) models technological progress as likely to have too little diversity, because companies fail to invest in alternative technologies, even when success can be predicted. His theoretical research finds that, while companies make use of innovations for current gain, they do not fully internalize the future benefits from these alternative innovations, because current mature innovations are likely to be deepened before alternative technologies can be profitably marketed.

2 The type of role played by governments varies markedly across these kinds of industries. For a discussion, see Nelson (2011).

3 See Agarwal and Gaule (2021).

4 Cohen and Levinthal (1990) discuss the duality of private companies' R&D in terms of innovation input and absorptive capacity. Crepon *et al*. (1998) further explore empirically how absorptive capacity, R&D inputs and outputs, and productivity relate.

5 These are largely compatible frameworks referring to a complex environment of innovation-related stakeholders. Edquist (1997), Carlsson *et al*. (2002), Bikar *et al*. (2006), Godin (2006) and Sharif (2006) provide comprehensive reviews of the literature relating to innovation environments. The main conceptual frameworks are: "National Innovation System" (Pavitt, 1984; Freeman, 1995; Lundvall, 1988; Nelson, 1993); "Knowledge-based Economy" (David and Foray, 1995; Foray, 2018); "New Production of Knowledge" (Gibbons *et al*., 1994); and "Triple Helix" (Leydesdorff and Etzkowitz, 1996). Founders of the "National Innovation System" and the "Knowledge-based Economy" approaches have discovered a lot of common ground (Foray and Lundvall, 1996), once discussion about tacit and codified knowledge is put to one side (Cowan *et al*., 2000; Cowan and Foray, 1997; Johnson *et al*., 2002). Founders of the "Triple Helix" framework have suggested analytical similarities with the "National Innovation System" and the "Knowledge-based Economy" approaches, at the same time as claiming a higher generality (Etzkowitz and Leydesdorff, 2000; Leydesdorff and Meyer, 2006).

6 *World IP Report 2019* (WIPO, 2019, Chapter 1) summarizes the interplay between geography and innovation. The conceptual frameworks "Regional Innovation system" (Cooke, 1992) and "Local Innovation System" (Breschi and Lissoni, 2001) re-conceptualize the innovation environment geographically bounded to subnational levels.

7 The conceptual frameworks "Sectoral Innovation System" (Breschi and Malerba, 1997; Malerba, 2002) and "Technological Innovation System" (Carlsson, 1997; Carlsson and Jacobsson, 1997) re-conceptualize the innovation environment to the same industries – including international supply chains – or to blocks of related technologies. In the same spirit, the *World IP Report 2017* (WIPO, 2017) explores how intangible assets (including knowledge and innovation) flow within global value chains.

8 WIPO's *World IP Report 2019* describes the global innovation networks that connect the most innovation-dense hotspots in the world (WIPO, 2019, Chapter 1). Several conceptual frameworks include explicitly the international aspect of innovation (see Amable *et al*., 1997; Barnard and Chaminade, 2012; Carlsson, 2006).

9 Kline and Rosenberg (1986) define this as "accumulated knowledge," to include "known science" and "stored knowledge." This term encompasses "the available knowledge already in the head of the people in the organization doing the work." Schmookler (1962a) goes further by stating that "[t]he 'state of knowledge' includes not only science and technology but also any other aspects of thought, e.g., art and religion, which affect Man's perception of the material universe."

10 Hedy Lamarr developed several inventions while being a successful Hollywood actress. In 1941, she filed a patent for one of these as Markey Hedy Kiesler, which was granted in 1942.

11 Acemoglu (2010) refers Habakkuk's claims about the relationship between labor scarcity and labor-saving technologies in the 19th century. Both Hicks and Marx were supportive of the notion that cost of labor and capital – the factor prices – can induce innovation (Antonelli, 2009; Dosi and Nelson, 2010).

12 See Scherer (1982) and Schmookler (1962a, 1962b).

13 See Schmookler (1962a).

14 See a discussion in Nelson (2011).

15 See also Sampat (2015), and *World IP Report 2015* (WIPO, 2015, Chapter 2).

16 Griliches (1980) found a strong and consistent relationship between U.S. companies' investments in R&D and various indicators of firm productivity. Griliches and Lichtenberg (1984) found a similar result for 193 U.S. industries.

17 There are the typical caveats about measuring the direction of science using large digital collections of scientific publications, such as the Microsoft Academic Graph. In particular, these collections do not have a perfect geographical, language or scientific field representation. Regarding the

latter, it is worth mentioning that the distinctions between different scientific fields did not exist to the same extent 200 years ago. In the 1800s, the publications of savants readily merged concepts from modern hard sciences and humanities. Hence, the figures are to be interpreted as general trends and used with caution.

18 See chapter 3 of the *World IP Report 2015* (WIPO, 2015) for an introduction to 3D-printing innovation.

19 See Kuhn's comments to Siegel (1962) and Multhauf (1959) about the unprecedented and increasing closeness of science and technology since the 1860s.

20 See Dosi and Nelson (2010), Kline and Rosenberg (1986) and Pavitt (1984).

21 See Pavitt (1984).

22 Carlsson (1984) documents the major impact on productivity in the manufacturing industry made by this kind of industry.

23 Joseph Schumpeter (1942) discusses extensively the concept of "creative destruction."

24 The widening process corresponds with Joseph Schumpeter's early impressions of new industries composed of smaller and younger firms. Such was the case at the inception of the automotive industry, when a nascent industry was nurtured by small, almost artisanal, workshops competing to establish their products. The deepening corresponds with his later impressions of the same industries, where for instance large established firms characterized the same automotive industry. Malerba characterizes these two processes as *Schumpeter Mark I* and *Schumpeter Mark II* (see Breschi and Malerba, 1997; Malerba and Orsenigo, 1993).

25 "[T]he production of new knowledge entails significant externalities that are difficult to appropriate, thus opening up a wide gap between social and private rates of return to inventive activities. Such a gap, coupled with acute risk and the specter of moral hazard in financing R&D, results in systemic underinvestment in R&D, lower than socially desirable rates of innovation, and hence slower economic growth" (Trajtenberg, 2011).

26 For a discussion on solar panels in the space industry specifically, see Chapter 2.

27 Perez (2003) explores how in terms of economics technological trajectories take the form of long-lasting, "Kondratiev" waves of cumulative technology.

28 See Bresnahan (2010) for a further discussion on general-purpose technologies.

29 Jennifer Doudna and Emmanuelle Charpentier's research on CRISPR (clustered regularly interspaced short palindromic repeats) DNA sequences for the Cas9 protein provided a platform for genome editing that revolutionized biological research. They won the Nobel Prize in Chemistry 2020 for their discovery.

30 Schumpeter (1939) explored the complexity of the external factors affecting the interaction between industrial systems and business cycles. His considerations are in line with the systemic shocks described in this section.

31 See Gross and Sampat (2020).

32 The quantity and quality of R&D resources invested in different activities are aspects of the operation of an innovation system. Integral to the innovation system concept is how resources allocated to the advancement of know-how are organized and governed (Nelson, 2011).

33 This adoption-stimulating mechanism is, of course, much less direct and certain. For a discussion, see *World Intellectual Property Report 2013* (WIPO, 2013).

34 See Arrow (1962) and *World Intellectual Property Report 2011* (WIPO, 2011) for a discussion on innovation as a public good.

35 "[I]n the area of policy research and discussion the last three decades have been dominated by the argument that market failures need to be corrected in order to reach the desirable level of investments, but where these investments should go should not be a concern for policies. It is much better to leave this issue to the magical chaos of the 'blind watchmaker.' Any notion of specialization policy or top-down strategic initiatives has become a taboo in policy discussion, particularly in the large international policy forums as well as in the European Commission" (Foray, 2011).

36 Ergas (1987) characterizes these market-neutral policies as "diffusion-oriented," in contrast to the "mission-oriented" policies discussed in the next subsection.

37 Ergas (1987: 1).

38 See Foray (2011), Foray *et al*. (2012), Mowery and Nelson (1996) and Ergas (1987).

39 See, for instance, the United States Innovation and Competition Act of 2021 (USICA) and the Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act of 2021.

40 Mazzucato (2018) proposes an alternative innovation policymaking toolkit where mission-oriented programs shape existing markets and "co-create" complementary markets more than they fix them.

41 Ergas (1987).

42 Hertzfeld (2002).

43 Mazzucato (2018) derives lessons from mission-oriented innovation policies. Edquist and co-authors (Edquist and Hommen, 1999; Edquist and Zabala-Iturriagagoitia, 2012) point to the importance of technological public procurements. Acemoglu (2011) predicts that a policymaker optimizing social returns to innovation will need to induce a more diverse innovation portfolio to generate a growth rate higher than the market allocation.

44 See Mazzucato (2018).

45 Different strands of economic thought arrive at a similar conclusion when addressing issues relating to the grand

challenges. But they differ on how to approach the matter. See Aiginger and Rodrik (2020), Rodrik and Stantcheva (2021), Mowery (2012), Schot and Steinmueller (2018) and Mazzucato (2018).

46 See Diercks *et al*. (2019), Mowery (2012), Mowery *et al*. (2010), and Schot and Steinmueller (2018).

47 See Mowery *et al*. (2010).

48 Archibugi and his co-authors (1999) argue that the concepts of national innovation systems and globalization of innovative activities should be analyzed together, even if they were developed independently. See also WIPO (2019).

49 See also WIPO (2017) and Kaplinsky (2011) for an overview of how these less developed economies were able to build absorptive and innovative capabilities.

50 See Fu and Gong (2011), Kaplinsky (2011) and WIPO (2019, Chapter 2).

51 See Eckaus (1987), Emmanuel (1982), Kaplinsky (2011) and Stewart (1978).

52 See Acemoglu *et al*. (2002) and Stewart (1978).

53 Parschau and Hauge (2020).

54 The concepts of "frugal", "*jugaad*" and "bottom-of-the-pyramid" innovations tend to overlap. But there are subtle differences in the definitions of these types of innovation. Scholars define "frugal" as innovations produced using locally-sourced and cheaper inputs, "*jugaad*" as innovations meeting the most basic needs of the poor, and "bottom-of-the-pyramid" as those innovations adapted to the lower purchasing power of developing economies. "*Jugaad*" innovation is essentially a "frugal" innovation with a social dimension present. See Fu (2020), Kaplinsky (2011) and Martin (2016) for further details.

55 See IDC (2020) and Deck (2020).

56 Qumer and Purkayastha (2019).

57 See Cabral *et al*. (2016).

58 M-PESA is a combination of the Swahili word for cash, *Pesa*, while "M" stands for mobile.

59 M-PESA was launched in March 2007 in Kenya. In its first month it had registered over 20,000 customers. Two years later, it had 8 million subscribers with a network of 13,000 agents. Over USD 3.7 billion was transferred through the platform over those two years.

60 The initiative behind M-PESA came from the British telecom company Vodafone's corporate social responsibility program to address the United Nations Millennium Development Goals. Initial funding for the initiative came from a public sector challenge grant, namely, the U.K. Government's Department for International Development (DFID) Financing Deepening Challenge Fund in 2003. Vodafone matched the GBP 1 million award with in-kind personnel costs. See more in Hughes and Lonie (2007) and Onsongo (2019).

61 ILO (2018) estimates that the informal sector accounts for over 85 percent of employment across Africa.

62 Fu (2020).

63 See Chandran Govindaraju and Wong (2011) and Immelt *et al*. (2009).

64 See Foray (2011).

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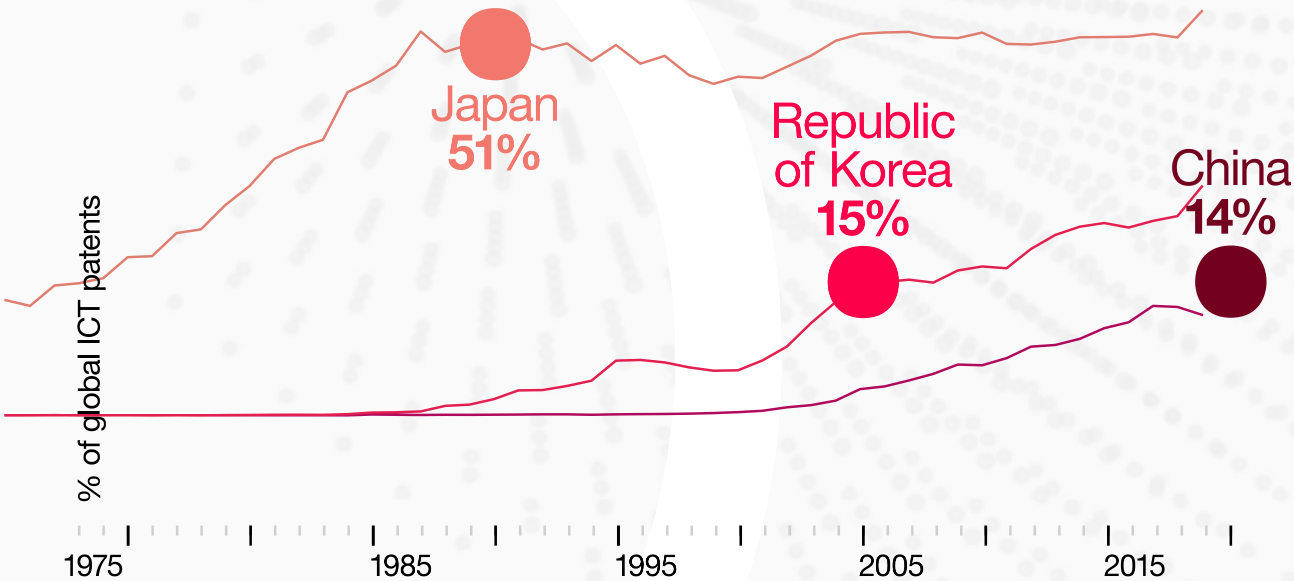
New technologies can spur development
and leverage local innovation ecosystems



Chapter 2

What history tells us about the direction of innovation

During the past century, and in particular after the Second World War, the world has seen numerous and sometimes abrupt changes in the direction of innovation. This chapter highlights three case studies that epitomize such periods of change – medical research during the Second World War, the space race and the initial rise of information technology (IT) industries in East Asia.

The ample data and detailed evidence available for all three cases and the significant length of time that has elapsed, allow for comparison of the direction of innovation before and after these periods. More interestingly, the predictability of the direction of innovation can be studied. While researchers working on penicillin in the 1930s could have had a sense of its tremendous potential, it would have been harder for scientists developing photovoltaic panels for the manned spaceflight programs of the 1960s to predict their widespread future uses.

As discussed in Chapter 1, economic forces can set the direction of innovation. The depth and strength of human curiosity and scientific knowledge act as guiding compasses for identifying promising avenues. Market demand also plays a crucial role in incentivizing the pursuit of certain technological paths. All these forces can affect decisions about funding and the allocation of resources.

The forces outlined above are at play in each of the following case studies, although their relative weights may vary. This chapter describes the historical background to the case studies, their innovation ecosystems and the role of the various stakeholders – governments, companies, individuals and universities – in steering the direction of innovation. As the historical case studies (the Second World War and the space race) discussed in this chapter show, some innovations, despite their immense impact, were not necessarily protected by intellectual property rights (IPR) for various reasons, such as norms of the time, security and confidentiality. The first case study looks at innovation during the Second World War, particularly in medicine, and its subsequent impact. The second examines the evolution of the space industry, from the Second World War to the present day. Finally, the third case study looks at the rise of the IT industry in selected East Asian economies.

It is important to point out that these case studies differ in the scope and scale of the innovations they cover. But they all serve as historical illustrations of the rich set of factors – and their interplay – that influence the direction of innovation.

2.1 Second World War[1]

The United States put science on a war footing

More than seven decades after the end of the Second World War, numerous medical innovations developed to meet battlefield needs are part of standard hospital practice across the world. Penicillin (see Box 2.1), antimalarial drugs and blood transfusions are examples of medical innovations spurred on by the needs of the armed forces but which, in time, became available to the civilian population and saved millions of lives.

While not every crisis can be resolved with innovation, natural hazards, wars and pandemics are examples of where it can often provide remedies.[2] The speed with which solutions are discovered is also of the utmost importance. If not addressed quickly, crises and their consequences can spiral out of control.[3] Researchers' intense efforts to find answers, coupled with the urgency that permits increased risk-taking, create fertile ground for scientific and technological advancement in crisis-related fields and even for the birth of new technologies. But it should also be noted that such emergencies may lead to the crowding out of attention and resources from non-crisis-related areas and, as a result, hinder or disrupt technological development paths in these fields.

This case study elaborates on how the U.S. Government mobilized civilian science to address wartime needs by creating and funding the Office of Scientific Research and Development (OSRD). In particular, it highlights the efforts of a subdivision of the OSRD – the Committee on Medical Research (CMR). The OSRD was disbanded in December 1947, but it has left a strong imprint on U.S. innovation policy. The formation and expansion of several current institutions, such as the National Science Foundation (NSF) and the National Institutes of Health (NIH), can be traced back to the Second World War research effort. These efforts produced a range of technological breakthroughs, including, but not limited to, radar, the atomic bomb, rocketry, jet propulsion and radio communications. Finally, the case study attempts to draw general lessons from these efforts for innovation in times of crisis.

War demanded cutting-edge technology

It was evident to the U.S Government that the Second World War was a technological battle and that without cutting-edge military technologies there was no chance of victory for the United States and the Allied powers. The OSRD was set up in June 1941 – several months before the United States formally entered the war – to mobilize the public and private sectors and the scientific community to ensure that the military had access to just such cutting-edge technologies and knowledge.[4]

Vannevar Bush,[5] President of the Carnegie Institution of Washington and a former Vice President and Dean of Engineering at the Massachusetts Institute of Technology (MIT), was assigned to lead the OSRD. He gathered a small but elite group of scientists to carry out research into the problems underlying the development, production and use of "mechanisms and devices" of warfare. By the end of the war, this small group had greatly expanded its areas of interest and its budget had increased from USD 6.2 million (in 1945 U.S. dollar terms) in 1940 and 1941 to USD 160–170 million in 1944 and 1945.[6] While the budget was low by today's standards, it was unprecedented for its time, almost 100 times more than the U.S. Government had previously been investing in science. By the end of the war, the OSRD had spent over USD 536 million on R&D, across more than 2,500 contracts.[7]

Box 2.1
Penicillin

Mass production of penicillin is the most celebrated accomplishment of the Second World War medical research effort. The CMR's most crucial early role was as coordinator. It persuaded skeptical firms with relevant capabilities to start developing a commercial process for production, organized meetings between firms and researchers at the U.S. Department of Agriculture's Northern Regional Research Laboratory (NRRL), a key player in penicillin development, brokered information-sharing and refereed conflicts that arose.[8] The CMR then assumed a prominent role in coordinating clinical and field trials. It spent nearly USD 2 million, about 8 percent of its total budget, on purchasing penicillin for testing. In some cases, the Government built the required production facilities; in others, private firms built them, confident in the knowledge that there was a large guaranteed market. Government agencies, including the War Production Board (WPB), set up to supervise U.S. war production, helped promote information-sharing and overcome technical bottlenecks in production.[9] Antibiotics would be the biggest selling medical drug for a quarter of a century after the war[10] and the focus of dozens of follow-on innovations. Throughout the war, the CMR funded a parallel program to chemically synthesize penicillin to avoid having to rely on organic production, which had very low yields. Although its efforts were unsuccessful, the knowledge developed, as Swann (1983) states, "paved the way for the general synthesis of penicillin in the 1950s, which led to the development of therapeutically invaluable semisynthetic penicillin."[11]

The CMR was not originally part of the OSRD. It was added later and, even though its budget was one-tenth that of the overall OSRD, its role was central. The CMR consisted of a handful of subdivisions, such as medicine, surgery, aviation medicine, physiology, chemistry and malaria (see Box 2.2), which had proved an unanticipated enemy in the First World War, infecting huge numbers of both combatants and civilians.[12] The Committee was mandated to determine (and recommend for funding) "the need and character of contracts to be entered into with universities, hospitals and other agencies conducting medical research activities."[13]

Large-scale federal support for medical research was a radical idea for its time. Chester Keefer, who became known as the "Penicillin Czar" for his work in rationing the wartime distribution of the drug to civilians, described the CMR as a "novel experiment in American medicine, for planned and coordinated medical research had never been assayed on such a scale." The CMR facilitated and supported the mass production of penicillin, the creation and production of vaccines (see Box 2.3) and the development of blood substitutes (see Box 2.4), along with research on hormones (see Box 2.5) and numerous other medical technologies. These efforts opened avenues for research and medical improvements that reached far into the future after the Second World War.

Box 2.2
Antimalarial drugs

The CMR invested the largest share of its budget in the search for drugs to combat malaria, which, as in the First World War, was a major threat in many combat zones, but particularly this time in the south Pacific. The Rockefeller Foundation and the National Research Council (NRC), which advises the U.S. Government on science and technology, had conducted research on malaria in the 1930s. The U.S. effort focused on identifying a substitute for the German antimalarial drug Atabrine, since the U.S. attempt to recreate it had produced a range of side effects, such as nausea and diarrhea. The Board for the Coordination of Malarial Studies, set up in 1942, included military representatives and civilian scientists. Since there were thousands of compounds to explore, the CMR had to coordinate the research efforts of individual firms and academic laboratories, making sure there was no excess duplication of effort, but also that there were no major holes. As with penicillin, it tried to promote information-sharing and collaboration without compromising proprietary interests. Surprisingly, the drug eventually used was Atabrine. Research had shown that it was "relatively non-toxic"' after all. The breakthrough on one of the molecules studied, chloroquine, came too late to be useful during the war effort but chloroquine would become a revolutionary malaria treatment in the years immediately afterwards. Research on this and other lead compounds of interest identified during the war continued.[14] Other compounds with links to the wartime effort include primaquine, mefloquine and Malarone. Demand from the U.S. military remained strong during the conflicts in Korea and Viet Nam, even though malaria was no longer a major domestic health issue.

Military-driven innovation proved long lasting

Role of government

In a sudden crisis, governments can play a crucial role by mobilizing forces, redirecting funding and coordinating the efforts of the public and private sectors. They may design innovation policy to meet a specific need, but the effect of the policy can persist long after the crisis is solved. The OSRD, for example, funded certain industries in order to gain a technological and military advantage. However, the results of those innovations are still benefiting civilians in the United States and elsewhere.

A government's agility in responding to an emerging crisis usually depends on how well prepared it is to react. Innovation policy, the preparedness of institutions, the existence of communication and coordination channels among different bodies – public, private and academic – are a few of the pre-crisis conditions that can change the course and efficacy of any response. Prior to the Second World War, the U.S. Government did not have a systematic innovation policy. The NIH had existed since the 1930s, but its research budget and focus were limited. With the exception of agriculture, there was little federal funding for academic research. Nevertheless, the OSRD's newness and small size somehow played in its favor, freeing it from sluggish bureaucratic procedures. The U.S. Government gave it complete freedom in deploying financial and human capital and in coordinating efforts locally between the military and U.S. firms and universities, as well as internationally with scientists in Allied countries. The centralized and coordinated approach brought battlefield needs directly to the scientists' benches and gave scientists immediate feedback on the performance of their output.

To summarize, the OSRD's core features included the funding of largely applied research activities that focused on crisis resolution, the setting of priorities in close cooperation with the military and designing policies (including for patents) to engage the most capable researchers. Another notable feature was its willingness to fund multiple rival efforts when it was uncertain where solutions might lie. This was the case, for instance, in its malaria and penicillin research. The OSRD's involvement was not limited to offering guaranteed purchases and advance contracts. It also coordinated decentralized R&D efforts, supporting not just research but also downstream production and product adoption and generally prioritizing time (rapid crisis resolution) over money. In addition to national efforts, the OSRD was also in charge of international collaboration, including, for example, cooperation between British and U.S. scientists in penicillin research.

As noted, the OSRD's influence on U.S. innovation endured long after the end of the Second World War. Studies show that overall patenting by U.S. inventors was 50 to 60 percent higher after the war in the top OSRD-supported technological categories, compared with sectors that were not supported. Supported categories included nuclear, X-rays, communications (e.g., radar and radio navigation), semiconductor devices (e.g., transistors) and computer hardware and software.[15] In contrast, patenting in France and the United Kingdom (U.K.), where there was no similar government support, shows no such trend after the war. Clearly, the Second World War triggered a marked shift in the U.S. direction of innovation.

Box 2.3
Vaccines

Even before the Second World War, the U.S. Government (through the U.S. Army Surgeon General's Office and other departments) had begun research into vaccines for a range of infectious diseases, including influenza. A particularly virulent strain of influenza had killed millions of soldiers and civilians worldwide at the end of the First World War, with more people dying than during the four years of fighting. The military performed basic research and groundwork on several vaccines, including against pneumococcal infections, which can lead to pneumonia, sepsis or meningitis, and influenza. The Rockefeller Foundation supported academic work on vaccines. By the time the OSRD was formed, the scientific feasibility of several potential vaccines had been established. It remained to find methods to scale up production and evaluate the vaccines for safety and efficacy.[16] The CMR contracted academics and industry to improve yields, standardize concentrations and boost production. It worked with industry to produce enough vaccine for trials, and then funded the trials and field-testing. The main government role was coordinating the work to identify which serotypes were most prevalent in military populations and to develop, scale up and test a vaccine containing these serotypes. The military's advanced record-keeping systems and its high disease rates within a controlled population offered an ideal testing ground for vaccines. Hoyt[17] calculates that the wartime effort helped to develop new or improved vaccines for 10 of the 28 vaccine-preventable diseases identified in the 20th century, including tetanus and botulinum toxoids, Japanese encephalitis and yellow fever. However, some of these vaccines, such as that for Japanese encephalitis (a viral brain infection), turned out to be commercially unsuccessful due to the low rates of occurrence in North America.

Role of private sector

From the outset, private firms, particularly in the electric, chemical and pharmaceutical industries, were highly engaged in contributing to wartime innovation. The OSRD and the CMR adopted policies and designed contracts in a way that was appealing to private firms, providing funding, reducing the risks of investment and promoting communication linkages among private firms. For projects that were not deemed too sensitive to be made public, the OSRD allowed firms to register and hold patents, although often with the proviso that they should be licensed to government agencies when needed.

Nevertheless, at times of crisis, and especially in the early phases, the scope and boundaries of problems can be vague and evolve rapidly. High levels of uncertainty may discourage private actors' involvement. Private-sector participants may hesitate to bear advanced R&D and physical and human capital costs without the assurance of a return on their investments. However, the private sector can also be moved to act by factors such as altruism or reputational benefits. During the Second World War, some (though not all) firms actively sought to contribute out of a sense of patriotism.[18]

Participation in wartime innovation efforts could prove very beneficial for the private sector. Companies developed tacit knowledge and where they were able to retain or gain IPR, these and other advantages persisted long after the war. Mass production of penicillin would have been impossible without the innovative production processes introduced by companies such as Merck, Squibb, Lilly and Pfizer.[19]

Penicillin research efforts were the precursor of antibiotics' development by pharmaceutical companies in the post-war decades. Prior to the Second World War, Pfizer was a chemical manufacturer, which in the 1910s and 1920s developed a method of fermenting citric acid, a key ingredient in soft drinks. In the 1940s, it was contracted to help scale up production of penicillin based on this fermentation method. Its successful involvement in the program led to its discovery in 1950 of oxytetracycline, one of the first antibiotics.[20] The large-scale development of antibiotics triggered a sharp decrease in mortality from bacterial infections and an overall increase in life expectancy.[21] The discovery of oxytetracycline, combined with a corporate strategic shift, transformed Pfizer into a major pharmaceutical company. In 2020, it was one of the firms at the forefront of developing a COVID-19 vaccine to help contain the coronavirus pandemic.

OSRD's recruitment process was highly selective

Table 2.1 Top 10 universities with OSRD contracts by total value, 1941–1947

University	Total value (USD)	%
Massachusetts Institute of Technology	106.8	23.1
California Institute of Technology	76.6	16.6
Harvard University	29.1	6.3
Columbia University	27.1	5.9
University of California	14.6	3.2
Johns Hopkins University	10.8	2.3
George Washington University	6.9	1.5
University of Chicago	5.7	1.2
Princeton University	3.6	0.8
University of Pennsylvania	2.9	0.6
Total	**284.0**	**61.5**

Source: Gross and Sampat (2020b).
Notes: Percentages measure each university's share of total OSRD research spending.

Box 2.4
Blood substitutes

Another critical need during the war was for blood or blood substitutes to replace blood lost due to injury, hemorrhage, burns or surgery.[23] Substitutes had to be capable of being easily stored and transported to distant locations.[24] A team headed by the chemist Edwin Cohen led the research on blood transfusion. Cohen's lab isolated the human serum albumin and tested it in early 1941. By the time of the Pearl Harbor attacks in December of that year, it was being used to treat casualties.[25] The techniques refined during the war later became important in surgical recovery, maintaining blood volumes during shock, when blood pressure drops sharply, tackling clotting issues and many other medical conditions, including treating measles.

Another major figure in this field was Charles Drew, a U.S. medical researcher. He developed and improved techniques for blood storage, leading to the creation of large-scale blood banks in Britain by 1940.

Role of academia

Most of the scientific effort during the Second World War focused on applied research – research designed to resolve specific problems. However, the discoveries achieved during wartime would not have been possible without the basic research done previously in universities, research labs and hospitals. For instance, it was the lack of such pre-war research that limited the CMR's ability to develop a successful vaccine against anthrax, which it was feared could be used as a biological weapon. In contrast, by the time war broke out in 1939, British bacteriologist Alexander Fleming, together with a team of Oxford University researchers, had been working on penicillin research for years. Fleming discovered penicillin in 1929. While the team's attempts to purify the penicillin molecule in large enough quantities for human testing did not pay off in the 1930s, they paved the way for success during the war. In fact, Howard Florey, one of the Oxford researchers, traveled to the United States and joined forces with the CMR.[22] Another example is a team of researchers led by Edwin Cohen, a physical chemist from Harvard Medical School that spearheaded research on blood transfusion (see Box 2.4).

The OSRD's recruitment process was highly selective, concentrating only on the top universities. For instance, it placed over a third of all funding with just two institutions, MIT and the California Institute of Technology (Caltech) (see Table 2.1). Similarly, the CMR's collaboration with academia was also highly focused on a handful of elite universities (see Table 2.2).

CMR's academic collaboration concentrated in a few elite universities

Table 2.2 Top universities and hospitals contracted for penicillin and malaria projects, 1941–1947

Penicillin	Malaria
Massachusetts Memorial Hospital (66.6%)	University of Chicago (15.8%)
Cornell University (6.8%)	Columbia University (11.0%)
Johns Hopkins University (4.7%)	New York University (9.7%)
University of Michigan (4.1%)	Johns Hopkins University (8.7%)
University of Pennsylvania (3.67%)	

Source: Gross and Sampat (2020b).
Notes: Percentages measure each institution's share of total project research spending.

Box 2.5
Hormones

Even before the Second World War, research had begun on isolating, producing and administering hormones for a range of diseases and conditions, from constipation to obesity.[26] The CMR ramped up research on cortical hormones, which helped in overcoming altitude sickness in aviators and dealing with combat fatigue, treating battlefield trauma and in surgery.[27] After the war, hormone therapy took off and cortisone became a "miracle" drug in the decades that followed. Follow-on research showed that cortical hormones can reduce inflammation and relieve arthritic pain, as well as treating allergic-type reactions.

Case study conclusions

Crises, such as wars, pandemics and natural hazards, can be catalysts for technological, market or political forces that spur innovation. They are a shock to the innovation system and affect various parameters of the technological ecosystem. The impact of crisis innovation can be long lasting where demand persists and the solutions remain applicable. Otherwise, once the crisis dissipates, so will the impact.

The story of the OSRD is one of crisis innovation, but with a special characteristic: it had a sole customer – the military. The OSRD had a top-down, centralized approach and recruited only a small number of elite scientists, firms and universities. Other crises, such as pandemics, might need to cater to a diverse range of customers. It might then be more appropriate to take a more decentralized approach and engage a broader range of collaborators.[28]

The OSRD's institutional and administrative approach to innovation continued to be reflected in the postwar U.S. innovation system. For instance, the OSRD's contracting style, which purchased R&D rather than specific products – a revolutionary idea for its time – became the basis for an emerging extramural research grant program at the NIH.[29] The NIH's postwar, peer-review system was also modeled on the CMR approach. CMR used medical scientists from the NRC to review and grade the feasibility of projects of interest to the military and eventually fund the high-scoring ones.[30]

The medical discoveries driven by the CMR benefited from research efforts made before the war. Follow-on medical innovations in subsequent decades continued along the same scientific path, as more and more civilian applications were found. While the development of penicillin, antibiotics, hormone therapy and similar discoveries was revolutionary, the innovative path that led to them was cumulative and therefore somewhat predictable (see Chapter 1).

2.2 Space industry[31]

A classic case of mission-oriented innovation

Rapid economic expansion and national security concerns characterized the 1950s and 1960s. Geopolitical tensions between the United States and the Soviet Union resulted in military and technological rivalry. Space programs in both countries were born out of an ambition to be the first to put a man on the Moon as a symbol of power and leadership in the aeronautical and space technology. While the motivation in both countries was similar, their innovation ecosystems differed. This case study focuses on the U.S. ecosystem. The Cold War led to an expansion in U.S. federally-funded R&D, with "mission-oriented" R&D (such as the mission to the Moon) dominating the U.S. innovation funding landscape.[32] But funding, although crucial, was not the only essential ingredient for innovation in the U.S. space program. Technical ability and organizational capability, coupled with political will and close collaboration between public, private and academic entities, were also necessary.

Innovation in space endeavors had two goals. First, getting into space and, second, being able to function once there. Technologies developed for the man-on-the-Moon mission had to overcome some special problems – three in particular. First, there was the question of reducing mass (both weight and volume) (see Box 2.6); second, there was the need to generate and store energy (see Box 2.7); and, finally, human beings and the equipment had to be protected in a harsh environment. Many of the technologies developed had later civilian applications that, in turn, gave birth to completely new technologies. Solar panels, artificial intelligence (AI) and computer hardware and software are examples of such technologies (see Box 2.8). These technologies are also examples of unintended directional change in innovation (see Chapter 1). They are by-products of intended (mission-oriented) innovation that later developed in unpredicted ways.

This case study discusses the key technologies of the space industry and how their maturation from the 1980s onwards has provided opportunities for the private sector to enter the industry. It presents some examples of innovation in energy storage, digital processing, computers, AI and carbon fiber composites. Finally, it suggests potential avenues for further innovation.

Box 2.6
Carbon fiber

The aerospace industry has been the primary driver of the carbon fiber and carbon fiber reinforced plastics (CFRP) industry. Carbon fiber was first tried out during R&D efforts at the U.S. Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA), largely driven by the need to find low-mass materials (both in weight and in volume) to make spacecraft bodies. Since escaping Earth's gravity to reach space requires a huge amount of energy, lightweight materials were – and still are – an essential component in optimizing the available rocket's propulsion system and getting as much payload into space as possible.

Carbon fiber's extraordinary mechanical properties (its strength, conductivity and lightness) were valuable enough to justify its high price. Its light weight improves energy efficiency. Carbon fiber can also be molded into virtually any shape. Each mold can be designed so that several different parts are combined into one mold, thereby significantly reducing the number of parts needed to build a spacecraft. This property resulted in improved manufacturing and assembly times and the potential to reduce costs. Carbon fiber also offered additional benefits in space exploration, such as enhanced thermal protection and greater solar radiation resistance.[33] The Apollo capsule launched in 1969 used early composite technology, such as fiberglass, in the form of a heat shield. Since Apollo, carbon fiber technology has advanced and has been used in launch vehicles, the Space Shuttle, satellites, space telescopes and the International Space Station (ISS).[34] But carbon fibers are brittle and not bendable, which can limit their use, and the manufacturing process is highly specialized.

Demand for these specialized products is still scarce. Research is ongoing to replace traditional fiberglass blades in wind turbines with optimized carbon fiber blades. Using carbon fiber, blades can be made larger but with reduced mass, which results in the harnessing of greater amounts of energy. As more civilian applications become viable, the use of carbon fiber will become more cost effective.

The race into space

The end of the Second World War saw the emergence of a fierce struggle for power between the United States and the Soviet Union. One aspect of this competition was the development of advanced rockets, mainly for military purposes. In late 1957, the Soviet Union surprised the rest of the world by being the first country to launch a satellite (Sputnik 1) into low Earth orbit. Shocked, the United States responded by establishing NASA a year later. This new civilian agency was put in charge of the peaceful and scientific exploration of space. In a famous speech to Congress in 1961, U.S. president John F. Kennedy announced a program to put a man on the Moon by the end of that decade. Great political commitment and a large budget, coupled with NASA's and the scientific and engineering community's technical ability, saw the goal achieved in October 1969.

But with the mission accomplished, U.S. governments began redirecting federal funding away from large-scale human space exploration programs and cut NASA's budget. Instead, NASA was commissioned to design and fly a new space vehicle – the Space Shuttle – that could be reused in providing human and robotic access to space. In 1972,[35] President Richard Nixon approved the shuttle project. It maintained the human spaceflight program as a symbol of U.S. space leadership and had national security uses. But the principal reason for backing the shuttle was its promise of routine flights and lower costs.

During the late 1960s and 1970s, other nations also developed space capabilities. The European Space Research Organization merged with the European Launch Development Organization to create the European Space Agency (ESA) in 1975. During the mid-1970s, Canada also started cooperating with the U.S. space program, notably in the development of Canadarm, a robotic arm for maneuvering rocket payloads. By the 1980s, many nations had developed telecommunications satellites and most nations were actively involved with Intelsat, an intergovernmental organization developing the worldwide use of space telecommunications.

By the end of the century, the space programs had spawned telecommunications satellite technologies and fueled commercial involvement in space activities. A competitive commercial space sector, with new commercial space actors, is becoming an important component of all space programs in the United States and in other countries. During the first decade of the 21st century, companies and industries began to invest in and rely evermore heavily on space technologies, beginning with telecommunications services. Advanced industrial economies have become increasingly dependent on space systems for their IT, remote sensing imagery, position, navigation and timing (PNT) data and other applications.

Who is at the controls?

Role of government

Ever since their inception, space programs in almost every country have been mainly a national security issue and a symbol of technological progress. Governments are the main drivers behind two of the three defining features that set the direction of innovation in this field – political will and funding. The third element is the technical ability of, and advances made by, scientists and engineers in the private sector and academia. Various U.S. government bodies, including NASA, the DoD and the Department of Energy (DoE), have been behind multiple innovations in the space industry. For instance, the Global Positioning System (GPS) of satellites, which features in a huge range of civilian devices, is a U.S. DoD developed, owned and operated PNT system. While NASA was created to conduct all non-military space activity, the Advanced Research Projects Agency (ARPA), today known as Defense Advanced Research Projects Agency (DARPA), was set up in February 1958 to develop space and other technologies for military applications. Many other space products, such as remote sensing satellites, which allow, for example, the remote collection of information about the Earth, have also stemmed from military needs. Although space programs have historically had the Government as a primary customer, there have long been private clients too. For example, in 1962, a private telecommunications satellite called Telstar, owned and operated by AT&T, was launched. It even had private insurance cover and at the time it was famous enough for a top-selling pop record to be made about it. In recent years, a new wave of private and commercial markets have emerged for space products.

Box 2.7
Energy storage

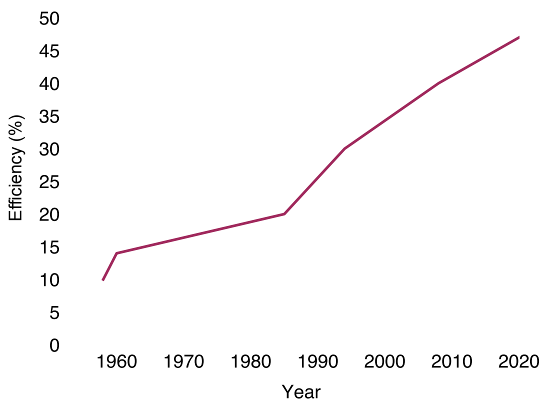
Space missions require reliable, consistent and safe energy sources. Energy-related technologies and innovations have enabled and enhanced deep space exploration, human space flight and space-based terrestrial services. Two energy-related technologies are briefly described below.

Photovoltaics
Modern solar cells that can harness the Sun's energy were first developed by physicists at the Bell Laboratories in the United States in 1953. However, due to their high price, silicon solar cells could not find any practical application until the U.S. military decided, in 1958, that they would be the ideal power source for Earth-orbiting satellites.[36] Since then, several incremental advancements have been made to increase the amount of sunlight that the cells can convert into energy. The percentage of sunlight converted is known as the cells' efficiency (see the graph below).

Despite their ubiquity in space equipment, solar cells have some limitations. These photovoltaic systems do not generate energy when in shadow and their generating capacity declines with increasing distance from the Sun. If a mission requires continuous, uninterrupted energy, a combination of energy sources might be more suitable. However, if interruptions, occasional shutdowns and hibernations are acceptable, solar panels can be an excellent, long-lasting source of energy. The Opportunity robot rover, one of NASA's most successful Mars exploration programs, was launched in 2003 with an expected lifetime of 92 (Earth) days. It suffered multiple shutdowns due to dust accumulating on its solar panels. However, thanks to the winds raging on Mars, which regularly cleared away these dust build-ups, the rover operated successfully for over 14 years, 57 times longer than its initial life expectancy.[37]

Photovoltaic improvement during the space age

Figure 2.1 Solar efficiency, in percentage, 1960-2020



Source: Department of Energy.
Notes: These data represent the efficiency achieved under ideal lab conditions. Practical state-of-the-art solar cell efficiency in space is approximately 30 percent.

Nuclear energy
Nuclear power has been seen as a potential energy source for space exploration since the 1950s. Its history of performance and reliability seemed to provide a secure foundation for developing future uses. However, only a limited set of nuclear energy technologies have been thoroughly exploited. Several projects have been terminated due to budgetary and safety concerns. Radioisotope power systems (RPS)

are an exception, with hundreds of space applications since 1961.[38] The RPS convert heat generated by the natural decay of plutonium-238 – a radioactive isotope – into electrical power.[39] The European Space Union, the People's Republic of China, the Russian Federation and the United States have all continued to be innovative with RPS technologies, improving their design and the materials used to achieve greater efficiency and safety.[40]

Role of the private sector

Private companies in the United States have always been integral to space innovation. From the very beginning, about 80 percent of NASA's funding has been spent on contracts with industry. However, as noted, it is only recently that private companies have begun to invest in and rely heavily on space systems. Although private funding has increased drastically in the 21st century (see Figure 2.2), there is an important caveat relating to private sector investment and innovation in space technologies. Very few of the successful "new" space companies operate in a truly price-driven market. Without sales to governments, many of these companies would not exist. Space Exploration Technologies Corp. (SpaceX), which now designs, manufactures and launches advanced rockets and spacecraft, had its initial infusion of substantial funding through NASA's Commercial Orbital Transportation Services program in the early 2000s. This provided hundreds of millions of dollars for a new launch vehicle to resupply the ISS, a collaborative, multinational space station in low-Earth orbit. SpaceX has been successful in winning very large and long-term government contracts from both NASA and the DoD. The company has many private customers as well. But without the government business, it is questionable whether there would have been enough launch business to support these types of products.

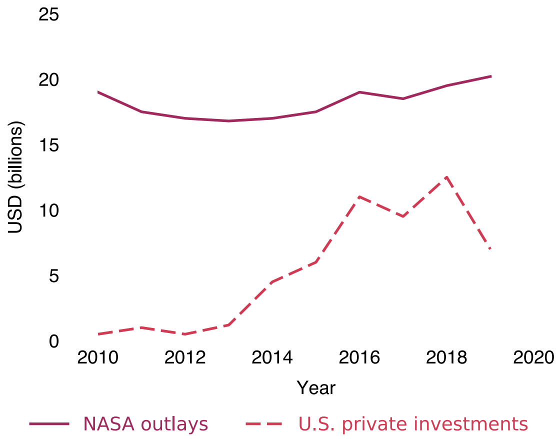
Summer 2021 in the northern hemisphere saw private jaunts into space by companies such as SpaceX, Virgin Galactic and Blue Origin, all of which have billionaire backers. Despite the media frenzy, it is too early to say if this is the dawn of private space tourism, because the huge cost limits such trips to the ultra-rich, for now.

Role of academia

In December 1958, soon after its creation, NASA gained control of the Jet Propulsion Laboratory (JPL), a contractor facility operated by Caltech. University labs have long been one of NASA's main collaborators. One could argue that today's personal computers were born at the MIT labs (see Box 2.8). Universities have also been the main producers of NASA's astronauts, with around 40 NASA astronauts being graduates of MIT, Purdue and Stanford universities.[41]

Space private investment booms, but still outclassed by space public funding

Figure 2.2 NASA outlays and U.S. private investments on space, 2010–2019



Source: WIPO based on U.S. Government (2021) *Economic Report of the President*, figure 8.1, p. 229.

Box 2.8

Digital processing, computers and Artificial Intelligence (AI)

The history of early computers is closely associated with the history of spaceflight. The Apollo program, launched in 1961 to meet Kennedy's goal of reaching the Moon, was the starting point for the use of computers, microchips and automation in space exploration.

Microchip technology

Borrowing from aeronautical technologies, space exploration gradually employed computerized systems to assist with tasks such as navigation and guidance. The very high costs of accessing space underscored the need for smaller and lighter components for onboard technology systems. Integrated circuits, commonly known as microchips, have been particularly attractive for spacecraft. They tend to be notably smaller than traditional electrical circuits, consume less power, increase operational speed and offer incremental reductions in costs per electronic function.[42]

The Apollo guidance computer

NASA wanted a more autonomous system for the Apollo missions to deal with the potential navigation, guidance and flight control issues that might occur. MIT Instrumentation Lab become the main contractor for the design, development and construction of the Apollo guidance computer's (AGC) hardware and software systems.[43] This was the first time a manned spaceflight program had used computers continuously in all mission phases. The MIT lab had a partnership with Fairchild Semiconductor to supply silicon microchips for the AGC, which became the first computer to be based on them. The decision to use silicon microchips was a bold one, since the technology had not yet been widely tested.[44] The AGC was successfully used on Earth-orbital missions, all lunar-landing missions, Skylab missions and the 1975 joint U.S.–Soviet project, Apollo-Soyuz. The AGC's multiple technological innovations, including its hardware, software and microchips, were set to revolutionize not only onboard spacecraft computers, but also the computer consumer market for the next half century.

Artificial intelligence

AI can be broadly described as algorithms capable of accomplishing tasks that traditionally required human intelligence to complete. NASA developed AI to substitute for the decision-making of mission controllers on Earth since telecommunications latency between the Earth and Mars makes real-time decisions for robotic missions impossible.[45] Successive inventions made computer processing faster, chips lighter and integrated software more specialized. Today, AI is built into our way of life. Navigation apps use AI to analyze the speed of road traffic; smart vacuum cleaners use AI to scan the size of a room, identify obstacles and determine the most efficient routes. AI is fundamental to the operation of autonomous road vehicles.[46]

Most innovations to come out of NASA did not find immediate, scalable and commercial civilian demand

Case study conclusions

The story of the U.S. space program is a classic case of mission-oriented innovation.[47] The innovation efforts also had specific characteristics. They had a primary customer: the Government or one of its agencies. NASA leveraged private enterprises and universities effectively by aligning its goals and objectives with their research activities. While NASA's approach has varied in terms of degrees of involvement and autonomy given to its contractors, it has remained mainly centralized, largely defining targeted, niche tasks for its contractors. Space programs are complex projects that deal with various fields of technology. NASA's role has been to coordinate and bring together scientists and industries from different disciplines to share knowledge and accomplish a single objective.

Mission-oriented innovations draw on cutting-edge knowledge to attain targeted, well-defined goals within a specific timeline.[48] NASA's man-on-the-Moon mission can be considered a success as it achieved its goal by its original target date.[49] NASA's approach has predominantly focused on articulating and specifying the problems and bottlenecks rather than imposing solutions on its contractors. Moreover, opting for a wide but relevant range of expertise helped it to come up with solutions that bridged otherwise separate fields of technology. Timely monitoring of the alignment of actions and resource allocation, to avoid straying from the original goal, was another strength of NASA's innovation approach. Could a similar approach work for dealing with some of today's great global challenges? Chapter 3 will expand the discussion on what innovation policies could be needed.

Most innovations to come out of NASA did not find immediate, scalable and commercial civilian demand. However, these innovations proved to be incubators for several technologies and industries.[50] Albeit with varying degrees of time lag, many of those technologies have served as the base for derivative, largely unintended and yet immensely important civilian applications. Charged-coupled device (CCD) sensors, which contain grids of pixels, stemmed from NASA's goal to design and build the Hubble Space Telescope,[51] a space-based observatory first launched in 1990. Hubble's CCD sensors allowed for high-quality deep-sky imaging. CCD sensors became a multi-billion-dollar industry, ubiquitous in everyday products, such as webcams and smartphone cameras. This is a case in which the civilian follow-on innovation path that emerged out of a NASA program was neither straightforward nor predictable.

The U.S. and Soviet space programs emerged from geopolitics. But several programs born afterwards in other countries have had more earthly commercial goals, focusing more on applications in telecommunications, navigation and the satellite industry. This

The short life cycle of high-tech innovation, combined with interventionist government policies created windows of opportunity for learning and catching up

holds true for the ESA and probably is its main contrast with NASA. In the past few years, several other large and small countries, including more than 20 African ones,[52] have joined in the exploration of space. The falling costs of satellite technology and the "disruptive" nature of its development, which means that, as with IT, some phases can be skipped, facilitating the entry of latecomers, have created windows of opportunity for smaller developing economies. The next case study elaborates on these concepts by looking at the IT industry in East Asia.

A return to the Moon is back on the agendas of the major space agencies, such as NASA and the ESA. The technical objectives may differ but the competitive pressure – this time from China's space program – remains. Moreover, envisioned projects, such as a mission to Mars or even the creation of permanent human settlements on the Red Planet, require close collaboration between governments, private companies and academia. Cooperation will be needed for the development of propulsion systems, for the development of technologies to provide protection from cosmic rays and for finding sustainable energy solutions. The same goes for projects such as the cultivation of foodstuffs on the Moon and the extraction of lunar resources. Opinions are split on whether space programs are an efficient use of R&D recourses. But the new space rivalry between the United States and China may trigger innovative – and unpredictable – technologies in the decades to come.

2.3 Rise of IT in East Asian countries

Leapfrogging into the lead

The direction of innovation in East Asian economies during the past 60 years is intertwined with their development and economic catch-up stories. These economies stand out in having nurtured cutting-edge technological capabilities in several sectors. In recent decades, the emergence of leading innovators in a broadly defined IT sector has been a central and recurring feature of the region's economic development. For instance, Japan's industrial rise is closely associated with its burgeoning consumer electronics industry in the 1970s and 1980s. The Republic of Korea and Taiwan Province of China subsequently emerged as leading innovators and suppliers of semiconductors and computer monitors. China's more recent growth has gone hand in hand with the rise of its communications and Internet-based companies.[53]

Many of the scientific breakthroughs in and initial commercialization of products underlying the IT industry took place elsewhere. But the East Asian economies managed to acquire the knowledge behind these technologies, "leapfrog" into the latest product cycles and engage in world-leading product innovation. So much so that the East Asian region is currently playing an important role in shaping the direction of innovation in the IT industry globally.

Characteristics of the IT sector can partially explain the success of the East Asian region in this sector. It combines rapid technological change with a short product life cycle and promises quick and high returns to investments. Frequent innovation can quickly make incumbent technologies outdated and therefore lower the entry barriers for a latecomer. Another prominent factor is the role of East Asian governments and the development policies that have nurtured IT innovation in the region.

This case study takes a brief historical look at industrial policy in the region, particularly in mainland China, the Republic of Korea and Taiwan Province of China. It discusses the mechanisms through which technological development in the IT industry has happened in these economies. It elaborates on how windows of opportunity allowed them to leapfrog into different sub-sectors of IT. Finally, it discusses the role of IP in technological development in East Asia.

Rapid modernization and high-tech investment

East Asia has experienced accelerated growth over the past few decades, particularly compared to other regions, notably Latin America and Africa. Although initiated at different times, East Asian countries' steady growth has been thanks to rapid modernization and investment in high technologies. Starting with Japan in the 1960s and 1970s, the main IT products that East Asian economies produced and exported were labor-intensive and low-end consumer products, such as radios, small (analog) calculators, televisions (TVs) and refrigerators. However, the short life cycle of high-tech innovation, combined with the interventionist government policies described below, created windows of opportunity for learning and catching up. The 1980s saw the East Asians enter the markets for personal computers (PCs), videocassette recorders (VCRs), audio cassette players and telecommunication equipment, like fixed-line telephone switches and fax machines. In the 1990s, came memory chips and wireless cell phones, and the 2000s brought various digital products, including digital TVs, wireless telecommunication systems and smartphones.

Economists and historians have long tried to explain the Asian success story through different models, with the "Flying Geese Model" and the "Best" model[54] being the most frequently cited. Japan's economic take-off between 1955 and 1975 spilled over into a similar take-off in the Republic of Korea and Taiwan Province of China in the 1970s and 1980s. The "Flying Geese Model" sees Japan as a role model for economic policy and as a supplier of technology and finance for the labor-intensive, export-oriented industrialization in neighboring Asian economies. This model, however, does not fit the rise of China after 1980. The size of the Chinese market and the diversity of industry at various levels of development, along with the complexity of relations between local and central governments in China, necessitate two or more model types.

Looking at strategies for learning and gaining access to a foreign knowledge base, for example, some unique Chinese features can be observed. First, there has been an emphasis on so-called forward engineering, through which new or nascent scientific and technological knowledge is acquired in university labs before being applied in a top-down fashion to the development of commercial products. This is most visible in the creation of spin-off firms from Chinese universities, which are discussed further below. This approach contrasts with the reverse engineering of the Republic of Korea and Taiwan Province of China,[55] in which know-how was developed in a bottom-up process, by autopsying imported products.[56] Second, China has acquired technology and brands through international mergers and acquisitions.[57] Finally, it has used parallel learning from foreign direct investment firms to promote domestic companies.[58] These three elements can be considered to comprise the "Beijing" model, as they have not been explicitly adopted by either the Republic of Korea or Taiwan Province of China.[59]

Despite the variations, the development of all East Asian economies has common elements. These include economic catch-up, promotion of the capabilities of private firms and industries, and government measures to reduce the risks involved for firms entering new industries. This is the "Best" (Beijing–Seoul–Tokyo) model. Governments promoted their firms' capacity building via four avenues. First, they arranged access to the existing knowledge base and learning opportunities through, for example, government research institutes and consortiums. Second, they encouraged export-based engagement with the global economy as a means of acquiring further knowledge. Third, they selected industries/technologies for development and promoted import substitution to make their markets less lucrative for foreign firms. Finally, to avoid companies being restricted to producing low-margin or low value-added products, governments encouraged the constant upgrading of firms' activities in value-added terms, either within the same industry or by moving to new, higher value-adding industries. For example, Taiwanese firms moved from electronic calculators to laptops, because the old industry had matured and was degrading into a low value-adding business.

Path-following or path-creating?

Firms can follow different trajectories for catching up in the IT sector. One way is to evolve from being a so-called original equipment manufacturer (OEM) – making components for use by another company – to being an original design manufacturer (ODM), which includes both design and production. The final step is to become an original brand manufacturer (OBM).[60] In the initial stage, a customer – usually a foreign multinational corporation (MNC) – subcontracts the OEMs to produce a finished product in accordance with certain specifications. ODMs are more technologically advanced and can both produce and conduct most of the product design process, while the customer firm runs the marketing operation. In the TV industry in the late 1960s and 1970s, Taiwanese firms were mainly OEMs. As local Taiwanese engineers working in these firms mastered the design skills, they left and started their own original design manufacturing firms.

OBMs work on their own brands, designing and manufacturing new products, conducting R&D and managing sales and distribution. However, upgrading from OEM to ODM and then to OBM is not easy or straightforward, and it does not necessarily take place in a linear manner. Firms may skip a stage and directly start from the next one. For example, many Korean IT firms decided to start out with their own brands.

Transition and catch-up can follow the three patterns listed below.[61] First, there is a "path-following" catch-up, which means that the latecomer firm follows the same linear path taken by its forerunners, but in a shorter time. The second pattern is a "stage-skipping" catch-up, where the latecomers follow the path but skip some stages. The third pattern is a path-creating catch-up, which means that the latecomer firms create their own path of technological development. For example, in the 1980s, when Samsung was considering producing 16K-bit dynamic random-access memory (D-RAM) chips, the technology was going through a period of transition. Samsung took advantage of this window of opportunity and skipped directly to the production of 64K-bit D-RAM. In doing so, it jumped ahead of other firms that, due to inertia, had not yet initiated 64K-bit D-RAM production.

In general, industrial catch-up processes can be closely tied to the characteristics of a particular sector. In sectors where innovations are infrequent and highly predictable – which is not the case in IT – path-following or stage-skipping strategies by private firms may be enough. But in sectors like IT, where technologies are highly fluid, involve high risks and have large capital requirements, a successful catch-up may require public–private collaboration and a path-creating strategy.

Role of government

In the East Asian context, the governments' role in steering the direction of innovation is centered on the development and catch-up phase. Government policies have aimed at accessing existing knowledge and reducing uncertainty for local private firms. For instance, in the Republic of Korea, private firms were helped during the early days by government research institutes (GRIs) granting them free or cheap access to their R&D results. They were also able to participate in public–private R&D consortiums for their large-scale and high-risk projects. In 1989, the Korean Government established a committee for co-development of high-definition TV, with the participation of 17 institutions, including private firms, GRIs and universities.

Additionally, Asian governments have provided export subsidies for local private firms to promote their entry into the global economy and as a means for them to gain knowledge. Another notable government intervention has been through the targeting of industries/technologies for development and by promoting import substitution. They achieved this by controlling the number of new entrants in a certain sector to ensure that the sector benefited from stable profits. Entry control has been one of the key elements of Japanese industrial policy.[62]

Role of the private sector

The private sector has also been playing a very important role in steering the direction of innovation in East Asia. Although the timing has been different for each country, the local IT industry has managed to catch up and surpass Western IT firms. The transition of Taiwanese private small and medium-sized enterprises (SMEs) from OEMs to ODMs peaked in the 1980s in the electronic calculator era. This then prompted companies like Acer, a Taiwanese firm, and others to enter the laptop PC and cellphone markets (see above).[63]

Korean companies Samsung and LG are among the leading global technology firms. Samsung started as a textile and refined sugar company and did not enter the electronics market until 1969. However, by emphasizing economies of scale, vertical integration and large investments in R&D, Samsung not only became a large OEM, but also one of the top global OBMs.

A similar pattern was evident in China toward the end of the 20th century, with firms like Huawei and ZTE evolving to become leading global OBM firms. In more recent years, China has successfully generated three giants in the platform business, where firms harness and create large, web-based networks of users and resources that can be accessed on demand. These firms – Baidu, Alibaba and Tencent – are leading China into the era of the Fourth Industrial Revolution, and their status and businesses are considered to be on a par with Google, Amazon and Facebook.[64] Their stellar performance in the realms of platform and e-commerce businesses is due to their successful combination of technical ability and a deep knowledge of China's large local market. In other words, they show remarkable agility in both developing cutting-edge technology and adapting it to the Chinese context.

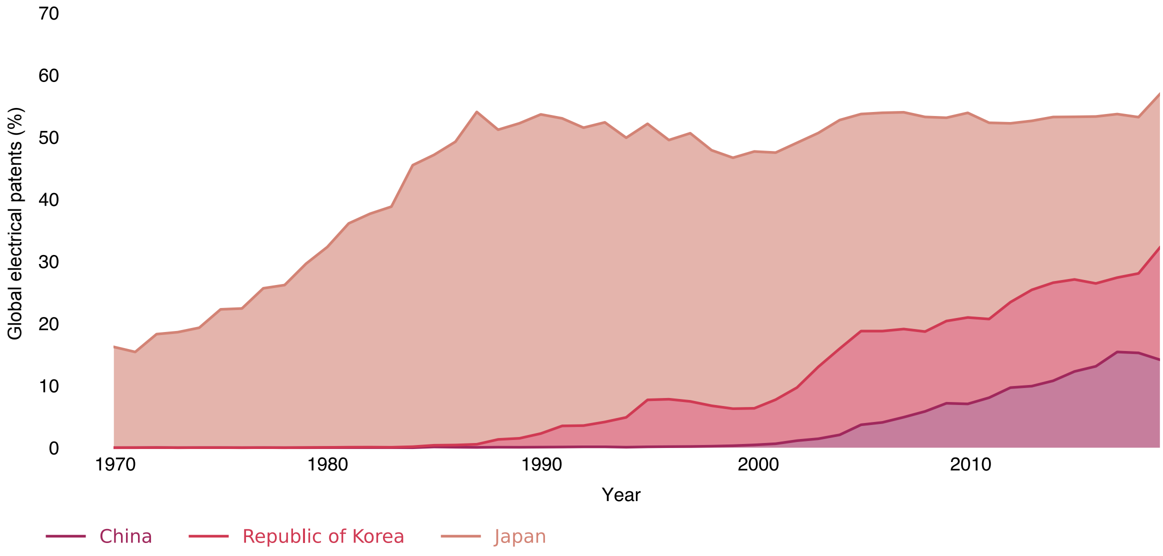
Role of academia

East Asian governments have strengthened their education systems remarkably over the years, from primary school through universities, which has provided industry with a large pool of skilled labor. In the early days of technological rise, these governments supported students going abroad to study engineering and science, but increasingly they have built up their own strong university systems. This has required large and ongoing public investments. For instance, China has put huge emphasis on academia and the building of basic scientific knowledge. China has also benefited from a reverse "brain drain," with many Chinese graduates from leading Western universities returning to become professors and/or found their own companies.[65]

Many Chinese universities run their own businesses, which differ from ordinary spin-offs. Not only does the university established them, but it also staffs, funds and managerially controls them.[66] An example of a university spin-off is Lenovo, the multinational technology company, which was founded in 1984 in

Asian economies dominated global innovation in electrical-related technologies within a few decades

Figure 2.3 Share of global electrical patenting, selected Asian countries, 1970–2018



Source: European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT, October 2021).
Notes: Based on WIPO technological fields applied to first filings only. Global electrical patenting refers to worldwide patenting in audio-visual technology, basic communication processes, computer technology, electrical machinery, apparatus and energy, IT methods for management, semiconductors and telecommunications.

Beijing by a team of 11 engineers from the Institute of Computing Technology of the Chinese Academy of Sciences. The first listed software company in China is also a university spin-off, Dongruan, which is run by Dongbei University in Shenyang. Universities and industry have a relatively close relationship in China, in contrast with the situation in Japan and the Republic of Korea where historically universities have had only weak, indirect relationships with industry. Overall, academia and scientific institutes, at least in the early stages of development of the East Asian economies, have not generally been as pivotal in terms of economic development as government ministries and the private sector.

Role of intellectual property rights

Intellectual property rights are important in IT technology because products are often made of a slew of components that rely on a wide range of complex technologies. These technologies are cumulative, rapidly advancing and have a short shelf life. The technologies that go into a smartphone, which consists of around 2,000 physical parts, range from semiconductors, batteries, memory and storage, cameras and sensors to computer or communication technologies.[67]

No single firm owns all the patents associated with these technologies. However, incumbent IT firms tend to hold large patent portfolios to minimize the need for third-party patents and to increase their royalty revenues from firms whose technology might rely on these patents.[68] East Asian economies realized this early on and promoted patenting by their domestic firms as they entered and gained a foothold in the global IT market. For instance, Texas Instruments' litigation with Samsung over semiconductors in the 1980s spurred the Korean Government and Samsung to invest heavily in patents. The surge in IT patenting in East Asian economies is illustrated in Figure 2.3.

Over the past two decades, the geography of standard essential patent (SEPs) ownership has also gradually changed, with the emergence of new technologies and the growth of shared platforms, such as the Internet. An SEP is a patent that a manufacturer needs to use to produce a standard-compliant product. SEP holders commit to license them on fair, reasonable and nondiscriminatory (FRAND) terms. SEP holders sometimes also manufacture the standard-compliant product that incorporates their own SEPs.[69]

East Asian economies have come to dominate SEPs in several new IT technologies, wireless technology being an example. Several current and future technologies rely on 5G – the fifth-generation mobile network. Examples include autonomous vehicles, smart homes and wearable health monitors, which are among those devices and objects collectively known as the Internet of Things (IoT). The SEPs necessary for IoT and 5G technologies are dominated by East Asian companies (for example, LG, Samsung, Panasonic, ZTE, Huawei, Haier and NEC), followed by U.S. companies (such as Cisco, Microsoft, Google/Alphabet, Microsoft, Qualcomm, Apple and IBM) and European companies (Ericsson and Nokia).

Case study conclusions

Understanding the innovation path that East Asian economies have taken can provide invaluable insights for other developing economies. Therefore, it is important to understand the idiosyncrasies, too. First, despite the rivalry and historical differences among East Asian economies, technological changes in one have eventually spilled over to neighboring economies. Second, their technological catch-up has been closely correlated with an upswing of the IT industry in the region. Technological change in the IT industry has specific characteristics that facilitate this process. Government policies were tailored to these characteristics to promote the building and enhancing of capabilities in the private sector. Mere replication of these policies under different contexts in other industries might not yield the same results. Chapter 1 expands on these concepts by discussing the current needs of developing countries.

The impact of the East Asian development paradigm on the global direction of innovation has also been immense. East Asian economies have provided the global market with low-cost IT products. They have also contributed to various incremental process and product innovations when manufacturing these low-cost goods. However, their innovative contribution is not limited to these aspects. By generating cutting-edge technologies, East Asian economies are also contributing to the future direction of innovation in the third and fourth industrial revolutions.

2.4 Chapter summary and conclusions

The direction of innovation has taken many turns, particularly since the second half of the 20th century. Chapter 1 discussed the various conceptual elements behind the shifts in direction. This chapter provides three historical instances that exemplify those conceptual elements – the Second World War, the space race and the rise of the IT industry in East Asia.

Innovations born out of the efforts of the OSRD and the CMR are textbook examples of crisis innovation (that also have some elements of mission-oriented innovation), whereas the man-on-the-Moon program represents archetypal mission-oriented innovation. The rise of IT in East Asia is a classic development story. There are some similarities and differences between the approaches and methods adopted in each example. The OSRD and NASA both adopted a top-down, centralized approach to articulating problems. They both engaged universities and private firms to achieve their objectives. Apart from providing human, physical and political capital, their crucial contribution was the bringing together, organization and management of the diverse elements at their disposal. The importance of this function cannot be overstated. The main role of government in both cases was knowledge brokerage – that is, creating direct channels for communication and coordination among the participants, which reduced redundancy and increased efficiency.

A key difference between the three case studies is the nature of the associated demand. In both the Second World War and in the space race, the U.S. Government drove demand as the initial and primary customer. In the case of IT development in East Asia, demand was driven by large commercial markets, both domestic and foreign. The main role of the East Asian governments was in supporting domestic private firms with policies that reduced risk and facilitated their access to cutting-edge knowledge. Another difference was the speed at which demand had to be met. The urgency of war meant that innovation needed to be developed rapidly. While speed was also important in the astropolitical competition between the United States and the Soviet Union, the timeline of both the space race and East Asian IT innovations was longer. The nature of and the time lag until the follow-on innovations and industries that emerged afterwards also differed. Many of the innovations born out of the efforts of the OSRD and the CMR, like vaccines and penicillin, found immediate civilian markets after the Second World War. Innovations coming out of the space programs, like AI and solar panels, which were at the scientific frontier at the time, took longer to take off. Once they did, their impact became immense. Many other innovations created for the space program were highly specific to that program and had virtually no direct commercial applications (a fact that is still true today). However, applications of the innovations were often generic enough to have long-term impacts on different commercial products and services.

With the world facing grand global challenges, such as climate change, whose solutions require new ideas and innovations, it is important to recognize moments in history when society has spurred dramatic technological changes. As shown in the three case studies, there are many ways in which governments and markets can interact with each other, which in turn can have short- and long-term implications for the direction of innovation.

Notes

1 This case study draws on Sampat (2022).
2 See Gross and Sampat (2020b).
3 See Gross and Sampat (2020b).
4 OSRD's predecessor agency, the National Defense Research Committee (NDRC), was formed in July 1940.
5 See Bush (1970).
6 See Gross and Sampat (2021).
7 See Gross and Sampat (2021).
8 See Neushul (1993).
9 See Neushul (1993).
10 See Achilladelis (1993) and WIPO (2015).
11 See Swann (1983).
12 See Brabin (2014).
13 See Andrus (1948).
14 See Slater (2009).
15 Gross and Sampat (2020a).
16 See Hoyt (2006).
17 See Hoyt (2006).
18 See Gross and Sampat (2021).
19 See Agarwal *et al*. (2021).
20 See Gross and Sampat (2021).
21 See WIPO (2015).
22 See Gross and Sampat (2021).
23 See Andrus (1948).
24 See Creager (1999).
25 See Creager (1999).
26 See Rasmussen (2002).
27 See Rasmussen (2002).
28 See Gross and Sampat (2021).
29 See Swain (1962) and Fox (1987).
30 See Fox (1987).
31 This case study draws on Hertzfeld et al (2022).
32 See Smith (2011).
33 Visit https://technology.nasa.gov/patent/TOP2-226.
34 Visit https://www.compositesworld.com/articles/composites-in-space(2).
35 Visit https://www.nasa.gov/feature/50-years-ago-president-nixon-directs-nasa-to-build-the-space-shuttle.
36 See Perlin (1999).
37 See O'Neill (2014) and visit https://en.wikipedia.org/wiki/Opportunity_(rover).
38 See Bennett (2021).
39 Visit https://www.energy.gov/ne/office-nuclear-energy.
40 See Cataldo and Bennett (2011).
41 Visit https://www.usnews.com/education/best-colleges/slideshows/12-colleges-that-have-produced-the-most-astronauts.
42 See Mathematica, Inc. (1976).
43 See "MIT chosen as hardware and software contractor" in Chapter 2 of *Computers in Spaceflight: The NASA Experience*, available at: https://history.nasa.gov/computers/contents.html.
44 See Ceruzzi (2015).
45 See Bluck (2004).
46 See WIPO (2019).
47 See Mazzucato (2018).
48 See Ergas (1987).
49 See Agarwal *et al*. (2021).
50 See Moeen and Agarwal (2017).
51 See Roy *et al*. (2019).
52 Visit https://www.economist.com/middle-east-and-africa/2021/06/17/africa-is-blasting-its-way-into-the-space-race.
53 See Lee (2021).
54 See Lee and Mathews (2010).
55 See Eun *et al*. (2006).
56 See Kim (1997).
57 See Huang and Sharif (2015).
58 See Mu and Lee (2005).
59 See Lee *et al*. (2011).
60 See Hobday (1994).
61 See Lee and Lim (2001).
62 See Johnson (1982).
63 See Amsden and Chu (2003).
64 See Wang (2012).
65 See WIPO (2017).
66 See Eun *et al*. (2006).
67 See WIPO (2017).
68 See Hall and Ziedonis (2001).
69 Visit https://www.wipo.int/wipo_magazine/en/2015/03/article_0003.html.

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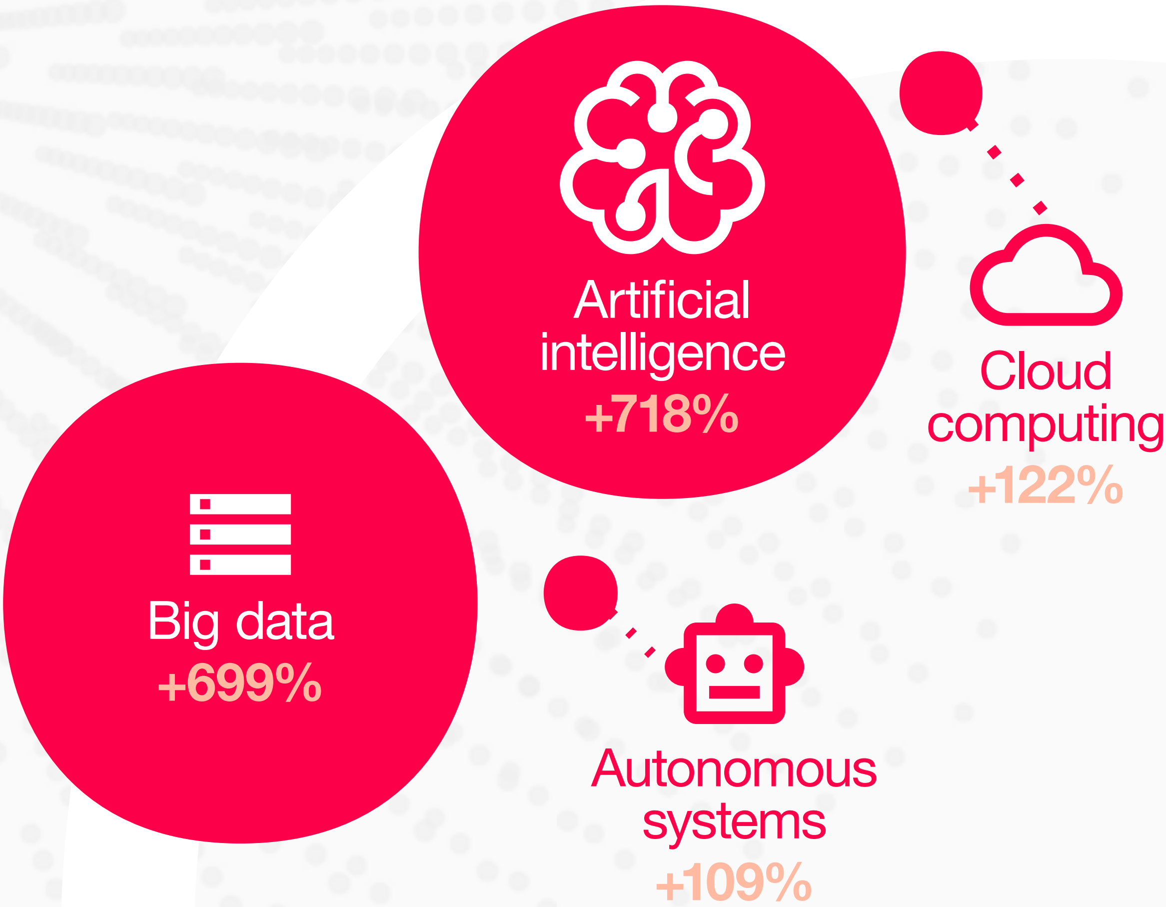
Fast-growing digital technologies
2015-2020 patenting activity



Chapter 3

The direction of innovation: future challenges

As we enter the third decade of the 21st century, new and powerful forces are driving the direction of innovation in science, technology and medicine. While there are many forces at work, three stand out.

First, the COVID-19 pandemic generated and, in part, accelerated demand for new technologies with which to fight the virus's spread and treat infection. The scientific and technological community rose to the challenge by developing, with significant government assistance, a range of vaccines in record time. This global health crisis has profoundly affected how people work, travel, communicate and entertain themselves. It is too early to say what the post-pandemic "normal" will look like, but many changes are here to stay. The pandemic prompted faster digitalization (discussed below) and broke many taboos about work and social life. Innovators stepped in, and will do so further in the coming years, to supply the technologies needed to support this new environment.

Second, fighting climate change has become an imperative at the top of policy agendas around the world. Achieving ambitious carbon emission-reduction targets will depend on innovative technologies and their adoption. Policy measures and public funding will increasingly prioritize investments in new technologies. There are already encouraging signs of progress – as exemplified by the fall in the price of renewable energy technologies such as solar panels. However, more is required. Enabling a transition to carbon neutrality, where carbon emitted and carbon absorbed is in balance, will be a motivation driving innovators in the decades to come.

Lastly, the third force at work is the digital revolution, or what some bill as the Fourth Industrial Revolution. It has seen the pervasive deployment of digital technologies (digitalization); extremely large data sets (big data) for analyzing trends and human interactions; ever more sophisticated processes of automation and AI. These are all examples of general-purpose technologies, which are technologies applicable across many industries and sectors that can lead to new, incremental follow-on innovations (see Chapter 1).[1] The power of these new digital general-purpose technologies and their networked character give rise to national security issues, because of the potential vulnerability of defense systems to hacking, for example. Governments, in turn, have prioritized the development of national technological capacity, prompting a new generation of innovation-oriented industrial policies around the world.

In light of the forces at work, what directions will innovation take? Most innovation investments set well-defined end goals, as in the Moon program (see Chapter 2), which allows predictions to be made about the technological changes to come in the short- to medium-term. Yet the actual trajectory of innovation remains uncertain – some end goals will be missed, others surpassed. In addition, if history is any guide, long-term changes in the direction of innovation and their socioeconomic consequences cannot be predicted with any confidence.

This chapter examines the three forces outlined above in some detail. In doing so, it explores shifts in innovation ecosystems that re-shape the direction of innovation. It will also ask how public policies can steer the direction of innovation in a way that best responds to the needs of society and the world's grand challenges.

The chapter is divided into four parts. The next three sections provide case studies illustrating how innovation ecosystems are addressing some of the global challenges. Section 3.1 examines the COVID-19 crisis and highlights how the concerted efforts of the public and private sectors resulted in several vaccines that offer high degrees of protection against the new virus. It underscores the importance of having a robust innovation ecosystem able to respond in a similar manner in the future. Section 3.2 focuses on the urgency of addressing climate change. It explores the nature of this grand challenge and underscores how all relevant innovation stakeholders, including households, will have a role to play in tackling the problem. Section 3.3 considers the rise of digital general-purpose technologies and how they can trigger the innovations needed to meet the various challenges highlighted in this chapter. Section 3.4 distills important insights from these three case studies to make the case for governments and policymakers taking an active role in promoting solutions to society's challenges, while at the same time acting to mitigate the possible disruptive effects of these innovations in areas such as employment.[2] Lastly, Section 3.5 concludes with some key policy messages.

3.1 The lessons of COVID-19

The spread of the SARS-CoV-2 virus in the early months of 2020 shook the world. The virus quickly overwhelmed hospital emergency rooms and intensive-care units and resulted in a high number of deaths over a relatively short period of time. The World Health Organization reported COVID-19 responsible for nearly 5.5 million deaths as of January 11, 2022.[3] This figure is widely considered an underestimate.

Governments imposed containment and mitigation measures to stop, or at least slow, its spread. Lockdowns in many countries saw the temporary closing of offices and factories, other than those providing key services, and the confinement of people to their homes. This adversely affected activities requiring a physical presence, such as those in the services sector.[4] Many businesses eventually failed, and many people lost their jobs. Economists at the World Bank found that 97 million people were pushed into poverty in 2020 due to the crisis.[5] The global economy contracted by 3.2 percent in 2020, arguably the worst recession since the Second World War.[6]

The COVID-19 crisis prompted all actors in the innovation ecosystem to urgently find solutions – governments, the private sector, research institutions and universities, international communities, and non-governmental organizations (NGOs), including philanthropic foundations.

Successful public–private collaboration

Concerted efforts by participants in the global innovation ecosystem led to the development of several COVID-19 vaccines within a short space of time. Less than two years after the day the first case was reported – December 31, 2019 – 20 COVID-19 vaccines were being administered globally, 114 vaccine candidates were undergoing clinical trials and 185 in pre-clinical development.[7]

The speed at which COVID-19 vaccines were identified, tested and deployed is a record. Chinese scientists published the mapped genetic sequence of the

Public expenditure played a significant role in supporting the development of COVID-19 vaccines

Figure 3.1a Share of funding for COVID-19 vaccines by type in percentage

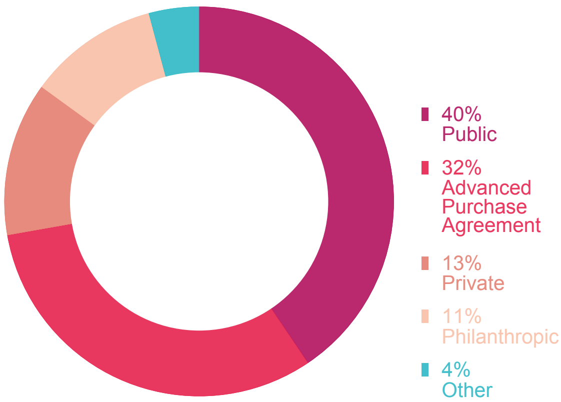
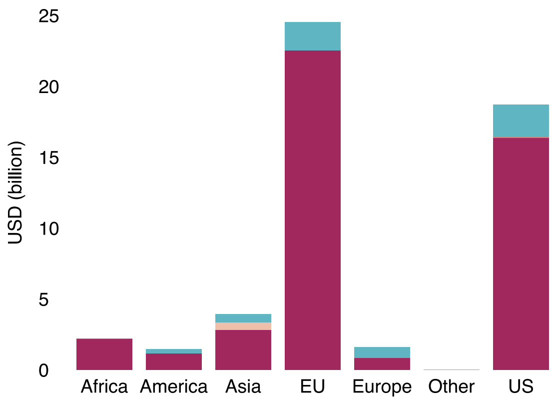


Figure 3.1b Funding for COVID-19 vaccines by type and region in USD billions



Source: Global Health Centre (2021).
Note: These figures represent COVID-19-specific investments by the public and private (non-pharmaceutical firms) sectors, philanthropes and other funders as determined by the Global Health Center database. They are based on publicly available figures. Data for private sector funding does not include pharmaceutical firms and is thus under-represented. The APAs and R&D investments may include manufacturing capacity scaling-up, as well investments to advance clinical developments.

SARS-CoV-2 virus early in January 2020.[8] Three months later, four companies and one university had identified their vaccine candidates. On August 31, 2020, the first COVID-19 vaccine, SinoVac, was approved for use by the Chinese authorities.[9] By early December, the Medicines and Healthcare Products Regulatory Agency (MHRA) had approved the Pfizer-BioNTech vaccine (see below) for use in the United Kingdom.

Four main factors explain how the vaccines could be developed so fast.

First, the scale of the pandemic and the fact that it affected a large share of the global population created an important incentive for the private sector to find a technological solution. Market size is an important factor in innovation, especially in the field of medicine, because, as noted in Chapter 1, the larger the market, the bigger the potential reward.[10, 11] In assessing whether to undertake research and development (R&D) investments, innovators have to evaluate the likely costs and risks of investing against the expected returns.

Second, governments gave significant financial support to the private sector, including for clinical trials and for vaccine developers with promising vaccine candidates, to build large-scale manufacturing capacity. The European Commission (EC), for example, committed EUR 137.5 million for R&D into diagnostics, therapies and vaccines and EUR 164 million for start-ups and SMEs working on solutions to the health crisis.[12] The Coalition for Epidemic Preparedness Innovation (CEPI), a global partnership launched in 2017 to develop vaccines to stop future epidemics, provided USD 1.3 billion for COVID-19 vaccine R&D.[13]

In addition, several governments committed to purchase specific quantities of the vaccine candidates. These advance purchase agreement (known as APAs) helped mitigate some of the commercial risks of developing the vaccine candidates. Some of these AMCs were upfront payments, paid even before a vaccine candidate had undergone clinical trials.

More public support to address the crisis came in the form of government-initiated programs, such as those by the U.S. and U.K. governments, similar to the mission-oriented policies discussed in Chapter 2.[14] These programs were designed to speed up regulatory assessment, in addition to helping find a vaccine for COVID-19.[15] In the past, even with the most optimistic outlook, a vaccine would take a minimum 18 months to develop and market.[16] Most took five to 10 years due to the time needed to find promising candidates and then gain regulatory approval.[17] Box 3.1 looks at the U.S. Operation Warp Speed (OWS) program of COVID-19 vaccine development, while Box 3.2 highlights the U.K.'s Vaccine Taskforce (VTF).

Box 3.1

Operation Warp Speed shortened vaccine development times

Operation Warp Speed (OWS) launched on May 15, 2020, as an inter-agency partnership led by the U.S. Department of Health and Human Services (HHS) and the U.S. Department of Defense (DoD). Its purpose was to accelerate the development and distribution of safe and effective vaccines, therapeutics and diagnostics for the SARS-CoV-2 virus, by coordinating, funding and otherwise supporting vaccine candidate developers, mostly in the private sector.

The initiative was inspired by the Manhattan Project, a mission-oriented program which ran from 1942 to 1946.[18] The Manhattan Project brought together scientists and the military, along with concentrated R&D investments, to create an atomic weapon within two-and-a-half years. The OWS adopted this same mission-oriented concerted R&D effort approach, along with a military operation structure, in developing the COVID-19 vaccine.[19]

In addition, the OWS program adopted many of the best practices of the DoD's Defense Advanced Research Projects Agency (DARPA) model.[20] DARPA was created in 1958 to build up U.S. technological capacity and compete against the Soviet Union in a race to the Moon. To do so, it was prepared to pursue commercially risky R&D projects. The agency has been successful in developing important military technologies, some of which have found a non-military commercial use (see Chapter 2). The OWS employed DARPA's portfolio approach and invested in several vaccine candidates that relied on different and competing technologies, albeit with larger R&D investment and over a shorter and limited duration.[21] In doing so, it raised the chance of funding at least one successful candidate, while reducing the risk of overall failure. Firms developing the successful vaccine candidates then competed with one another to reach the market first.

One novel and innovative aspect of the initiative was that vaccine developers were able to carry out the different clinical trial phases concurrently without compromising the high safety and efficacy standards set by the U.S. Food and Drug Administration (FDA). Typically, vaccine and drug development can only move from one phase to another once all criteria for progress have been met. Vaccine developers were also able quickly to start manufacturing those candidates with the most promising clinical trial results, as the program helped build the large-scale manufacturing capacity needed.[22]

The program was renamed the Countermeasures Acceleration Group in 2021.

Box 3.2

Taskforce-facilitated clinical trials and vaccine manufacturing

The Vaccine Task Force (VTF) was established in April 2020 in order to seek U.K. access to the most promising vaccines as quickly as possible.[23] It is a partnership between the Department for Business, Energy and Industrial Strategy (BEIS) and the Department of Health and Social Care (DHSC) and includes nine steering group members from the private sector.

As with the U.S. OWS program, the task force invested in a portfolio of promising vaccine candidates across competing technologies.[24] Its investments were in the form of R&D funding and advanced purchase agreements with vaccine developers.

The task force signed up volunteers through its National Health Service COVID-19 vaccine registry to take part in clinical trials.[25] It also helped develop testing standards to permit comparison of efficacy and protection levels between the vaccine candidates. The initiative financed the large-scale manufacture of vaccine candidates. Oxford-AstraZeneca was one vaccine developer that received early manufacturing subsidies from this campaign.[26]

Given the U.K.'s limited vaccine manufacturing capability, the task force provided funding to vaccine developers such as the U.S. Novavax, French company Valneva and Germany's Cure-Vac to either establish or extend manufacturing facilities within the country. This move complemented the Government's own Vaccine Manufacturing and Innovation Centre, created in 2018 to strengthen efforts to deal with future pandemics.[27]

Third, important advances in the biomedical field, which began during the golden era of vaccines during and after the Second World War (see Chapter 2), helped fuel the rapid development of COVID-19 vaccine candidates.[28] The SARS-CoV-2 virus was quickly identified, and its gene sequenced. The sequencing cleared the way for trials of a vaccine based on mRNA technology, which, as noted in Chapter 1, delivers a piece of genetic code from the virus so as to stimulate an immune response and produce antibodies. This technology is likely to change the innovation process in the biomedical field by shortening the time it takes to develop new vaccines for future diseases and stimulating further investment in this approach.

The mRNA technology had been in use, or in development, for at least a decade before the emergence of COVID-19. The U.S.'s DARPA was one organization that had been supporting its development.[29] Researchers were therefore able to re-direct efforts quickly toward finding vaccine candidates.

Fourth and finally, scientists and researchers that had never worked with one another started collaborating.[30] Some even crossed scientific fields to help with the endeavor. For example, epidemiologists joined with sociologists and economists to understand how the virus spread and how to contain it. In addition, researchers shared their work openly, even before it had been peer-reviewed, so as to speed up the diffusion of knowledge between scientists and researchers. This helped in the fast dissemination of the latest research findings.

Innovation in medicine[31]

The impact of the pandemic has reached beyond the immediate search for an effective vaccine to affect innovation in other areas of medical research and medical practice.

Changing the direction of medical research

As noted, the development of COVID-19 vaccines based on mRNA technology will likely spur future scientific advances and pharmaceutical inventions. Since the mid-2000s, researchers had been touting mRNA platform technology as a game-changer.[32] The technology works by modifying the mRNA, a gene that tells the body how to make the proteins it needs. Edited mRNA instructs the body's immune system to produce antibodies to defend itself against the SARS-CoV-2 virus.

Pre-pandemic, this technology was being tested in the protection against several infectious diseases, including the Ebola and Zika viruses. It was even being used in some cancer work.[33] But beyond prophylactic applications, the mRNA platform was not being seriously considered by major pharmaceutical companies. This was partly because pharmaceutical companies are less likely to invest in preventative treatments like vaccines.[34] But the success of mRNA-based COVID-19 vaccines has provided strong evidence that the research platform works well and could have other applications. For the patient, the mRNA technology is efficient and safe.[35] For the manufacturer, it is cheaper and faster than traditional methods, since only minor adjustments to the production process are needed in order to change from tackling one disease to tackling another.

The success of the mRNA vaccine platform for COVID-19 could usher in a new golden era for vaccine development. In addition, U.S. and U.K. government support in

Important advances in the biomedical field, which began during the golden era of vaccines during and after the Second World War, helped fuel the rapid development of COVID-19 vaccine candidates

building large-scale manufacturing facilities for the new mRNA vaccine platform complements and reinforces further research into the technology.

But the wide-scale use and adoption of this new platform technology still faces certain obstacles.[36] First, creating and deploying it require a highly skilled labor force and well-equipped research labs. Second, the mRNA can degrade easily if the manufacturing conditions are not right, which potentially adds to the cost of production. Third, many places in the world do not have the infrastructure required to ship and store mRNA.

A focus on new mRNA vaccine technology may also be detrimental to other medical research (see Chapter 1, Box 1.1). During the COVID-19 lockdown, many research labs were re-purposed from other existing lines of research toward COVID-19. Some institutions not working on COVID-19 had either to close labs or restrict their activity. Some lost their funding. Many universities and research institutions had to re-prioritize and re-allocate their budgets.

However, switching from one line of research to another is costly.[37] For now, the re-prioritization and changes in funding seem to have delayed research progress rather than changed it entirely.[38] A study comparing the number of new clinical trials by diseases between 2019 and 2020 found that COVID-19 trials came at the expense of new clinical trials on other diseases. However, this may be only a temporary displacement.[39]

The speed of COVID-19 vaccine development shows how quickly new vaccines and drugs can reach the market while meeting the high safety standards of regulators.[40] There could be a case to be made for drug development timelines being shortened from the industry's average five to 10 years.

The success of the U.S. and U.K. vaccine development programs argues for continued public–private partnerships in the prevention and treatment of diseases such as COVID-19. Both initiatives played pivotal roles in supporting breakthrough technologies, right through from theory to practice. They did this by investing in a portfolio of competing technologies that were relatively unproven, and by helping build manufacturing capabilities supporting the application of those technologies.

Changing medical practice

The pandemic has accelerated the adoption of digital technologies (see Section 3.3) by medical practitioners and hospitals. A report by McKinsey & Company in 2021 noted that the biopharmaceutical industry saw more digital transformation in the first 10 months of COVID-19 than it did in the previous decade.[41] Companies in the medical industry are revamping their systems to fully embrace digital systems and making greater use of data to optimize their activity. In Switzerland, patients can have their medical records stored in an online medical portal and arrange appointments through the same portal.

In health care, more and more doctors are using digital platforms to diagnose and care for patients.[42] During the lockdown in 2020, for example, some doctors conducted consultations using online video communication platforms. Hospitals are relying on analysis of incoming patients to better manage staff and hospital bed use. Although many such changes were already underway, the pandemic created an urgent need to "go digital" and the opportunity to introduce needed operational improvements.

3.2 Addressing the climate change imperative[43]

Fossil fuel as an energy source for electricity and transportation is the biggest contributor to climate change attributable to human activity. Since 1970, carbon dioxide (CO_2) emission resulting from human activity, particularly the burning of fossil fuels and industrial processes, has contributed approximately 78 percent of global greenhouse gas (GHG) emissions.[44] These gases absorb and re-emit heat back into the atmosphere, affecting the speed at which the climate changes. They include CO_2, methane and nitrous oxide.

The faster the climate changes the greater the impact on the world will be as there will be less time to adapt to the changes.

Global warming jeopardizes global economic growth and, more importantly, the sustainability of life on Earth. It threatens food security and access to clean water, and it causes extreme weather events and rising sea levels. It also hurts plant growth, which in turn impacts Nature's ability to regulate CO_2 in the atmosphere. The World Bank estimates the annual global cost of extreme weather at USD 520 billion in lost well-being, reflecting the disproportionate impact of climate change on the poor, with 26 million people being pushed into poverty every year.[45]

Governments are coming under increasing pressure to address climate change. Under the 2015 Paris Agreement, 196 countries committed themselves to limiting the rise in global temperatures to less than 2°Celsius (C) by the end of the century and preferably to halting the rise at 1.5°C.[46] Six years later in Glasgow, Scotland, signatories reiterated this commitment and a few, including Argentina, China, the European Union (EU), South Africa, the United Kingdom and the United States, agreed to stiffen their existing plans for limiting emissions.[47] For example, the EU will aim to reduce greenhouse gas emissions by at least 55 percent by 2030 – up from the 40 percent initially proposed. Many countries – representing 80 percent of the world economy – have announced targets of net-zero emissions by 2050, and large emitters such as China and India have voiced similar goals for 2060 and 2070, respectively.

Progress toward change

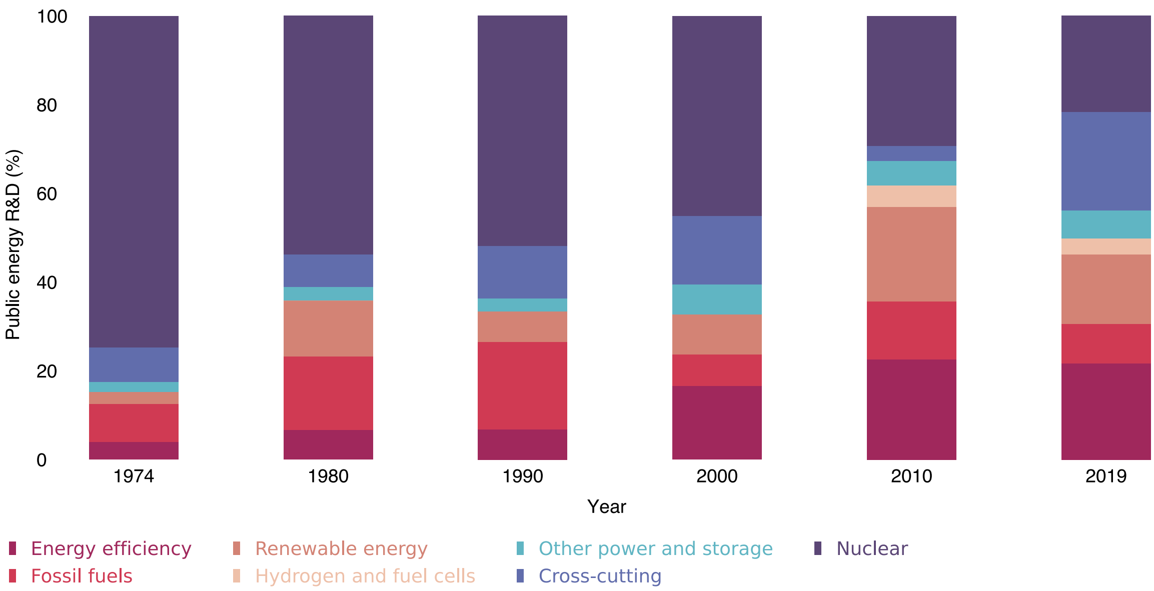
Strides have been made by governments and the private sector alike to direct innovation toward technologies that reduce the adverse impact of economic activity on the environment. These include in climate-change mitigation technologies for energy, transport and construction, as well as environmental management and water-related adaptation technologies.

Mitigation technologies aim to reduce greenhouse gas emission, increase energy efficiency, improve resource use, minimize waste and improve reuse and recycling.[48] Referred to as low-carbon technologies, they generate relatively lower CO_2 emissions than fossil-fuel energy. In transport, an example would be electric vehicles (see below). In energy production, examples include solar photovoltaic (PV) energy, wind turbines and coal-fired power plants fitted with carbon-capture storage facilities.[49] Carbon dioxide removal and capture technologies, for example power plant storage facilities, reduce CO_2 emission by capturing and storing gases either in reservoirs (geological, terrestrial or in the ocean) or in products such as wood.[50]

Governments mostly in developed economies, and more recently China, are using subsidies, regulations and standards to promote environmental technologies. In response, businesses are increasingly investing in and adopting these technologies. Importantly, governments' long-term commitment to environmental policies provides an important reassurance to businesses that they, too, can safely make the necessary long-term investments in low-carbon technologies.

The changing composition of public R&D funding into energy

Figure 3.2 Share of public energy R&D investment spending by technology in percentage, 1974–2019



Source: IEA (2020a).
Note: Cross-cutting refers to technologies that can be applied to several energy sectors, such as fossil fuels, other power and storage, and so on. The U.S. Department of Energy (DoE) Office of Science reports it under its basic energy science.

Funding for alternatives

Governments have been funding R&D into alternative energy sources since the 1970s. As part of its Moon program (see Chapter 2), the United States began experimenting with solar PV panels and wind turbines as sources of energy. At the same time, the sharp rise in oil prices during 1973 and 1979 threatened economic growth in Europe and North America and raised energy security concerns. This prompted countries such as France and Brazil to fund research into nuclear energy and ethanol, respectively, while Japan initiated energy efficiency programs.

Governments helped mitigate some of the risks and uncertainties associated with investing in new, relatively untested alternative energy technologies. Germany's subsidy and feed-in-tariffs policies (see Box 3.3) in the early 1990s have been credited with creating an early push in the demand for solar technologies.[51] In addition, government support played a significant role in developing and demonstrating the practical application of new technologies and, therefore, their potential for commercialization.

Studies show that state funding of initiatives positively affected the rate and direction of environmental innovation in the EU and the United States.[52] Subsidies provided by EU countries facilitated the generation of electricity through solar and wind power by cutting the costs for firms of developing the technology.[53] According to researchers at Imperial College London, most of the offshore wind farms in Europe could be operational without the need for subsidies by 2025.[54]

Figure 3.2 shows how, since the mid-1970s, the global public funding of R&D for energy sources has moved away from investments in fossil fuels. According to the International Energy Agency (IEA), public funding for fossil fuels declined by almost half in the decade to 2020, from 13 percent down to 7 percent of the total public R&D spending on energy.[55]

Standards, rules and regulations

As noted, government standards, rules and regulations play key roles in the adoption of environmental technologies by both industry and private households. The number of policies geared to the adoption and diffusion of environmental technologies has been growing steadily.[56] At the local level, such policies have included subsidies to install solar panels on rooftops, construct energy-efficient houses and buildings and purchase electric-powered bicycles and vehicles. In response, small communities, farmers, municipalities and environmentally-conscious producers and households have diversified toward using environmental technologies.[57]

However, the impact of such policies varies according to the type of incentive – inducement mechanism – employed (see Box 3.3).[58] Technologies at an early stage of development – basic and/or applied research stage – tend to be less certain of success and therefore may require public funding to mitigate the risks.[59] For example, carbon-removal technologies are expensive both to build and to maintain. While such technologies have been demonstrated to work, which is known as "proof of concept," developing them on a large scale is risky. Nonetheless, in 2021 more than 100 new carbon-capture storage facilities were announced with government backing.[60]

Box 3.3 shows how different inducement mechanisms affect innovation in low-carbon technologies. Inducement mechanisms are government policies aimed at producing a specific behavior that may not have otherwise occurred. In the case of environmental policies, participants in the innovation ecosystem are encouraged to work toward developing technologies (both product and process) that ameliorate carbon emissions, such as low-carbon technologies and/or climate-change mitigation technologies (CCMTs).

There are also mechanisms, such as taxes on carbon emissions, which facilitate the adoption of environmental technologies and steer consumers away from a reliance on fossil fuels. The World Bank reports that some 45 countries are presently implementing carbon pricing initiatives, either through emission trading systems, emission-reduction funds, carbon taxes or variations of these.[61] Moreover, the United Nations Framework Convention on Climate Change (UNFCC) reports that approximately 100 countries are evaluating carbon pricing as a national strategy for reducing CO_2 emission.[62]

Box 3.3

Inducement mechanisms and type of innovation

Studies of climate change policies tend to agree that the inducement mechanisms which work best are market based. Carbon-pricing policies, such as carbon taxes and emission trading systems, are examples. Firms must price their carbon emissions into production costs, which they can expect to rise if they continue to rely on high-carbon technologies. This encourages firms to invest in low-carbon technologies and facilitates their shift away from high-carbon ones. Such an investment in low-carbon technologies helps create a demand and a market for them. In addition, governments often receive revenues from carbon-pricing policies, especially in the case of permits. This means that carbon-pricing policies are less likely to be suddenly withdrawn than, say, subsidies, which can fluctuate with electoral and budgetary cycles. For firms, the implementation of carbon-pricing policies that penalize high-carbon activities can signal that a government has a long-term commitment to carbon-reduction policies.[63]

However, even market-based policies can run into problems. The German Government relied on market-based policies to induce investments in solar PV technology as an energy source. Initially, it used feed-in tariffs guaranteeing prices for solar-generated electricity higher than those for electricity generated through conventional fossil fuels.[64]

But the feed-in tariffs had two major disadvantages. First, they obscured the "real" price of solar-powered electricity. Second, they did not necessarily encourage firms to reduce production costs.

Regulators now rely on auctions and other competitive mechanisms in addition to feed-in tariffs. For example, in Germany's system of power purchasing agreements or tenders, developers of solar PV submit bids for new power generation projects, with the most cost-competitive bids being selected. Since competition is on price, suppliers and project developers are motivated to reduce their costs, which can benefit the whole value chain.

Another instance where market-based incentives may not work is in the case of renters versus owners of energy-efficient buildings. If the cost of paying the energy bill falls on the renter, then the owner of the apartment or house will have no incentive to invest in new energy-saving technologies like insulation or energy-efficient appliances. In this instance, energy performance standards work better than energy taxes in stimulating the use of environmental innovations in buildings.[65]

Source: Noailly (2022), Popp (2019) and Popp *et al.* (2010).

One downside of market-based policies is that they target technologies and innovations close to commercialization – those that have demonstrated their workability – and do not necessarily stimulate new ideas. Government support, either through help financing pilot projects to test ideas or by providing the technological support to develop them, may be better directed at commercially-risky low-carbon technologies, such as large-scale carbon-capture facilities. Investment in new technologies and their development tend to require government involvement, in cooperation with universities and the private sector.

CCMT related to energy is the fastest growing of the clean technologies

Figure 3.3a Total patent filings in clean technologies by categories

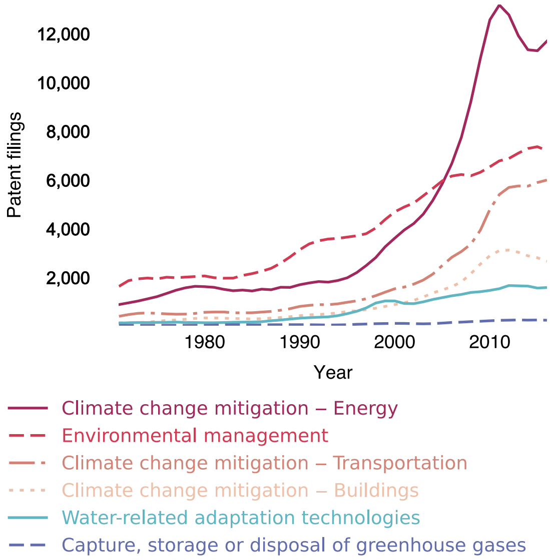
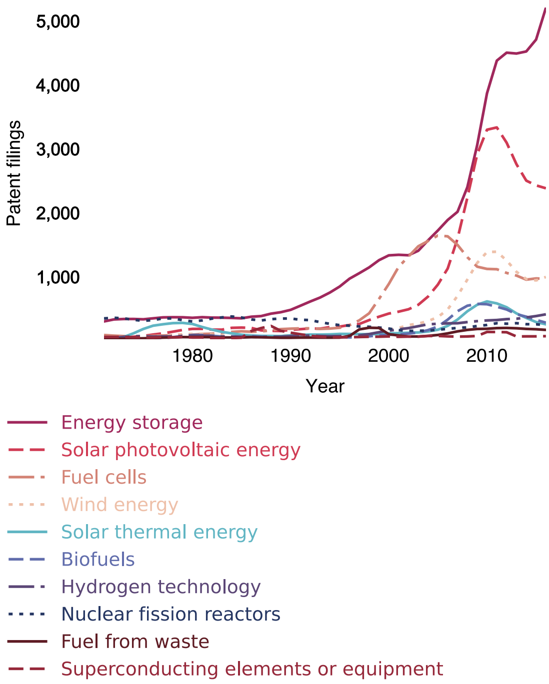


Figure 3.3b Climate-change mitigation technologies in energy by subcategories

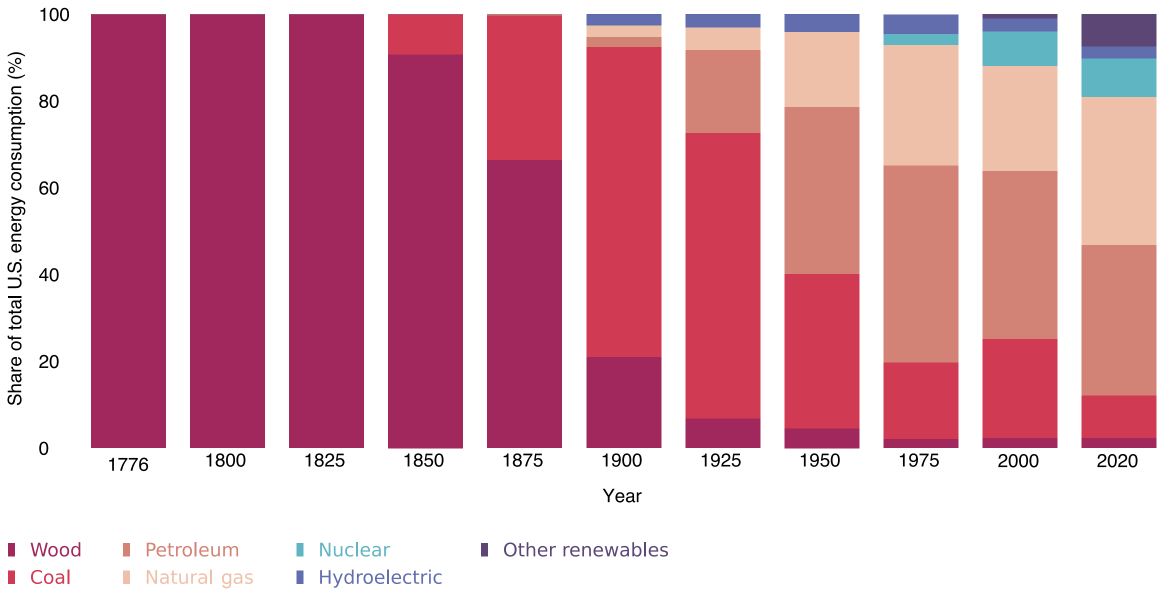


Source: WIPO.
Note: Patent filings refer to patent documents filed in at least two IP offices.

Legislation enacted by many countries to induce the adoption of low-carbon technologies created demand for those technologies. The International Renewable Energy Agency (IRENA) reported that between 2013 and 2018, the private sector accounted for 86 percent of investments in renewable energy globally.[66]

The United States is increasingly diversifying its sources of energy

Figure 3.4 Share of total U.S. energy consumption by major energy source



Source: U.S. Energy Information Administration (April 2021).
Note: Other renewables include solar, wind, biofuels and geothermal.

Advances in alternative energy sources

Patent filings can serve as a rough illustration of the R&D investment efforts made by private companies in low-carbon emission technologies. In Figure 3.3, the sharp increase in patents filed after 2000 can be attributed to the growth of these technologies in the energy sector. Further analysis shows that they are associated with renewable energy sources, such as solar, wind and fuel cells, which are like batteries that do not run down or need recharging. Renewable energy sources account for one-third of the growth of patent filings in this field. Alongside this patenting of renewable energies there has been a growth in enabling technologies, such as batteries, hydrogen – a leading option for storing renewable energy – and smart grids. The latter improve the reliability of power supplies by helping existing power networks to compensate for fluctuations in supplies from renewable energy sources, caused, for example, by adverse weather conditions.

Studies on who is doing the majority of innovation in low-carbon emission technologies find that most of the disruptive technologies – those that make existing technologies obsolete, as happened in telecommunications with mobile phones – originate from small firms rather than incumbent large ones. Climeworks, a start-up spun off from the Swiss Federal Institute in Zurich, built the world's largest "directly from the air" carbon-capture and storage plant in Iceland. Completed in the summer of 2021, the Orca plant is expected to collect 4,000 tonnes of CO_2 per year, which it will store underground. Like many disruptive technologies in this field, Orca is expensive to operate and may not return a profit for some time. It demonstrates why existing firms may be reluctant to invest in this type of innovation.[67]

Large firms, operating mainly in the oil and gas industries, are also active innovators in low-carbon technologies. However, their innovations tend to focus on continuing to use existing fossil-fuel technologies but augmenting them with carbon-capture and storage facilities to remove carbon emissions.[68] They account for slightly more than one-third of global capital investments in carbon-capture, utilization and storage projects.[69]

Advances in developing alternative sources of energy have resulted in the increasing diversification of energy sources in the United States as shown in Figure 3.4.

The two case studies described below are examples of how governments have been instrumental in directing change toward alternative, more environmentally friendly technologies. The first is the development of solar PV as a source of renewable energy, while the second study is on the development of electric vehicles. These cases are instructive, as energy production and transport contribute most to global greenhouse emission worldwide.[70]

Solar PV

Governments are the main drivers behind the development of the solar PV industry.[71] As noted, the U.S. space program invested early in the development of solar panels. By 1958, the U.S. Vanguard I satellite relied on solar panels as its energy source.[72] In addition, in the 1970s, environmental activists in Germany and Denmark convinced their respective governments to develop non-fossil fuel-based sources of energy, including solar and wind.

Firms in Germany, the United States and Japan were the early innovators in solar PV. Developments spearheaded by NASA generated important technical progress in solar PV for use in space and eventually on Earth (see Chapter 2).[73] From the 1990s, Germany started providing large subsidies for solar PV technologies (see Box 3.3), which, as we have seen, guaranteed higher prices for energy generated through this method.[74]

As more countries offered incentives for the production and consumption of solar PV technologies, production capacity expanded and more competitors entered the market. Traditional innovators from Germany, Japan and the United States found themselves competing with companies from China and India.[75] Today, some of the largest exporters of solar PV components are firms from China, the United States, Japan, the Netherlands, Germany, Hong Kong SAR, the Republic of Korea, Singapore and Malaysia.[76]

The expansion of production capacity and the number of competitors led to significant reductions in the price of solar PV and boosted market demand for the technology. The solar PV industry attracted 46 percent of global investments in renewable energy sources between 2013 and 2018.[77] Over a period of eight years – 2010 to 2018 – the cost of producing electricity using solar PV fell 77 percent. Its cumulative installed capacity had risen by a factor of 100 by 2018 compared with 2005.[78] The IEA forecasts that solar energy will account for one-fifth of energy supply worldwide by 2050, if solar PV capacity increases 20-fold by then.[79]

Shortages of solar panel components, due to supply-chain disruptions caused by the COVID-19 pandemic, have recently raised the price of solar panels. In addition, trade tensions between the United States and China may lead to tariffs being imposed on key components. These developments could slow adoption of solar PV and hurt countries' decarbonization strategies.

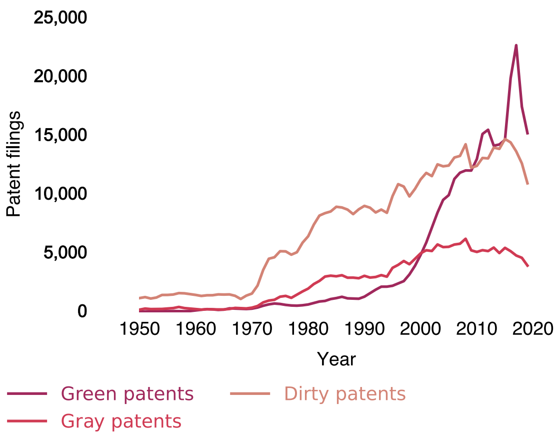
Electric vehicles

The technology for electric vehicles has been around since the mid-19th century, but their development was eclipsed by that of petrol-fueled rivals. However, at the turn of the 21st century interest in electric vehicles has returned strongly in response to growing concerns over carbon emission.

Electric vehicles are another example of how governments create early demand for low-carbon technology. Beginning in 2005, the U.S. Government offered a federal income tax credit of up to USD 7,500 on electric vehicle purchases. This incentive boosted demand. One study estimates that the tax credit accounted for at least 40 percent of total electric vehicle purchases during 2011–2013.[80] This does not include additional incentives offered at the state level, such as by California's Clean Vehicle Rebate Program.[81] Sales of electric vehicles dropped in China and the United States when key subsidies were cut in 2019.[82]

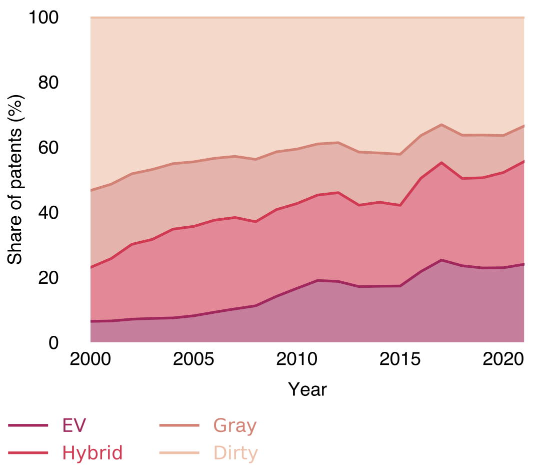
Electric and hybrid vehicle-related technologies account

Figure 3.5a Total patent filings in the car industry, by green (electric and hybrid), gray and dirty patents



Source: WIPO.
Note: A patent may refer to more than one category. Green patents are composed of both EV and hybrid vehicle-related patents. Dirty patents are the conventional internal combustion engine vehicle-related patents. Gray patents consist of patented technologies that improve the efficiency of conventional combustion engine ones.

Figure 3.5b Share of patent filings of green (electric and hybrid), gray and dirty technologies as share of patent filings in the car industry



Source: WIPO.
Note: A patent may refer to more than one category. Green patents are composed of both EV and hybrid vehicle-related patents. Dirty patents are conventional internal combustion engine vehicle-related patents. Gray patents consist of technologies that improve the efficiency of the conventional combustion engine ones.

More stringent emission standards have promoted investments in electric vehicles since the 1990s. By 2030, the EU and the United States are aiming to have electric vehicles account for 50 percent of automobile purchases. Moreover, some of their cities, and others in Canada, Israel, Japan, Mexico, Sri Lanka and the United Kingdom, have announced a sales bans on internal combustion engines by 2050.[83] These policies should increase R&D spending in this sector.

Advances in enabling technologies, such as improvements in battery storage capacity, battery thermal resistance and charging infrastructure, have made electric vehicles more attractive to consumers. By 2018, better batteries had improved the range of independent travel of electric vehicles fourfold compared with 2011.[84]

Figure 3.5a shows how patent filings for clean road-transport low-carbon technologies (electric and hybrid) had surpassed innovation in dirty high-carbon technologies (internal combustion engines) by 2009. Moreover, clean technologies account for at least half of all patenting activity in the car industry since 2016 (see Figure 3.5b).

Figure 3.6a shows how household demand for electric vehicles has been growing. Global market share of electric vehicle sales has risen steadily since 2011 up to about 4 percent of automobiles in 2019. This is despite the lower incentives (see Figure 3.6b) provided by governments, in the form of subsidies for electric vehicle purchases, implying that consumers are choosing these vehicles regardless. At their peak, government incentives covered 23 percent of the cost to consumers of electric vehicles, but had dropped to 10 percent by 2020.

Worldwide sale of electric vehicles is slowly on the rise

Figure 3.6a Global electric vehicles market share

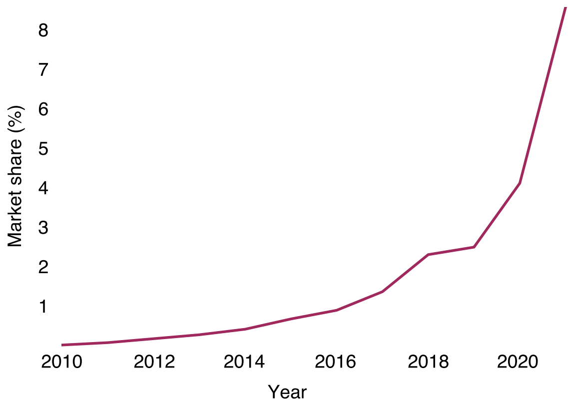
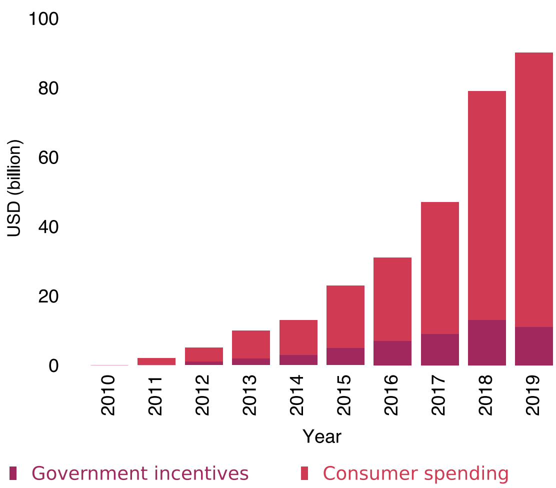


Figure 3.6b Spending on electric vehicles purchases by origin of funds



Source: IEA (2021a).

Public and private sectors react, but constraints remain

Over the last five years, there has been renewed commitment to addressing climate change from the private as well as public sector.

Pressure builds on private sector

An increasing number of private and public funds require investments go into green, low-carbon emission technologies. Initiatives such as Climate Action 100+, an investor-led pressure group, and "green" funds try to persuade the companies they work with to adhere to climate change goals. There are also initiatives to hold firms accountable for their green commitments. These include the Science Based Targets initiative (SBTi), which guides companies in a science-based target setting, and the Task Force on Climate-related Financial Disclosures (TCFD), which aims to increase reporting of climate-related financial information.[85]

Investments in green funds surpassed USD 178 billion in the first quarter of 2021, up by nearly 370 percent from the first quarter of 2020.[86] This huge increase reflects in part the launch during the period of 200 new environmental, social and governance (ESG) funds – funds that integrate ESG factors into their investment strategies.

Some public funds are abandoning investments in fossil fuel companies altogether. The Dutch pension fund group, ABP, one of the world's biggest, expects to sell more than EUR 15 billion of its holdings in fossil fuel companies by the first quarter of 2023.[87]

In addition, insurance and accounting companies are starting to take into consideration clients' climate change risk-mitigation strategies when calculating insurance premiums and values.[88] Firms that want to keep insurance premiums low and values high have to take climate issues seriously.

There is also the reputational side to consider. Public sentiment on climate change has shifted. Younger generations are much more aware of the issues and are advocating for change. Companies are taking note. Traditional fossil-fuel producers BP and Exxon have climate change activists on their board of directors.

More ambitious government action

Governments are setting more ambitious targets to meet their climate change commitments. In 2021, the U.S. Senate approved a USD 550 billion infrastructure bill to help overhaul U.S. reliance on fossil-fuel energy for transportation and move toward low-carbon emission technologies. Approximately 13 percent of this bill will be invested in clean energy transmission through power grids. It will be the largest investment in low-carbon emission technology in the country's history.[89]

The U.S. Government's Future of Sustainable Fuels in American Aviation aims to complement the infrastructure bill by funding and supporting the development of sustainable aviation fuel. It would also require investments in new technologies to improve aircraft fuel efficiency.[90] In addition, the proposed U.S. Build Back Better Framework sets aside USD 555 billion for investments toward fighting climate change.[91]

In 2019, the EU launched its European Green Deal with the aim of making Europe carbon neutral by achieving net zero by 2050.[92] The Chinese Development Bank has set aside RMB 500 billion to fund the country's energy sector, of which one-fifth is earmarked to build clean, low-carbon, safe and efficient energy systems.[93]

At the intergovernmental level, besides the net-zero emission targets, the 191 members of the ICAO endorsed calls to substitute a large share of current aviation fuels with sustainable fuels by 2050.[94]

In addition, governments have allied with the private sector in various public–private partnerships to address climate change. For example, a private–public partnership between Breakthrough Innovation, a network established by Bill Gates and several private investors, and Mission Innovation, a global alliance of 22 countries and the European Commission, intends to accelerate the commercialization of critical clean-energy technologies. They include green hydrogen, sustainable aviation fuel, direct air capture and long-duration energy storage. The collaboration was established at the time of the Paris Agreement in 2015 and expanded at Glasgow in 2021.[95]

These stronger and deeper commitments from the private as well as public sectors are likely to encourage further investments to address the climate change imperative. However, the speed with which these initiatives translate into significant advances in the development of low-carbon emission technologies will depend on many factors. These include political will, the ability to finance initiatives and access to low-carbon technologies for countries without the local capacity to innovate.

Constraints on the uptake of low-carbon technologies

Our ability to transition to green economies depends on many factors.

Firms still have a limited incentive to invest in non-polluting technologies, such as low-carbon technologies, despite environmental laws and government encouragement. Part of the reason is that fossil-fuel inputs are cheaper and more widely available. Fossil fuels received an average subsidy of 10 percent in 2020, which was passed on to consumers. In 2017, government subsidies to fossil fuels totaled USD 447 billion. By comparison, renewable energy technologies received USD 128 billion and biofuels USD 38 billion.[96] Some of this disparity in subsidies reflects the political complexity of withdrawing subsidies when they are often electorally popular.

Investing in non-polluting technologies is also both costly and risky, with, as noted, no guarantee of success. Firms usually take no account of potential benefits to the economic environment in which they operate – the so-called "externalities" discussed in Chapter 1 – or the technical knowledge generated from investing in low-carbon technologies.[97] Firms tend to focus instead on returns to investment in the relatively short- to medium-term and not take into consideration the potentially positive societal implications of low-carbon technology investments for the environment. This misalignment between private firms' profit-maximizing objective and society's overall well-being – the private and social returns – is one of the main arguments in support of government intervention. By imposing carbon taxes, for example, governments force companies to factor the costs of their CO_2 emissions into decision-making.

Newer, smaller and specialized firms that decide to invest in low-carbon technologies face substantial barriers to scaling up their operations. They find it more difficult to finance their activities than do other small firms operating in the fossil-fuel business.[98] They are also less likely to be acquired by larger firms.[99] An IEA study followed the development of clean technology start-ups in 2010 and found that 81 percent failed and/or exited the market.[100] Even those start-ups that do manage to develop new renewable technologies will need hundreds of millions of dollars to demonstrate their commercial viability.[101]

Firms may hesitate to invest in or shift to low-carbon technologies, including acquiring firms that specialize

These stronger and deeper commitments from the private as well as public sectors are likely to encourage further investments to address the climate change imperative

in them, because these technologies may end up competing with them for market share and even make their existing technologies redundant. Firms' reliance on fossil-fuel technologies in the past is likely to continue in the future. This is known as "path dependency."[102] Even where firms face higher prices for fossil-fuel inputs, they are more likely to substitute one fossil fuel for another than switch to low-carbon inputs.[103]

The strong inertia and technological path dependence on fossil-fuel technologies create feedback loops, the so-called "carbon lock-in." Firms face strong incentives to choose technologies with existing infrastructures rather than experiment with new ones, thereby trapping innovation trajectories in high-carbon areas.[104]

Market demand also has to be adequate in order to sustain investments in low-carbon technologies by profit-seeking firms. In addition, for the producers, there is a steep learning curve to innovating and deploying low-carbon technologies requiring a high-skilled workforce.[105] Even environmentally-concerned consumers may not know whether their electricity is produced by renewables or fossil-fuel sources. If they are made aware, they may demand that it is produced by renewables and even be willing to pay extra for it. This in turn could create a market incentive for the private sector to invest.

Lastly, investments in enabling technologies, such as energy storage facilities, are needed so as to create and sustain demand for low-carbon technologies. These technologies include the infrastructure necessary for the deployment of renewable energy along grid systems, such as smart grids.

3.3 Digitalization is changing the world

In the summer of 1956, a workshop was organized at Dartmouth College in Hanover, New Hampshire, to discuss how to program machines to gather data, analyze that data to solve problems and "learn" from what they had done. The premise of the workshop was that the process of learning can be described in sufficient detail for a machine to be programed to be intelligent.[106] Many consider this workshop to be the birth of artificial intelligence, or AI, a term used interchangeably with machine-learning technology. AI is the basis of a new wave of digitalization – digital general-purpose technologies – that is revolutionizing economic activities. This new wave includes technologies such as predictive technologies, highly sophisticated automation and big data.[107]

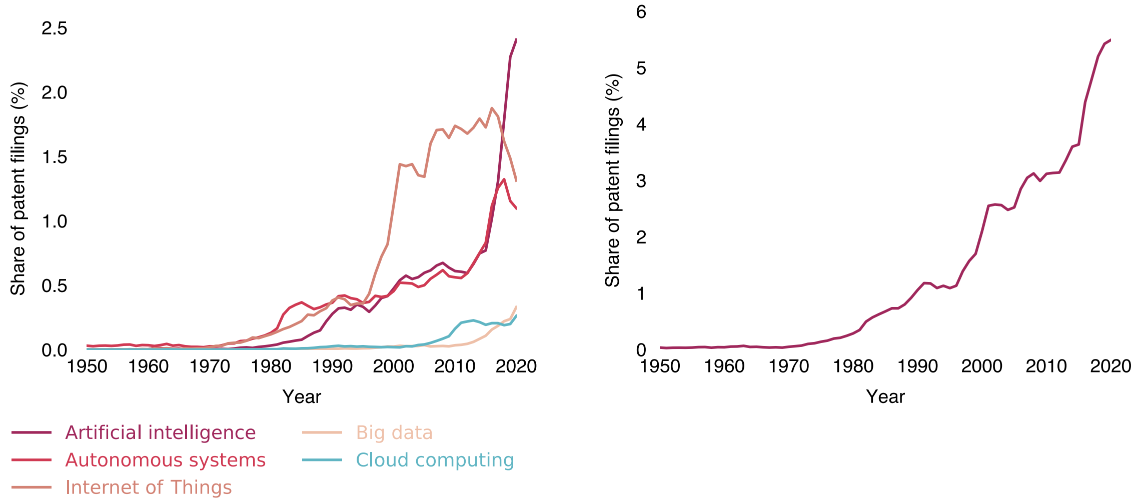
The nature of digital general-purpose technologies is that they are everywhere, spur innovation in complementary fields and can be applied across many sectors and industries. Previous general-purpose technologies, such as the steam engine, electricity, and information and communication technology (ICT) (see Chapter 1), are closely associated with the world's first three industrial revolutions. The full integration of digital technologies into economic activities arguably marks a fourth such revolution – a fully data-driven economy.[108]

Digital general-purpose technologies are a natural consequence of the general digitalization that comes from three interrelated but separate scientific and technical fields, namely, robotics, neural networks and symbolic systems. Both neural networks and symbolic systems are examples of how AI programs learn. These AI-based innovations are intelligent computational technologies that can execute a set of commands and improve their performance based on feedback and learning processes, without human intervention.
Advances in these fields have strong ties to government support through research grants, prizes and investments in enabling technologies. For example, the U.S. DARPA (see Box 3.1) held a competition in 2004, with a USD 1 million prize, for an autonomous vehicle (AV) – driverless or self-drive automobiles – able to complete a 240-km course.[109] The prize was considered important in stimulating research into AVs.

Incremental improvements in enabling technologies, such as in IT (see Chapter 2), together with increases in computing power and cloud computing – the delivery of different services, for example, data storage through the Internet – were supported by governments, especially at the initial stages.[110] Moreover, governments also made the necessary deep investments in complementary infrastructure, such as high-speed Internet.

Digital general-purpose technologies are growing faster than the average patent filings across all technologies

Figure 3.7 Share of digital general-purpose technologies by category (left), and as a percentage of all patent filings (right)



Source: WIPO based on PATSTAT.
Note: A patent may refer to more than one category.

As with climate-change technologies, governments will continue to play a role in the uptake of digital general-purpose technologies and the spurring of innovation by investing in enabling infrastructures, such as the networks needed for 5G wireless technology. 5G technology will deliver data in hugely greater volumes, at much higher speeds and with much greater reliability, making possible such revolutionary innovations as the Internet of Things (IoT) (see below).

In addition, our dependence on digital technologies and services has increased over the course of COVID-19 pandemic. During lockdowns, consumption patterns and business activities changed. Consumers made more home-based purchases and used digital services for almost everything.[111] Businesses able to adopt digitalization or work online were more resilient to the adverse impact of the pandemic. Those that were not faced having to close their doors.

Industries that supported remote working, such as video communication platforms, saw an uptick in their businesses. Those businesses that did not initiate remote working, or were unaccommodating, later found it difficult to get employees back to the office. Many restaurants and retail stores that required customers to be on the premises had to shut down.

At the heart of these new services are digital platforms, technology-enabled tools that facilitate transactions between people (online marketplaces), provide infrastructure to build new products or services (mobile applications) or create institutional infrastructure (the database block chain).[112]

Global patent filings – a proxy for the innovation going on – have exploded for digital general-purpose technologies in the past four decades, as Figure 3.7 shows. This growth is faster than for IT-related technologies.

However, the influence of these technologies across economic sectors and countries is uneven. Digitization of information is an essential component of how these technologies work. By accessing massive amounts of information, the technology is able to deduce patterns from the information provided, and with training learn to identify specific patterns and trends. But sufficient computing power is necessary to allow for the processing of large amounts of digitized information. This requirement could pose further difficulties for lesser developed economies in competing in the new economic age.

Innovation becomes a two-way street

Digital general-purpose technologies are transforming industries by bringing in new innovators, structures, practices and values. Traditional innovators face competition from IT-based firms. For example, traditional automobile manufacturers are having to compete with Silicon Valley-based technology companies in developing AVs.[113]

In health, smartwatch manufacturers are measuring vital health information – daily – which can provide useful insights during medical examinations. In defense and logistics, drones are being used for intelligence reconnaissance and deliveries.[114] Even in tourism, online services and mobile applications (apps) are ringing the changes, letting people organize travel in someone else's car, instead of a taxi, or sleep in someone else's house instead of a hotel.

The technologies are changing the kinds of innovations taking place. Much of today's innovation builds on digital technologies, giving rise to new industries, such as the IoT, a system of interrelated and Internet-connected objects and devices able to collect and transmit data without human intervention. Instead of advertising in magazines or buying airtime on television, cosmetic companies are reaching out to "influencers" or placing adverts on search engines and social media platforms. Products and services are crowdsourced, whereby users give feedback on the performance and services provided, which gives buyers useful insights before purchasing.

In the medical field, AI technology can be trained to detect abnormal cell growth in the body. It can contribute to research in precision medicine, whereby treatments are customized to specific patient conditions.[115]

In addition, digital general-purpose technologies are changing the way we use digital technologies themselves. They are interactive, learning from us as we are using them. This makes them different from the IT innovations of the late 20st century. Previously, interaction with technology was one way. Take the example of large robots in automobile manufacturing. These pre-programed robots allowed for the mechanization of certain repetitive, labor-intensive tasks. Any improvements to how the robots operated required the technical expertise of mechanical engineers and experts, plus trial and error learning from the users of those robots.

Nowadays, AI-based technologies are leveraging the large data collected with their huge data processing resources to self-improve.[116] A prime example is how we use the location application on smartphone devices. When we search for the fastest or most convenient route to reach a desired destination – given the traffic conditions – the information we provide includes location, time of search and where we want to go, among other things. Extrapolating this request to others results in a large dataset that feeds back into the location system, which in turn improves its usefulness and productivity in real time.

Another example is when we tag images of our friends on social media platforms. The large data collected through this effort trains the AI to better recognize faces, which it will then use to suggest future tagging efforts when identifying people in pictures. This interactivity and feedback makes the technologies smart and reactive.[117]

Speeding the process of innovation

Digital technologies have huge potential benefits. Universities and firms are relying on AI techniques, such as deep-learning neural networks, to advance science. Deep learning refers to the use of multiple layers of artificial neural networks, which are computing systems inspired by the neural systems of the human brain. Medical researchers are using these AI learning techniques to help identify, diagnose and treat diseases.

Machine translations let us understand websites in different languages. When eBay, a platform which facilitates online consumer-to-consumer and business-to-consumer sales, introduced machine translation in May 2014 in Latin America, its revenue increased by 13.1 percent and exports via eBay from the United States to Latin America grew by 17.5 percent.[118]

The application of digital general-purpose technologies in research is speeding up the process of innovation and making R&D more efficient. In agriculture, for example, digital technologies, such as soil sensors, are providing information on the condition of the soil. If soils are too dry, the sensors alert the system to hydrate the crops. This makes farming more efficient.

In the space industry, AI is expected to help develop technologies that will allow robots and machines to operate autonomously without human instruction. This will become necessary as exploration goes deeper into space, beyond the reach of communication with Earth (see Chapter 2).

The following sections take a more in-depth look at how digital general-purpose technologies are likely to influence and stimulate innovation in transportation, health care and education.

Optimizing transportation systems

As noted, digital general-purpose technologies, particularly AI, could help alleviate road congestion through "smart" traffic management. Mobile devices are currently being used by map apps, such as Waze and Google Maps, to suggest convenient routes to get to a specific location.

But the information about users' locations could also be used by public agencies, such as road and infrastructure authorities, traffic controllers and even public transport agencies, to address road congestion problems. Differentiated road-pricing policies could charge users for the time they spend on the road or whether they are car-sharing, for example. Higher road prices at specific times could encourage the use of public transport. In addition, public transportation agencies could use the data to decide the frequency of buses at different stops. Improvements in public transport through better reliability and punctuality might encourage greater use of the system, thereby reducing not only congestion but also carbon emissions.

Optimizing medical research and health care

Digitalization is transforming the medical care industry. A new wave of digital general-purpose technologies is making the R&D process in medicine more efficient. These technologies have the potential to improve disease detection and drug discovery.[119] AI technologies can scan patients' genetic codes and identify gene sequences indicating particular diseases better and faster than humans. For example, researchers are optimistic that AI can be used to conduct early screening for the SARS-CoV-2 virus and identify therapeutics able to contain future outbreaks.[120]

These technologies can customize health care provision to patients. Wearable devices, such as watches or wristbands, will help detect brain seizures and alert both the patient and others. These smart devices can also collect data, which can be analyzed by doctors and help provide better health care. They can help optimize how emergency care in hospitals is organized. When a patient is on the way to an emergency room, vital information about them could be communicated instantaneously to the hospital. In addition, patients who may not need immediate attention can be directed to visit the hospital at non-peak hours or to schedule an appointment with their general practitioners instead, so helping prevent unnecessary crowding in emergency rooms.

In some developing economies, drones are already helping overcome poor transport networks by delivering medical care and treatment. For example, during the COVID-19 pandemic, a public–private partnership between UPS (a postal service provider), start-up Zipline and GAVI (an intergovernmental organization aiming to provide vaccines for all) delivered vaccines to the Ashanti region of south Ghana. The drones can cover up to 69 km relatively quickly and transport vaccines without the need for cold storage to keep them viable.[121]

Improving access to education

Digital general-purpose technologies were already transforming aspects of teaching. But the global lockdown to contain the spread of COVID-19 quickened this process. It was arguably the largest educational experiment ever. The swift shift from in-person to virtual classrooms prompted changes in how teachers teach and how students learn. Teachers had to invent ways to reorganize and create content for the virtual classroom experience that engaged their students.

New research in facial recognition is being tested to signal to teachers when students are no longer listening, allowing them to adjust their teaching accordingly. This experimentation will lead to continuous innovation to provide more personalized education.

With more courses being offered online, students are better able to choose those that best fit their learning experience and needs. The effect should also be in some cases to improve access to education systems which, because of the long distances that sometimes needed to be travelled or the cost, were not always readily available to all.

Digital innovation will also transform what is being taught. AI, automation and other technologies will make certain occupations obsolete and give rise to new ones. These new occupations will require different sets of skills. The low-skilled labor of repetitive and routine work is likely to be displaced by automation. In its place will be a demand for high skill sets, with workers comfortable with AI and its related technologies. These skill sets are likely to include analytical, creative and adaptive abilities, as well as soft skills such as critical thinking, problem-solving, management and leadership.[122]

Up- and downsides of the new revolution

As we have seen, digital general-purpose technologies are changing the direction of innovation. Change will continue and could even quicken, given our increasing reliance on these technologies and the innovation they bring. But the benefits to economic growth are not automatic.

These technologies can spur economic growth when they generate innovation that complements and enhances human productivity. But they risk worsening economic inequality when innovation simply replaces the need for people.[123] Automation may affect a large part of a population, arguably more so than was the case with previous general-purpose technologies.[124] Rising unemployment would aggravate inequality. Even for those governments able to provide social safety nets for the unemployed, increasing unemployment could still strain budgets and might force them to reduce spending in important areas such as education and health.

Some developing economies may not be ready to benefit from a Fourth Industrial Revolution (see Chapter 1).[125] The new wave of technological advances requires major capital investment and a high-skilled labor force. But low-income economies are characterized by relatively abundant supplies of low-skilled labor and limited resources for capital investment. In addition, a lack of necessary infrastructure could further limit the potential benefits of digital general-purpose technologies in poorer economies.

As noted earlier, government authorities could use the huge amounts of data generated by digital general-purpose technologies to generate important social returns, such as improving public infrastructure or tracking the outbreak of diseases in populations.

But most of the data is held by a handful of large technological companies. These companies collect the data through the technological services they provide. Take the example of location apps. A user activating a location app in Malaysia will be sending information to servers owned by for-profit corporations headquartered outside the country. The data sent would include the location, time and the user's preferred mode of transport. Public transport agencies and epidemiologists could use the data to help generate analyses that, in this case, could benefit the Malaysian public. However, they may not have access to the information, because the data are stored on private servers in another country.

National security is also a concern in some countries. The interconnectedness between different digital technological innovations, with devices possibly providing sensitive information to third parties, calls into question how secure the technologies are. Governments worry about the extent to which highly confidential industries and bodies, such as national defense departments, should rely on them, given the risks of hacking.

Governments can attempt to direct digital, technology-led innovation in ways that maximize societal benefits, while safeguarding the interests of the private sector and markets. For example, governments could seek to encourage innovations that are job creating or welfare enhancing rather than job replacing.[126] Technologies that are enhancing include using AI technology to generate live captioning and simultaneous translations, which facilitate business transactions, increase productivity and generate economic growth. Technological innovations that are job replacing could include substituting robots for low-skilled labor, although evidence that this results in long-term job losses is far from conclusive. Two studies on high-income economies find that the adoption of industrial robots – relatively automated machines integrated within specialized industrial processes – has led to greater productivity.[127] It is unclear whether this findings can be extended to include poorer economies, where the share of low-skilled labor tends to be relatively higher.

Governments may also have an important role in data privacy, in particular in deciding what kind of information is being collected and how it is being used. Should the data collected from individuals from different parts of the world – even if anonymous – be owned by private companies? Could the information collected be used in a manner that would undermine market competition? Antitrust authorities in the U.K., the EU and the U.S., among others, are investigating these issues (see Box 3.4).[128]

The interests of private firms may not align with what society needs. Could access to private citizens' data, collected using privately-owned technologies, be governed in a way that ensures the widespread societal benefits of harnessing digital technologies for innovation, while respecting privacy and national security concerns? There are no obvious answers or solutions to this question. But the existence of concerns provides some justification for governments to intervene.

Box 3.4
Big tech firms: anti-trust concerns

Google/Alphabet, Apple, Facebook/Meta, Amazon and Microsoft own the world's most frequently used digital platforms.[129] These five IT-based companies provide different and competing services, including search engines, social networks, smart devices, such as wearable devices, cloud computing and more. Their business models are different. Google is a search engine that generates revenues by selling targeted advertisements. Amazon is the digital equivalent of a traditional retailer, selling merchandize through its platform.

The fast pace of technological development and the integrated nature of the digital market pose some challenges for competition law and policy. Their adaptation to new market realities and business models is critical to ensuring competitive and contestable markets.[130]

These five providers control substantial market power, especially in the digital market. Due to their vertically-integrated platforms, the information these firms gather from users could be leveraged to optimize downstream products and services. From an economic efficiency view, this is a welcome development. Product bundling, such as the interoperability between apps and payment methods for the app, is often in the interest of consumers and app producers alike.

From an anti-trust standpoint, a few firms controlling a large share of the economic system may be detrimental to further innovation and future economic growth. It raises competitive issues about whether leveraging market power in an upstream vertical segment might stifle competition and innovation downstream. For example, by using data collected from past user purchasing patterns on the digital platform to offer similar but competing products from the parent company of the digital platform, or selectively displaying those products ahead of others.

There are several economic arguments to counter suggestions of an anti-trust threat from the digital platforms. These companies are continuously innovating and competing with one another.[131] There is no barrier to entry in the traditional anti-competition sense. It is relatively easy for new products or new competitors to enter the market, and the costs are arguably low. Any IT firm can arguably set up its own digital platform and consumers can switch from one digital platform to another. Many of these services are provided at no monetary cost to the consumer. That said, these big firms may have a significant competitive edge over new rivals with regards to their first-mover advantages, such as with the creation of a product ecosystem and user lock-in. Users may be reluctant to choose a different platform, because they are used to the current one and the costs of switching may be burdensome.[132]

Moreover, digital platforms are only as good as the number of services they offer on their platform, which in turn is linked to the number of users. More apps imply more users and more users attract other app producers to build on the digital platform. Moreover, consumer data has become an important source of competitive advantage in many digital markets. So, attracting and having a critical volume of services and users may in some sense be considered a barrier to entry.

Several competition authorities are studying digital platforms from an anti-trust perspective.[133] Investigations by a select few include focusing on:
– the digital platforms' search results, because they are "self-preferencing" of their own products and services;[134]
– platforms' anti-competitive behaviors to preserve their market power;[135] and,
– mergers and acquisition activities to remove potential rivals.[136]

But how are competition authorities to address any anti-trust issues in this market? They may not have the capacity to deal with these giant technological firms and the complexities of their vertically-integrated platforms.[137] Moreover, any judgement may be difficult to implement and could even harm competition.[138]

3.4 Public policy can harness innovation to address the challenges

The process of innovation involves the interdependence or interaction of different stakeholders in the innovation ecosystem. In climate change, the interdependent behavior of a variety of actors influences the direction and pace of green technology innovation. These actors include start-ups specializing in environmental technologies, firms in the energy sector, government institutions, such as the U.S. Environmental Protection Agency, and universities, as well as intergovernmental organizations, such as the UNFCCC.

This section focuses on government action. Governments can get involved in various ways, from financing research to imposing regulations or setting targets to change the direction of innovation, as seen in the discussion of health (COVID-19), climate change and the rise of digital general-purpose technologies.

Encouraging innovation for society's benefit

Governments may wish to influence the direction of change to maximize societal benefits. There are generally three arguments in favor of policymakers doing so.

When the needs of society and the goals of for-profit private companies are misaligned, governments can, and probably should, step in. This is particularly the case, as we saw in Chapter 1, when the social returns to or benefits from addressing society's needs – to contain pollution, for example – far outweigh the private returns to continuing with business as usual.

In the case of climate change, government programs, policies, rules and standards are playing an important role in directing innovation toward mitigation technologies. With digital technologies, governments may seek to avert or soften potentially negative impacts, especially when the increased use of AI, for example, is likely to lead to big job losses, or where there might be data privacy, competition or national security issues.

Due to market competition, firms tend to invest in innovation activities that yield the highest payoff in the shortest time. Established firms avoid innovation activities that are risky and uncertain. This explains why most of the climate-change mitigation technology breakthroughs are by new-to-the-industry start-up firms.

In the biomedical field, firms will look to make investments in activities likely to have relatively immediate commercial applications.[139] This includes instances where pharmaceutical companies prefer to re-purpose existing technologies in order to continue treating diseases rather than invest in vaccines or new medical cures. For society, investing in medical research with a longer-lasting impact, but which requires more time and effort to materialize, is far preferable to re-purposing existing treatments and technologies.

Governments may need to react to crises with programs or initiatives. With the COVID-19 vaccine, the large amount of funding and support provided in finding ways to mitigate the impact of the SARS-CoV-2 virus quickly is justified by the importance of finding a solution.[140] Government support in developing and manufacturing vaccines on a large scale was key to their rapid deployment. Both the U.S. and U.K. initiatives (see Boxes 3.1 and 3.2) supported vaccine development, from the initial R&D into likely candidates, through their testing and final approval by regulatory agencies to the scaling up of production and distribution of the vaccines. Even those vaccine investments that led nowhere, because they proved unviable, cannot be regarded as money wasted, given the huge uncertainty at the beginning as to what would work.[141]

Similar governmental support in addressing climate change could be important in helping achieve the less than 2°C global warming target set for the end of the century. But action is needed at all levels, from the multilateral down to individual households. A report by the IEA recommends drastic changes to meet the goal set by governments in 2015 and reaffirmed in 2021.[142] Investment in low-carbon technologies should more than triple to around USD 4 trillion a year by 2030, it says. All sales of internal-combustion engine passenger cars should stop by 2035 and all coal and oil power plants be phased out by 2040. In short, a complete transformation of the global energy system is needed.[143]

Shaping the direction of innovation

Governments can impose rules and regulations that drive the private sector toward investing in certain types of innovation. In the case of climate change, policies such as carbon pricing are playing a role in inducing the private sector to adopt low-carbon or carbon-mitigation technologies.

Similarly, for the new digital technologies, governments can regulate the use of data collected from users. The EU's General Data Protection Rules (GDPR) are designed to prevent the misuse of information from private citizens, for example, for commercial marketing purposes or for unauthorized tracking of a user's movements. Intellectual property protection policies define what digital general-purpose technologies may or may not be patented – or rather, they do up to a point. AI can generate new inventions. However, in many jurisdictions, patents may only be applied to inventions made by humans. Those created by sophisticated computer algorithms are not covered.[144] AI-generated innovation may have to rely on other IP instruments, such as trade secrets, to ensure protection from imitation.

State investments in enabling and/or complementary technologies and infrastructures can facilitate the uptake of innovations in critical fields. For example, upgrading electricity grids to enable greater use of renewable energy sources could quicken the uptake of climate-change mitigation technologies and reduce CO_2 emission. Governments could invest in building battery-charging stations to encourage the use of electric vehicles. The potential benefits of investments made by the United Kingdom and United States governments in their countries' capacity to manufacture cutting-edge technology to combat COVID-19 could leave them well placed to react to similar pandemics in the future.

Box 3.5 provides an overview of selected government policies that target specific innovation activities considered critical for economic growth.

Box 3.5

Selected government policies for building innovative digital capacities

USICA[145]

The U.S. Innovation and Competition Act (USICA) of 2021 is one of the biggest industrial legislative proposals in U.S. history. It "aims to strengthen U.S. innovation ecosystems through new investments in research, commercialization and manufacturing." Key policies include:

- substantial funding for scientific research and the production, sale and licensing of specific technologies to consumers in critical fields, such as AI, robotics, 5G telephony and semiconductors.[146] Part of the funding would go to broadening education in science, technology, engineering and mathematics (STEM).
- ensuring continuity of supply chains for access to raw materials, for example; and
- establishing technological hubs in different parts of the United States to build capacities in those regions and stimulate economic growth.

Made in China[147]

"Made in China 2025" is a 10-year strategic plan, launched in 2016, to move China up the global value chain and make it one of the frontier economies in technologies. It will achieve this by:

- developing manufacturing capability in cutting-edge advanced technologies (namely, digital general-purpose technologies);
- prioritizing technologies relating to 10 fields: IT, robotics and automation, aerospace and aviation equipment, maritime engineering equipment and high-tech vessel manufacturing, rail equipment, energy-saving vehicles, electrical equipment, new materials, biomedicine and high-performance medical apparatus, and agricultural equipment.

Horizon Europe[148]

"Horizon Europe" is an EUR 100 billion research and innovation funding program that runs until 2027. It aims to build, develop and strengthen Europe's scientific and technological knowledge base. It has four pillars:

- building the EU's scientific competitiveness;
- investing in research to address societal challenges and strengthen industrial capacities;
- fostering the integration of education, research and innovation to facilitate innovation; and
- supporting EU members in building their innovative capacities.

Industry 4.0
Germany's "Industry 4.0," announced in April 2013, is a strategic plan for manufacturing that focuses on the digital transformation of the German economy. It covers fields such as industrial integration, industrial information integration, manufacturing digitization, the IoT and AI. Its basic mission is to take German industry into the digital age.

3.5 Conclusions and policy recommendations

The case studies on the COVID-19 crisis, the climate change imperative and rise of digital general-purpose technologies have shown how the direction of innovation has changed and will continue to change. They also suggest how public policies can steer innovation in a direction that best responds to societies' needs.

In the case of COVID-19, governments helped reduce investment uncertainty and mitigate the risks associated with first discovering and then developing a vaccine. In climate change, government policies, standards, rules and regulations are helping direct companies and households toward greener technologies. Finally, in the case of digital technologies, governments invested in and built enabling technologies – and in the case of 5G are continuing to do so – that facilitated innovations and their adoption.

It is difficult to say whether similar progress would have been made without government support. There is no comparable counterfactual. But there are strong arguments in support of the positive impact of government action in the speed and direction of innovation. Moreover, governments are uniquely placed to preempt any potentially negative impacts of innovation, for example, on employment, and to create the right incentives and enabling environment to promote and harness its potential.

Lessons learned through these case studies point to several key policy messages:

- The direction of innovation matters, because resources to invest in innovation are scarce. Policymakers should focus not only on how much is invested, but also in which areas.
- Policymakers have limited influence over the long-term direction of innovation, because long-term technological opportunities are unpredictable. However, through funding of basic science, governments play a crucial role in enabling scientific and technological breakthroughs that shape the future direction of innovation (even if in uncertain, unpredictable ways).
- Government policy shapes the direction of innovation in the short- to medium-term by:
  - aligning private innovation incentives with societal needs;
  - implementing policies that regulate new technologies (especially digital general-purpose technologies) and which can shape innovation and the adoption of new technologies. Examples include data governance, competition and even IP policies. However, a balance must be struck between facilitating innovation, promoting competition and protecting privacy rights;
  - funding education, health, infrastructure and other public goods. For example, digital general-purpose technologies offer a significant opportunity to improve education and health outcomes.

Notes

1 Bresnahan and Trajtenberg (1995).
2 This is different from the market failure concept, which justifies government intervention. In this chapter, government intervenes, because not everything should be left to the market (see Foray *et al*., 2012; Mowery *et al*., 2010).
3 World Health Organization. WHO Coronavirus (COVID-19) Dashboard [online]. *WHO Coronavirus (COVID-19) Dashboard*. Available at: https://covid19.who.int (accessed January 2, 2022).
4 Ansell and Mullins (2021), Crossley *et al*. (2021).
5 This number was revised downward by 20 million from the last estimate in January 2021. See Mahler *et al*. (2021).
6 See the *World Economic Outlook* (IMF, 2021) and Kose and Sugawara (2020).
7 https://www.gavi.org/vaccineswork/covid-19-vaccine-race.
8 Scientists at the Shanghai Public Health Clinic Center, led by Professor Zhang Yongzhen, mapped the COVID-19 virus genome in under 40 hours from when they received the first sample. They uploaded the genome map onto the U.S. National Center for Biotechnology Information (NCBI) on January 5, 2020. On January 11, 2020 the mapped sequence of COVID-19 was shared publicly (Campbell, 2020).
9 Bown and Bollyky (2021).
10 Acemoglu and Linn (2004), Clemens and Rogers (2020) and Kyle and McGahan (2011).
11 Many economists acknowledge that the size of a market alone may not provide sufficient incentive to innovate. Some of the factors that also influence whether pharmaceutical companies decide to invest in a disease relate to the costs and duration of finding a solution, and even the ability to pay for the innovation. Some diseases that may afflict a large population size but to a small number of patients. See Agarwal and Gaule (2021), Budish *et al*. (2015) and Kremer (2001, 2002).
12 Kelly (2020).
13 CEPI is a partnership between public, private, philanthropic and civil society organizations. See https://cepi.net/research_dev/our-portfolio.
14 Economists like Mariana Mazzucato (2016, 2018) have been advocating this type of intervention to address societal challenges for the last decade. Two economists, Pierre Azoulay and Benjamin Jones, wrote to the U.S. Government urging it to do so (2020).
15 Bown and Bollyky (2021).
16 Regalado (2020).
17 Wagner and Wakeman (2016).
18 Adler (2021) and Diamond (2021). It was initially referred to as "Manhattan Project 2" (Diamond, 2021).
19 Diamond (2021).
20 See Bonvillian *et al*. (2019).
21 Adler (2021) reports how OWS is thought of as DARPA at scale.
22 GAO (2021).
23 UK BEIS (2020).
24 For an explanation of the different types of COVID-19 vaccines and how they work, see https://www.gavi.org/vaccineswork/there-are-four-types-covid-19-vaccines-heres-how-they-work.
25 The sign-up and volunteer registry dashboard are online at the U.K.'s National Health Service websites: https://www.nhs.uk/conditions/coronavirus-covid-19/research and https://digital.nhs.uk/dashboards/coronavirus-covid-19-vaccine-studies-volunteers-dashboard-uk (accessed November 29, 2021).
26 Scheuber (2020).
27 Cookson (2021), Mancini *et al*. (2021).
28 Durmaz *et al*. (2015) and Gross and Sampat (2021).
29 Adler (2021).
30 This is known as "parachuting collaboration" (Liu *et al*., 2021).
31 This section is based on background report to WIPO by Bhaven Sampat (2022).
32 Pardi *et al*. (2018) and Schlake *et al*. (2012).
33 Pardi *et al*. (2018).
34 Most vaccines are targeted at lower income countries (Xue and Ouellette, forthcoming).
35 The mRNA cannot combine with the patient's DNA to change their genetic makeup. Once the synthetic mRNA has executed its function, it degrades and is eliminated from the body (Dolgin, 2021).
36 Shipman (2021).
37 See Myers (2020).
38 See Sohrabi *et al*. (2021).
39 Agarwal and Gaulé (2021).
40 These vaccines were approved using the Emergency Use Authorization scheme.
41 Agrawal *et al*. (2021).
42 Woolliscroft (2020).
43 This section is heavily based on the background report by Noailly (2022).
44 IPCC (2014).
45 Hellegatte *et al*. (2017).
46 See https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement, accessed online December 4, 2021.
47 In its 2015 nationally determined commitment (NDC), the U.S. stated its aim of reducing greenhouse gas emissions to 26–28 percent below its 2005 emission level by 2030. At Glasgow, the U.S. 2021 NDC deepens that commitment to reducing its 2005 emission level by between 50–52 percent by 2030. To access the NDC registry, see https://www4.unfccc.int/sites/NDCStaging/Pages/Home.aspx, accessed online December 4, 2021.
48 See the discussion of low-carbon technologies in Noailly (2022). Greenhouse gas emission refer to gases that keep the Earth warmer than it should be. These gases absorb and re-emit heat

into the atmosphere. They include CO_2, methane, nitrous oxide, ozone and water vapor.

49 Nuclear energy is also a climate-change mitigation technology (CCMT). Countries have different definitions of what they consider low-carbon technologies that align with climate mitigation goals. Nuclear and gas-fired power plants are technically considered low-carbon, but some countries do not define them as such (Noailly, 2022).

50 See the glossary of environmental-related terminologies (IPCC, 2018).

51 Gerarden (2018).

52 Lim *et al*. (2021) and Mundaca and Luth Richter (2015).

53 Jansen *et al*. (2020).

54 Johnson (2020).

55 IEA (2020a).

56 The IEA maintains a database on environmental policies implemented by member states. These policies can be searched by topic, sector and type. An example are policies targeted at technology, R&D and innovation: https://www.iea.org/policies?topic=Technology%20R%26D%20and%20innovation.

57 Bird *et al*. (2002).

58 Popp *et al*. (2010).

59 Popp (2019) and Popp *et al*. (2010).

60 McCulloch (2021).

61 https://carbonpricingdashboard.worldbank.org.

62 https://unfccc.int/about-us/regional-collaboration-centres/the-ci-aca-initiative/about-carbon-pricing#eq-6.

63 Rogge and Dütschke (2018).

64 The German feed-in tariff policy is arguably not a subsidy (Wilke, 2011).

65 Noailly (2012).

66 IRENA and CPI (2020).

67 The price for using its carbon-offset service is USD 1,000 per tonne. This is expected to decrease over time as the plant becomes fully operational (Sigurdardottir and Rathi, 2021).

68 Cohen *et al*. (2020) and Noailly and Smeets (2015).

69 Between 2015 and 2018, large firms in the oil and gas industry accounted for 37 percent of global capital investment in carbon capture, usage and storage (CCUS) projects (IEA, 2020b).

70 IPCC (2014).

71 WIPO (2017).

72 https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1958-002B.

73 https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf.

74 Gerarden (2018).

75 WIPO (2017).

76 WTO and IRENA (2021).

77 Between 2013 and 2019 (IRENA and CPI, 2020).

78 WTO and IRENA (2021).

79 IEA (2021c).

80 Li *et al*. (2017).

81 http://ww2.arb.ca.gov/sites/default/files/movingca/cvrp.html.

82 China cut subsidies for electric vehicles by half, while the U.S. tax credit program ran out for automakers such as General Motors and Tesla (IEA, 2020c).

83 IEA (2020c).

84 Li *et al*. (2017).

85 https://www.economist.com/finance-and-economics/2021/03/27/the-impact-of-green-investors.

86 Viscidi (2021). USD 38 billion in first quarter of 2020 versus USD 178 billion in first quarter of 2021.

87 Flood and Cumbo (2021).

88 O'Dwyer and Edgecliffe-Johnson (2021).

89 https://www.whitehouse.gov/briefing-room/statements-releases/2021/07/28/fact-sheet-historic-bipartisan-infrastructure-deal.

90 https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation.

91 https://www.whitehouse.gov/briefing-room/statements-releases/2021/10/28/president-biden-announces-the-build-back-better-framework. See also Lobosco and Luhby (2021) and Sommer (2021).

92 https://www.consilium.europa.eu/en/policies/eu-plan-for-a-green-transition/.

93 http://www.cdb.com.cn/English/xwzx_715/khdt/202106/t20210630_8759.html.

94 https://www.icao.int/environmental-protection/Pages/SAF_Stocktaking.aspx.

95 See Breakthrough Energy (2021).

96 Taylor (2020).

97 Popp (2019).

98 Gaddy *et al*. (2017).

99 Gaddy *et al*. (2017) and Noailly and Smeets (2015).

100 IEA (2021b).

101 Nanda *et al*. (2014).

102 Aghion *et al*. (2016) and Noailly and Smeets (2015).

103 Acemoglu *et al*. (2019).

104 Unruh (2000).

105 Fabrizio and Hawn (2013).

106 McCarthy *et al*. (2006) proposal states, "every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it."

107 Scholars debate whether AI and its related technologies are digital general-purpose technologies and/or enabling technologies or "invention of methods of inventions" (IMIs) (Bigliardi *et al*., 2020; Cockburn *et al*., 2019; Martinelli *et al*., 2021). Cockburn *et al*. (2019) argue there is a difference in technologies that are developed with relatively narrow tasks, such as robots, versus those with a technology-wide domain of applications. In trying to distinguish between the two, the co-authors alternate between categorizing AI and its related technologies as digital general-purpose technology (GPT) or "invention of a methods of inventions." They settled for GPT IMIs. Nonetheless, these digital technologies can influence the direction of innovation over the long-term.

108 There are debates about whether or not the rise of AI and such like technologies are extensions of the Third Industrial Revolution. Klaus Schwab, the Founder and

Executive Director of the World Economic Forum, arguably coined the term (Schwab, 2016).
109 See Chapter 3 on autonomous vehicles in WIPO (2019a).
110 Firms are more likely to adopt AI when already relying on big data and have sufficient computing power (Brynjolfsson and McAfee, 2014).
111 Yilmazkuday (forthcoming) found that consumer expenditure increased by 16 percent and online shopping by 21 percent in comparison to pre-pandemic trends.
112 Geradin (2018) and Hinings *et al*. (2018).
113 See chapter 3 on autonomous vehicles in WIPO (2019a).
114 See chapter 3 on robots in WIPO (2015).
115 See WIPO (2019b) for more examples.
116 Brynjolfsson *et al*. (2017).
117 See WIPO (2019b) on the ethical dilemma surrounding AI technologies.
118 Brynjolfsson *et al*. (2018).
119 See Kudumala *et al*. (2021) for further examples.
120 Dogan et al. (2021), Khan *et al*. (2021) and Vaishya *et al*. (2020).
121 https://about.ups.com/be/en/social-impact/the-ups-foundation/health-humanitarian-relief/delivering-what-matters--equitable-vaccine-access-globally.html.
122 Trajtenberg (2019).
123 Aghion *et al*. (2017) and Brynjolfsson and McAfee (2014).
124 Trajtenberg (2019).
125 Fu and Liu (2022).
126 Trajtenberg (2019).
127 See Cockburn *et al*. (2019); Graetz and Michaels (2018).
128 See Espinoza (2021), Espinoza and Beioley (2021), Kalra (2021) and Song (2021). The U.S. Department of Justice case files are available online at https://www.justice.gov/atr/case/us-and-plaintiff-states-v-google-llc.
129 The term digital platform is applied loosely here. These five firms provide different services and have different business models (Gilbert, 2021).
130 UNCTAD (2019).
131 Gawer (2021) and Varian (2021).
132 See OECD (2021), 7–8.
133 The Australian Competition and Consumer Commission, the French *Autorité de la concurrence*, and the UK's Competition and Markets Authority concluded their studies on September 21, 2021, June 7, 2021 and July 1, 2021, respectively. See https://www.accc.gov.au/publications/digital-advertising-services-inquiry-final-report, https://www.autoritedelaconcurrence.fr/fr/communiques-de-presse/lautorite-de-la-concurrence-sanctionne-google-hauteur-de-220-millions-deuros, https://www.gov.uk/cma-cases/online-platforms-and-digital-advertising-market-study for further information. The European Union opened its investigation on June 22, 2021 (see https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3143), while the U.S. Department of Justice is reportedly preparing to sue Google (see https://www.reuters.com/technology/us-doj-preparing-sue-google-over-digital-ads-business-bloomberg-news-2021-09-01).
134 For example, the European Commission's investigation into Amazon and Google (Geradin, 2018), and the Indian authorities into Amazon and Flipkart (Kalra, 2021).
135 For example, Google was arguably paying other service providers to keep its search engine as the default (Molla and Estes, 2020; Nellis, 2020; Park, 2021).
136 The U.S. Federal Trade Commission argues that Facebook's acquisition of Instagram and WhatApp amounts to anti-competitive behavior harmful to consumers. See https://www.ftc.gov/enforcement/cases-proceedings/191-0134/facebook-inc-ftc-v.
137 Gilbert (2021).
138 Waller (2009).
139 See Bryan *et al*. (2020), Budish *et al*. (2015) and Hanisch and Rake (2021).
140 Sampat (2022).
141 Nelson (1961) and Scherer (2011).
142 On December 12, 2015, 196 nations pledged to limit the rise global temperature to less than 2°Celsius at the 21st Convention of Parties of the United Nations Framework of Climate Change Convention (UNFCCC) in Paris, France. See https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement.
143 IEA (2021c).
144 The WIPO Conversation on IP and Frontier Technologies provides the forum to discuss these issues.
145 https://www.whitehouse.gov/wp-content/uploads/2021/05/SAP-S.-1260.pdf.
146 Of the USD 250 billion, slightly over USD 50 billion will go to the National Science Foundation (NSF).
147 http://english.www.gov.cn/premier/news/2017/01/29/content_281475554068056.htm.
148 https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en.

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Patent data

The patent data used in this report are from the European Patent Office's (EPO) Worldwide Patent Statistical Database (PATSTAT, October 2021) and WIPO's Patent Cooperation Treaty (PCT) collections.

The main unit of analysis is the first filing for a set of patent applications filed in one or more countries and claiming the same invention. Each set containing one first and, potentially, several subsequent filings is defined as a patent family.

Mapping strategies

The patent mapping strategy for each of the case studies – digital-general purpose technologies and low-carbon technologies – is based on prior studies and experts' suggestions. Whenever possible, each strategy relied on and was compared to existing equivalent patent mapping exercises. The summary of these can be found as follows, for more details please see Noailly (2022), and Trajtenberg, Hamdan-Livramento and Daly (2022).

The mapping strategies is based on a combination of patent classifications – namely, the International Patent Classification (IPC) and the Cooperative Patent Classification (CPC) – and keywords applied to PATSTAT data.

Digital-general purpose technologies

The digital-general purpose technologies mapping was based on the following strategies for subcategories.

Artificial intelligence (AI) and Machine learning (ML)

IPC/CPC symbols: A61B 5/7264; A61B 5/7267; A63F 13/67; B23K 31/006; B25J 9/161; B29C2945/76979; B29C 66/965; B29C 66/966; B60G2600/1876; B60G2600/1878; B60G2600/1879; B60T2210/122; B60T 8/174; B62D 15/0285; B65H2557/38; F02D 41/1405; F03D 7/046; F05B2270/707; F05B2270/709; F16H2061/0081; F16H2061/0084; G01N2201/1296; G01N 29/4481; G01N 33/0034; G01R 31/2846; G01R 31/2848; G01S 7/417; G05B 13/027; G05B 13/0275; G05B 13/028; G05B 13/0285; G05B 13/029; G05B 13/0295; G05B2219/21002; G05B2219/25255; G05B2219/32193; G05B2219/32335; G05B2219/33002; G05B2219/33013; G05B2219/33014; G05B2219/33021; G05B2219/33024; G05B2219/33025; G05B2219/33027; G05B2219/33029; G05B2219/33033; G05B2219/33035; G05B2219/33039; G05B2219/33041; G05B2219/33044; G05B2219/34066; G05B2219/39284; G05B2219/39286; G05B2219/39292; G05B2219/39385; G05B 23/024%; G05B 23/0251; G05B 23/0254; G05B 23/0281; G05D 1/0088; G06F 11/1476; G06F 11/2257; G06F 11/2263; G06F 16/243; G06F 16/3329; G06F 16/583; G06F 16/5838; G06F 16/5846; G06F 16/5854; G06F 16/5862; G06F 16/683; G06F 16/685; G06F 16/783%; G06F 16/7834; G06F 16/784%; G06F 16/785%; G06F 16/786; G06F 16/7864; G06F2207/4824; G06K 7/1482; G06K 9/6269; G06K 9/6277; G06K 9/6278; G06K 9/6285; G06N 20%; G06N 3/004; G06N 3/006; G06N 3/008; G06N 3/02; G06N 3/04%; G06N 3/06%; G06N 3/08%; G06N 3/10%; G06T2207/20081; G06T2207/20084; G06T 3/4046; G06T 9/002; G08B 29/186; G10H2250/151; G10H2250/311; G10K2210/3024; G10K2210/3038; G10L 15/16; G10L 15/18%; G10L 15/1%; G10L 17/18; G10L 25/30; G10L 25/33; G11B 20/10518; G16B 40/20; G16B 40/30; G16C 20/70; H01J2237/30427; H01M 8/04992; H02H 1/0092; H02P 21/0014; H02P 23/0018; H03H2017/0208; H03H2222/04; H04L2012/5686;

H04L2025/03464; H04L2025/03554; H04L 25/0254; H04L 25/03165; H04L 41/16; H04L 45/08; H04N 21/466%; H04Q2213/054; H04Q2213/13343; H04Q2213/343; H04R 25/507; Y10S 128/924; Y10S 128/925; or, Y10S 706%.

IPC/CPC and keywords: (G01R 31/367; G06F%; G06F 16/245%; G06F 16/3334; G06F 16/3335; G06F 16/3337; G06F 16/35%; G06F 16/36%; G06F 16/374; G06F 16/435; G06F 16/436; G06F 16/437; G06F 17/16; G06F 17/2%; G06F 19%; G06K 9%; G06K 9/00973; G06K 9/46%; G06K 9/60%; G06N%; G06T%; G10L 15%; G10L 17%; G10L 21%; G10L 25%; G16B 40%; or; G16H 50%); and, (neural network; *supervis*.?learn*; *supervised*.?train*; adaboost; adaptive learning; adaptive.?boost*; adversar* network*; ANN; artific* intellig*; auto.?encod*; autonom* comput*; autonomous learning; back.?propagation*; bayes*.?network*; Bayesian learning; Bayesian model; blind signal separation; boosting algorithm; bootstrap aggregat*; brownboost; chat.?bot*; classification algorithm; classification tree; cluster analysis; CNN; cognitiv* comput*; cognitive automation; cognitive modelling; collaborat* filter*; collision avoidance; computation* intellig*; computer vision; conceptual clustering; connectionis[mt]; convnet[s]?; convolutional network; decision model*; decision tree*; deep forest; deep.?belief net*; deep.?learning*; dictionary learning; differential*.?evol* algorithm*; dimensional*.?reduc*; emotion recognition; ensemble learn*; evolution* algorithm*; evolution* comput*; expert system*; extreme.?learning.?machine; factori[sz]ation machin*; feature learning; fuzzy environment*; fuzzy logic; fuzzy set; fuzzy system; fuzzy.?c; fuzzy.?logic*; gaussian mixture model; gaussian process*; generative adversarial net*; genetic program*; genetic* algorithm*; gradient boosting; gradient model boosting; gradient tree boos*; Hebbian learning; hidden markov model; hierarchical cluster*; high.?dimensional* data; high.?dimensional* feature*; high.?dimensional* input*; high.?dimensional* model*; high.?dimensional*; space*; high.?dimensional* system*; hyperplane; independent component analysis; inductive* logic* program*; inference *learn*; inference *train*; Instance.?based learning; intelligent agent; intelligent classifier; intelligent geometric computing; intelligent infrastructure; intelligent machines; intelligent software agent; K-means; K-nearest neighbo[u]?r; latent dirichlet allocation*; latent semantic analys*; latent.?variable*; layered control system; learning{1,3}algorithm*; learning.?automata*; learning*.model*; linear regression; link* predict*; logi* regression; logic learning machine; logitboost; long.?short.?term memory; LPboost; LSTM; machine intelligen*; machine.?learn*; madaboost; Markov* decision process; memetic algorithm*; meta learning; multi agent system*; multi task learning; multi.?agent system*; multi.?layer perceptron*; multi* label* classif*; multi*.?objective* algorithm*; multi*.?objective* optim*; multinomial nave Bayes; natural language understanding; natural.?language* generat*; natural.?language* process*; nearest neighbour algorithm; neural.?turing; predictive mode; probabilist{1,2}algorithm*; probabilistic graphical model; random.?forest*; random* gradient*; rankboost; regression tree; reinforc* learn*; relational learning; rule.?based learning; self organising map; self.?learning*; self.?organising map; self.?organising structure; similarity learning; simultaneous localisation mapping; single.?linkage clustering; sparse represent*; stacked.?generali?ation; statistical relational learning; stochastic gradient descent; support.?vector machine*; support.?vector regress*; SVM; temporal difference learning; totalboost; training algorithm; transfer.?learn*; trust region policy optimization; variational inference; or, xgboost).

Autonomous systems

IPC/CPC symbols: A61B 34/32; A63B2047/022; A63H 27/00; B25J 9/0003; B60C 25/185; B60K2370/175; B60L2260/32; B60T2201/02%; B60W2030%; B60W2040%; B60W2050%; B60W2400%; B60W2420%; B60W2422%; B60W2510%; B60W2520%; B60W2530%; B60W2540%; B60W2552%; B60W2554%; B60W2555%; B60W2556%; B60W2710/00; B60W2720/00; B60W275%; B60W2900/00; B60W 30%; B60W 40%; B60W 50%; B60W60%; B61L 27%; B61L 27/04; B62D 15%; B62D 15/0255; B62D 15/026; B62D 15/0265; B62D 6%; B63B2035/007; B63G2008/002; B63G2008/004; B64C2201%; B64G 1/24%; B64G2001/247; E02F 3%; E02F 3/3645; E02F 3/434; E02F 3/437; E02F 3/439; E02F 5%; E02F 9%; E02F 9/2041; E21B 44%; G01C 21%; G01C 22%; G05D 1%; G05D 1/0061; G05D 1/0088; G05D 13%; G05D2201/0207; G05D2201/0212; G05D 3%; G06K 9/00624; G06K 9/0079%; G06K 9/0080%; G06K 9/0081%; G06K 9/0082%; or, G08G%.

IPC/CPC and keywords: (A63H 27/00; B62D 15%; B64G 1/24%; E02F 3%; E02F 5%; E02F 9%; G01C 21%; G01C 22%; G05D 1%; G05D 13%; G05D 3%; G06K 9/00624; G06K 9/0079%; G06K 9/0080%; G06K 9/0081%; G06K 9/0082%; or, G08G%); and, (self adapted cruise; self control; self guided; self guiding; self steering; UAV; or, unmanned aerial vehicle).

Big data

IPC/CPC symbols: B60W2556/05; G06F%; G06F 16%; G06F 16/2465; G06F 16/283; G06F 17/3%; G06F2216/03; G06F 3%; G06F 30%; G06F 9/5072; G06Q%; or, G16B 50%.

IPC/CPC and keywords: (G06F%; G06F 16%; G06F 3%; G06F 30%; G06Q%; or, G16B 50%); and, (Accumulo; Aster; big dat*; Cassandra; crowd sourc*; data fusion; data mine*; data warehous*; data mining*; Datameer; DataStax; distributed database; distributed process*; distributed quer*; distributed server; elasticsearch;

enormous data*; FICO Blaze; Hadoop; HANA; hp veritca; huge data*; informatic*; kafka; large data*; MapReduce; Marklogic; massive data*; massively parallel database; massively parallel process*; massively parallel software; nosql; open dat*; Platfora; Splunk; Vertica; or, Yarn).

Cloud computing

Keywords: *as-a-service; Aneka; cloud app*; cloud architectur*; cloud based; cloud based computing; cloud comput*; cloud data*; cloud infrastructure; cloud networking; cloud process*; cloud securit*; cloud serv*; cloud software; cloud solution*; cloud storage; cloud system*; cloud technolog*; cluster comput*; concurrent comput*; data portability; distrubuted comput*; grid comput*; hybrid cloud[s]?; Hyper-V; hypervisor*; InterCloud; multi.?core; multitenan*; parallel comput*; parallel process*; parallel software; private cloud; public cloud; service[.]?orient*; utility comput*; utility orient*; virtualization; VMware; or, web service*.

IPC/CPC and keywords: (G06F%) and (*as-a-service; Aneka; cloud app*; cloud architectur*; cloud based; cloud based computing; cloud comput*; cloud data*; cloud infrastructure; cloud networking; cloud process*; cloud securit*; cloud serv*; cloud software; cloud solution*; cloud storage; cloud system*; cloud technolog*; cluster comput*; concurrent comput*; data portability; distrubuted comput*; grid comput*; hybrid cloud[s]?; Hyper-V; hypervisor*; InterCloud; multi.?core; multitenan*; parallel comput*; parallel process*; parallel software; private cloud; public cloud; service[.]?orient*; utility comput*; utility orient*; virtualization; VMware; or, web service*).

Internet-of-Things (IoT):

IPC/CPC symbols:G16Y%; H04L 29/06%; H04L 29/08%; H04W 4/70; H04W 72/04%; H04W 72/06%; H04W 72/08%; H04W 72/10; H04W 84/18; H04W 84/20; or, H04W 84/22.

IPC/CPC and keywords: (H04B 7/26%; H04L 12/28%; or, H04W4%); and, (ambient intelligence; connected* device*; device* network*; digital life; IIoT; industrial internet; internet of everything*; internet of thing*; IoT; M2M; machine-to-machine; network* device*; pervasive comput*; smart device*; smart dust; smart grid*; smart home*; smart meter*; smart sensor*; smarter planet; ubicomp; ubiquitous computing; virtual plant*; or, web of thing*).

Robotics

IPC/CPC symbols:A47L2201/00; A61B2034/30%; A61B 34/30; A61B 34/30; A61B 34/37; A61F2002/4632; A61F2002/704; A61H2201/1659; A61N 5/1083; A63H 11%; B01J2219/00691; B07C2501/0063; B25J 19/0029; B25J 19/0033; B25J 19/0037; B25J 19/0041; B25J 9/065; B29C2945/76317; B29C 66/863; B32B2038/1891; B60C 25/0587; B64G2004/005; B65F2230/14; B65H2555/31; B67D2007/0403; B67D2007/0405; B67D2007/0407; B67D2007/0409; B67D2007/041%; B67D2007/042%; B67D2007/043%; F16H2061/0071; G01S 13/881; G05B2219/39; G05B2219/40%; G05B2219/43119; G05B2219/45058; G05B2219/45059; G05B2219/45061; G05B2219/45062; G05B2219/45064; G05B2219/45065; G05B2219/45066; G05B2219/45068; G05B2219/45073; G05B2219/45074; G05B2219/45079; G05B2219/45081; G05B2219/45082; G05B2219/45083; G05B2219/45084; G05B2219/45085; G05B2219/45086; G05B2219/45087; G05B2219/45088; G05B2219/45089; G05B2219/45091; G05B2219/45092; G05D2201/0217; H01H2231/04; H04Q 1/147; Y10S 320/34; Y10S 700/90; or, Y10S 901%.

IPC/CPC and keywords: (A63F 13/803; B23K 11/314; B23K 26/0884; B29C 70/38; B62D 57%; or, H01L 21%); and, (cobot; mechatronic*; robot; or, robotics).

Low-carbon technologies

The low-carbon technologies mapping was based on the following strategies for subcategories.

Environmental management

IPC/CPC symbols: A23K 1/06; A23K 1/07; A23K 1/08; A23K 1/09; A23K 1/10; A43B 1/12; A43B 21/14; A61L 11/; B01D 46/; B01D 47/; B01D 49/; B01D 50/; B01D 51/; B01D 53/34; B01D 53/35; B01D 53/36; B01D 53/37; B01D 53/38; B01D 53/39; B01D 53/40; B01D 53/41; B01D 53/42; B01D 53/43; B01D 53/44; B01D 53/45; B01D 53/46; B01D 53/47; B01D 53/48; B01D 53/49; B01D 53/50; B01D 53/51; B01D 53/52; B01D 53/53; B01D 53/54; B01D 53/55; B01D 53/56; B01D 53/57; B01D 53/58; B01D 53/59; B01D 53/60; B01D 53/61; B01D 53/62; B01D 53/63; B01D 53/64; B01D 53/65; B01D 53/66; B01D 53/67; B01D 53/68; B01D 53/69; B01D 53/70; B01D 53/71; B01D 53/72; B01D 53/92; B01D 53/94; B01D 53/96; B01J 23/38; B01J 23/39; B01J 23/40; B01J 23/41; B01J 23/42; B01J 23/43; B01J 23/44; B01J 23/45; B01J 23/46; B03B 9/06; B03C 3/; B09B; B09C; B22F 8/; B29B 7/66; B29B 17/; B30B 9/32; B62D 67/; B63B 35/32; B63J 4/; B65D 65/46; B65F; B65H 73/; C02F; C03B 1/02; C03C 6/02; C03C 6/08; C04B 7/24; C04B 7/25; C04B 7/26; C04B 7/27; C04B 7/28; C04B 7/29; C04B 7/30; C04B 11/26; C04B 18/04; C04B 18/05; C04B 18/06; C04B 18/07; C04B 18/08; C04B 18/09; C04B 18/10; C04B 33/13*; C05F 1/; C05F 5/; C05F 7/; C05F 9/; C05F 17/; C08J 11/; C09K 3/32; C09K 11/01; C10G 1/10; C10L 5/46; C10L 5/47; C10L 5/48; C10L 10/02; C10L 10/06; C10M 175/; C21B 7/22; C21C 5/38; C22B 7/; C22B 19/28; C22B 19/29; C22B 19/30; C22B 25/06; D01G 11/; D21B 1/08; D21B 1/09;

D21B 1/10; D21B 1/32; D21C 5/02; D21H 17/01; E01H 15/; E02B 15/04; E02B 15/05; E02B 15/06; E02B 15/07; E02B 15/08; E02B 15/09; E02B 15/10; E03C 1/12; E03F; F01M 13/02; F01M 13/03; F01M 13/04; F01N 3/; F01N 5/; F01N 7/; F01N 9/; F01N 11/; F01N 13/; F02B 47/06; F02B 47/08; F02B 47/09; F02B 47/10; F02D 21/06; F02D 21/07; F02D 21/08; F02D 21/09; F02D 21/10; F02D 41/; F02D 43/; F02D 45/; F02M 3/02; F02M 3/03; F02M 3/04; F02M 3/05; F02M 23/; F02M 25/; F02M 25/07; F02M 27/; F02M 31/02; F02M 31/03; F02M 31/04; F02M 31/05; F02M 31/06; F02M 31/07; F02M 31/08; F02M 31/09; F02M 31/10; F02M 31/11; F02M 31/12; F02M 31/13; F02M 31/14; F02M 31/15; F02M 31/16; F02M 31/17; F02M 31/18; F02P 5/; F23B 80/; F23C 9/; F23C 10/; F23G 5/; F23G 7/; F23G 7/06; F23J 15/; F27B 1/18; G01M 15/10; G08B 21/12; G08B 21/13; G08B 21/14; H01B 15/00; H01J 9/52; H01M 6/52; or, H01M 10/54.

Water-related adaptation technologies

IPC/CPC symbols: A01G 25/02; A01G 25/06; A01G 25/16; A47K 11/02; A47K 11/12; C12N 15/82*; E03B 1/04; E03B 3/00; E03B 3/02; E03B 3/03; E03B 3/06; E03B 3/07; E03B 3/08; E03B 3/09; E03B 3/10; E03B 3/11; E03B 3/12; E03B 3/13; E03B 3/14; E03B 3/15; E03B 3/16; E03B 3/17; E03B 3/18; E03B 3/19; E03B 3/20; E03B 3/21; E03B 3/22; E03B 3/23; E03B 3/24; E03B 3/25; E03B 3/26; E03B 3/40; E03B 5/; E03B 9/; E03B 11/; E03C 1/08; E03D 1/14; E03D 3/12; E03D 5/01; E03D 13/00; F01D 11/; F01K 23/08; F01K 23/09; F01K 23/10; F16K 21/06; F16K 21/07; F16K 21/08; F16K 21/09; F16K 21/10; F16K 21/11; F16K 21/12; F16K 21/16; F16K 21/17; F16K 21/18; F16K 21/19; F16K 21/20; F16L 55/07; Y02B 40/46; or, Y02B 40/56.

Climate-change mitigation technologies related to energy generation, transmission of distribution

IPC/CPC symbols: Y02E; Y02E 10/; Y02E 10/10; Y02E 10/11; Y02E 10/12; Y02E 10/13; Y02E 10/14; Y02E 10/15; Y02E 10/16; Y02E 10/17; Y02E 10/18; Y02E 10/20; Y02E 10/21; Y02E 10/22; Y02E 10/23; Y02E 10/24; Y02E 10/25; Y02E 10/26; Y02E 10/27; Y02E 10/28; Y02E 10/30; Y02E 10/31; Y02E 10/32; Y02E 10/33; Y02E 10/34; Y02E 10/35; Y02E 10/36; Y02E 10/37; Y02E 10/38; Y02E 10/40; Y02E 10/41; Y02E 10/42; Y02E 10/43; Y02E 10/44; Y02E 10/45; Y02E 10/46; Y02E 10/47; Y02E 10/50; Y02E 10/51; Y02E 10/52; Y02E 10/53; Y02E 10/54; Y02E 10/55; Y02E 10/56; Y02E 10/57; Y02E 10/58; Y02E 10/60; Y02E 10/70; Y02E 10/71; Y02E 10/72; Y02E 10/73; Y02E 10/74; Y02E 10/75; Y02E 10/76; Y02E 20/; Y02E 20/10; Y02E 20/11; Y02E 20/12; Y02E 20/13; Y02E 20/14; Y02E 20/15; Y02E 20/16; Y02E 20/17; Y02E 20/18; Y02E 20/18*; Y02E 20/30; Y02E 20/31; Y02E 20/32; Y02E 20/33; Y02E 20/34; Y02E 20/35; Y02E 20/36; Y02E 30/; Y02E 30/10; Y02E 30/11; Y02E 30/12; Y02E 30/13; Y02E 30/14; Y02E 30/15; Y02E 30/16; Y02E 30/17; Y02E 30/18; Y02E 30/30; Y02E 30/31; Y02E 30/32; Y02E 30/33; Y02E 30/34; Y02E 30/35; Y02E 30/36; Y02E 30/37; Y02E 30/38; Y02E 30/39; Y02E 30/40; Y02E 40/; Y02E 40/10; Y02E 40/11; Y02E 40/12; Y02E 40/13; Y02E 40/14; Y02E 40/15; Y02E 40/16; Y02E 40/17; Y02E 40/18; Y02E 40/20; Y02E 40/21; Y02E 40/22; Y02E 40/23; Y02E 40/24; Y02E 40/25; Y02E 40/26; Y02E 40/30; Y02E 40/31; Y02E 40/32; Y02E 40/33; Y02E 40/34; Y02E 40/40; Y02E 40/50; Y02E 40/60; Y02E 40/61; Y02E 40/62; Y02E 40/63; Y02E 40/64; Y02E 40/65; Y02E 40/66; Y02E 40/67; Y02E 40/68; Y02E 40/69; Y02E 40/70; Y02E 50/; Y02E 50/10; Y02E 50/11; Y02E 50/12; Y02E 50/13; Y02E 50/14; Y02E 50/15; Y02E 50/16; Y02E 50/17; Y02E 50/18; Y02E 50/30; Y02E 50/31; Y02E 50/32; Y02E 50/33; Y02E 50/34; Y02E 60/; Y02E 60/10; Y02E 60/11; Y02E 60/12; Y02E 60/13; Y02E 60/14; Y02E 60/15; Y02E 60/16; Y02E 60/17; Y02E 60/30; Y02E 60/31; Y02E 60/32; Y02E 60/33; Y02E 60/34; Y02E 60/35; Y02E 60/36; Y02E 60/50; Y02E 60/51; Y02E 60/52; Y02E 60/53; Y02E 60/54; Y02E 60/55; Y02E 60/56; Y02E 60/70; Y02E 60/71; Y02E 60/72; Y02E 60/73; Y02E 60/74; Y02E 60/75; Y02E 60/76; Y02E 60/77; Y02E 60/78; or, Y02E 70/.

Capture, storage, sequestration or disposal of greenhouse gases

IPC/CPC symbols: Y02C; Y02C 10/; Y02C 10/00; Y02C 10/01; Y02C 10/02; Y02C 10/03; Y02C 10/04; Y02C 10/05; Y02C 10/06; Y02C 10/07; Y02C 10/08; Y02C 10/09; Y02C 10/10; Y02C 10/11; Y02C 10/12; Y02C 10/13; Y02C 10/14; Y02C 20/; Y02C 20/00; Y02C 20/01; Y02C 20/02; Y02C 20/03; Y02C 20/04; Y02C 20/05; Y02C 20/06; Y02C 20/07; Y02C 20/08; Y02C 20/09; Y02C 20/10; Y02C 20/11; Y02C 20/12; Y02C 20/13; Y02C 20/14; Y02C 20/15; Y02C 20/16; Y02C 20/17; Y02C 20/18; Y02C 20/19; Y02C 20/20; Y02C 20/21; Y02C 20/22; Y02C 20/23; Y02C 20/24; Y02C 20/25; Y02C 20/26; Y02C 20/27; Y02C 20/28; Y02C 20/29; or, Y02C 20/30.

Climate-change mitigation technologies related to transportation

IPC/CPC symbols: Y02T; Y02T 10/; Y02T 10/10; Y02T 10/11; Y02T 10/12; Y02T 10/13; Y02T 10/14; Y02T 10/15; Y02T 10/16; Y02T 10/17; Y02T 10/18; Y02T 10/19; Y02T 10/20; Y02T 10/21; Y02T 10/22; Y02T 10/23; Y02T 10/24; Y02T 10/25; Y02T 10/26; Y02T 10/27; Y02T 10/28; Y02T 10/29; Y02T 10/30; Y02T 10/31; Y02T 10/32; Y02T 10/33; Y02T 10/34; Y02T 10/35; Y02T 10/36; Y02T 10/37; Y02T 10/38; Y02T 10/39; Y02T 10/40; Y02T 10/41; Y02T 10/42; Y02T 10/43; Y02T 10/44; Y02T 10/45; Y02T 10/46; Y02T 10/47; Y02T 10/48; Y02T 10/49; Y02T 10/50; Y02T 10/51; Y02T 10/52; Y02T 10/53; Y02T 10/54; Y02T 10/55; Y02T 10/56; Y02T 10/62; Y02T 10/64; Y02T 10/70; Y02T 10/72; Y02T 10/80; Y02T 10/81; Y02T 10/82; Y02T 10/83;

Y02T 10/84; Y02T 10/85; Y02T 10/86; Y02T 10/90; Y02T 10/91; Y02T 10/92; Y02T 30/; Y02T 30/00; Y02T 30/01; Y02T 30/02; Y02T 30/03; Y02T 30/04; Y02T 30/05; Y02T 30/06; Y02T 30/07; Y02T 30/08; Y02T 30/09; Y02T 30/10; Y02T 30/11; Y02T 30/12; Y02T 30/13; Y02T 30/14; Y02T 30/15; Y02T 30/16; Y02T 30/17; Y02T 30/18; Y02T 30/19; Y02T 30/20; Y02T 30/21; Y02T 30/22; Y02T 30/23; Y02T 30/24; Y02T 30/25; Y02T 30/26; Y02T 30/27; Y02T 30/28; Y02T 30/29; Y02T 30/30; Y02T 30/31; Y02T 30/32; Y02T 30/33; Y02T 30/34; Y02T 30/35; Y02T 30/36; Y02T 30/37; Y02T 30/38; Y02T 30/39; Y02T 30/40; Y02T 30/41; Y02T 30/42; Y02T 50/; Y02T 50/00; Y02T 50/01; Y02T 50/02; Y02T 50/03; Y02T 50/04; Y02T 50/05; Y02T 50/06; Y02T 50/07; Y02T 50/08; Y02T 50/09; Y02T 50/10; Y02T 50/11; Y02T 50/12; Y02T 50/13; Y02T 50/14; Y02T 50/15; Y02T 50/16; Y02T 50/17; Y02T 50/18; Y02T 50/19; Y02T 50/20; Y02T 50/21; Y02T 50/22; Y02T 50/23; Y02T 50/24; Y02T 50/25; Y02T 50/26; Y02T 50/27; Y02T 50/28; Y02T 50/29; Y02T 50/30; Y02T 50/31; Y02T 50/32; Y02T 50/33; Y02T 50/34; Y02T 50/35; Y02T 50/36; Y02T 50/37; Y02T 50/38; Y02T 50/39; Y02T 50/40; Y02T 50/41; Y02T 50/42; Y02T 50/43; Y02T 50/44; Y02T 50/45; Y02T 50/46; Y02T 50/47; Y02T 50/48; Y02T 50/49; Y02T 50/50; Y02T 50/51; Y02T 50/52; Y02T 50/53; Y02T 50/54; Y02T 50/55; Y02T 50/56; Y02T 50/57; Y02T 50/58; Y02T 50/59; Y02T 50/60; Y02T 50/61; Y02T 50/62; Y02T 50/63; Y02T 50/64; Y02T 50/65; Y02T 50/66; Y02T 50/67; Y02T 50/68; Y02T 50/69; Y02T 50/70; Y02T 50/71; Y02T 50/72; Y02T 50/73; Y02T 50/74; Y02T 50/75; Y02T 50/76; Y02T 50/77; Y02T 50/78; Y02T 50/79; Y02T 50/80; Y02T 50/81; Y02T 50/82; Y02T 50/83; Y02T 50/84; Y02T 50/85; Y02T 50/86; Y02T 50/87; Y02T 50/88; Y02T 50/89; Y02T 50/90; Y02T 70/; Y02T 70/00; Y02T 70/01; Y02T 70/02; Y02T 70/03; Y02T 70/04; Y02T 70/05; Y02T 70/06; Y02T 70/07; Y02T 70/08; Y02T 70/09; Y02T 70/10; Y02T 70/11; Y02T 70/12; Y02T 70/13; Y02T 70/14; Y02T 70/15; Y02T 70/16; Y02T 70/17; Y02T 70/18; Y02T 70/19; Y02T 70/20; Y02T 70/21; Y02T 70/22; Y02T 70/23; Y02T 70/24; Y02T 70/25; Y02T 70/26; Y02T 70/27; Y02T 70/28; Y02T 70/29; Y02T 70/30; Y02T 70/31; Y02T 70/32; Y02T 70/33; Y02T 70/34; Y02T 70/35; Y02T 70/36; Y02T 70/37; Y02T 70/38; Y02T 70/39; Y02T 70/40; Y02T 70/41; Y02T 70/42; Y02T 70/43; Y02T 70/44; Y02T 70/45; Y02T 70/46; Y02T 70/47; Y02T 70/48; Y02T 70/49; Y02T 70/50; Y02T 70/51; Y02T 70/52; Y02T 70/53; Y02T 70/54; Y02T 70/55; Y02T 70/56; Y02T 70/57; Y02T 70/58; Y02T 70/59; Y02T 70/60; Y02T 70/61; Y02T 70/62; Y02T 70/63; Y02T 70/64; Y02T 70/65; Y02T 70/66; Y02T 70/67; Y02T 70/68; Y02T 70/69; Y02T 70/70; Y02T 70/71; Y02T 70/72; Y02T 70/73; Y02T 70/74; Y02T 70/75; Y02T 70/76; Y02T 70/77; Y02T 70/78; Y02T 70/79; Y02T 70/80; Y02T 70/81; Y02T 70/82; Y02T 70/83; Y02T 70/84; Y02T 70/85; Y02T 70/86; Y02T 70/87; Y02T 70/88; Y02T 70/89; Y02T 70/90; Y02T 90/; Y02T 90/10; Y02T 90/11; Y02T 90/12; Y02T 90/13; Y02T 90/14; Y02T 90/15; Y02T 90/16; Y02T 90/30; Y02T 90/31; Y02T 90/32; Y02T 90/33; Y02T 90/34; Y02T 90/35; Y02T 90/36; Y02T 90/37; Y02T 90/38; Y02T 90/40; Y02T 90/41; Y02T 90/42; Y02T 90/43; Y02T 90/44; Y02T 90/45; or, Y02T 90/46;

Climate-change mitigation technologies related to buildings

Y02B; Y02B 10/; Y02B 10/00; Y02B 10/01; Y02B 10/02; Y02B 10/03; Y02B 10/04; Y02B 10/05; Y02B 10/06; Y02B 10/07; Y02B 10/08; Y02B 10/09; Y02B 10/10; Y02B 10/11; Y02B 10/12; Y02B 10/13; Y02B 10/14; Y02B 10/15; Y02B 10/16; Y02B 10/17; Y02B 10/18; Y02B 10/19; Y02B 10/20; Y02B 10/21; Y02B 10/22; Y02B 10/23; Y02B 10/24; Y02B 10/25; Y02B 10/26; Y02B 10/27; Y02B 10/28; Y02B 10/29; Y02B 10/30; Y02B 10/31; Y02B 10/32; Y02B 10/33; Y02B 10/34; Y02B 10/35; Y02B 10/36; Y02B 10/37; Y02B 10/38; Y02B 10/39; Y02B 10/40; Y02B 10/41; Y02B 10/42; Y02B 10/43; Y02B 10/44; Y02B 10/45; Y02B 10/46; Y02B 10/47; Y02B 10/48; Y02B 10/49; Y02B 10/50; Y02B 10/51; Y02B 10/52; Y02B 10/53; Y02B 10/54; Y02B 10/55; Y02B 10/56; Y02B 10/57; Y02B 10/58; Y02B 10/59; Y02B 10/60; Y02B 10/61; Y02B 10/62; Y02B 10/63; Y02B 10/64; Y02B 10/65; Y02B 10/66; Y02B 10/67; Y02B 10/68; Y02B 10/69; Y02B 10/70; Y02B 10/71; Y02B 10/72; Y02B 20/; Y02B 20/00; Y02B 20/01; Y02B 20/02; Y02B 20/03; Y02B 20/04; Y02B 20/05; Y02B 20/06; Y02B 20/07; Y02B 20/08; Y02B 20/09; Y02B 20/10; Y02B 20/11; Y02B 20/12; Y02B 20/13; Y02B 20/14; Y02B 20/15; Y02B 20/16; Y02B 20/17; Y02B 20/18; Y02B 20/19; Y02B 20/20; Y02B 20/21; Y02B 20/22; Y02B 20/23; Y02B 20/24; Y02B 20/25; Y02B 20/26; Y02B 20/27; Y02B 20/28; Y02B 20/29; Y02B 20/30; Y02B 20/31; Y02B 20/32; Y02B 20/33; Y02B 20/34; Y02B 20/35; Y02B 20/36; Y02B 20/37; Y02B 20/38; Y02B 20/39; Y02B 20/40; Y02B 20/41; Y02B 20/42; Y02B 20/43; Y02B 20/44; Y02B 20/45; Y02B 20/46; Y02B 20/47; Y02B 20/48; Y02B 20/49; Y02B 20/50; Y02B 20/51; Y02B 20/52; Y02B 20/53; Y02B 20/54; Y02B 20/55; Y02B 20/56; Y02B 20/57; Y02B 20/58; Y02B 20/59; Y02B 20/60; Y02B 20/61; Y02B 20/62; Y02B 20/63; Y02B 20/64; Y02B 20/65; Y02B 20/66; Y02B 20/67; Y02B 20/68; Y02B 20/69; Y02B 20/70; Y02B 20/71; Y02B 20/72; Y02B 30/; Y02B 30/00; Y02B 30/01; Y02B 30/02; Y02B 30/03; Y02B 30/04; Y02B 30/05; Y02B 30/06; Y02B 30/07; Y02B 30/08; Y02B 30/09; Y02B 30/10; Y02B 30/11; Y02B 30/12; Y02B 30/13; Y02B 30/14; Y02B 30/15; Y02B 30/16; Y02B 30/17; Y02B 30/18; Y02B 30/19; Y02B 30/20; Y02B 30/21; Y02B 30/22; Y02B 30/23; Y02B 30/24; Y02B 30/25; Y02B 30/26; Y02B 30/27; Y02B 30/28; Y02B 30/29; Y02B 30/30; Y02B 30/31; Y02B 30/32; Y02B 30/33; Y02B 30/34; Y02B 30/35; Y02B 30/36; Y02B 30/37; Y02B 30/38; Y02B 30/39; Y02B 30/40; Y02B 30/41; Y02B 30/42; Y02B 30/43; Y02B 30/44; Y02B 30/45; Y02B 30/46; Y02B 30/47; Y02B 30/48; Y02B 30/49; Y02B 30/50; Y02B 30/51; Y02B 30/52; Y02B 30/53; Y02B 30/54; Y02B 30/55; Y02B 30/56; Y02B 30/57; Y02B 30/58; Y02B 30/59; Y02B 30/60; Y02B 30/61; Y02B 30/62; Y02B 30/63;

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Car industry

Green patents

B60L 11; B60L 3; B60L 15; B60K 1; B60W 10/08; B60W 10/24; B60W 10/26; B60K 6; B60W 20; B60L 7/01; B60L 7/20; B60W 10/28; B60L 11/18; H01M 8

Gray patents

F02M 3/02-05; F02M 23; F02M 25; F02D 41; F02B 47/06; F02M 39-71

Dirty patents

F02B; F02M; F02D; F02F; F02N; F02P.

Acronyms

AGC	Apollo guidance computer
AI	artificial intelligence
AMC	advance market commitment
AV	autonomous vehicle
CalTech	California Institute of Technology
CCD	charged-coupled device
CEPI	Coalition for Epidemic Preparedness Innovation
CFRP	Carbon fiber and carbon fiber reinforced plastics
CMR	Committee on Medical Research
COVID	coronavirus disease, also COVID-19
CO_2	carbon dioxide
DARPA	U.S. Defense Advanced Research Projects Agency
DoD	U.S. Department of Defense
DoE	Department of Energy
D-RAM	Dynamic random-access memory
ESA	European Space Agency
ESG	environmental, social and governance
EU	European Union
EV	electric vehicle
FDA	U.S. Food and Drug Administration
FRAND	fair, reasonable and nondiscriminatory
GDP	gross domestic product
GRI	government research institutes
ICAO	International Civil Aviation Organization
ICT	information and communications technology
IEA	International Energy Agency
IoT	Internet of Things
IP	intellectual property
IPR	Intellectual property rights
IRENA	International Renewable Energy Agency
IT	information technology
JPL	Jet Propulsion Laboratory
MIT	Massachusetts Institute of Technology
mRNA	messenger Ribonucleic acid
NASA	National Aeronautics and Space Administration
NGO	non-governmental organization
NIH	National Institutes of Health
NRC	National Research Council
NRRL	Northern Regional Research Laboratory
NSF	National Science Foundation
OBM	original brand manufacturer
ODM	original design manufacturer
OECD	Organization for Economic Co-operation and Development
OEM	original equipment manufacturer
ORSD	Office of Scientific Research and Development
OWS	Operation Warp Speed (renamed the Countermeasures Acceleration Group in 2021)
PNT	position, navigation and timing data
PV	photovoltaic
R&D	research and development
RPS	Radioisotope power systems
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SME	small and medium-sized enterprise
SMS	short messaging services
U.K.	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States of America
USPTO	United States Patent and Trademark Office
VTF	Vaccine Taskforce
WPB	War Production Board

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