THE NEXT PRODUCTION REVOLUTION

A REPORT FOR THE G20

OECD
BETTER POLICIES FOR BETTER LIVES

This report has been prepared by the Organisation for Economic Co-operation and Development (OECD), with inputs from the United Nations Conference on Trade and Development (UNCTAD) and the United Nations Industrial Development Organisation (UNIDO). It was prepared at the request of the G20 New Industrial Revolution Task Force, as reflected in the Hangzhou Summit Communiqué, under the Chinese 2016 G20 Presidency.

This report draws on material from the OECD's work on the Next Production Revolution (NPR) – a two-year project aiming to inform governments how these technologies may develop in the future and to provide advice on how countries can proactively plan to reap the benefits.

Table of contents

Executive summary 4

Introduction 6

1. Productivity and the technologies of the next production revolution 9

2. Digital technologies and future production 14

3. Bio-production and industrial biotechnology 21

4. Nanotechnology: An enabler to the next production revolution 23

5. 3D printing, production and the environment 25

6. New materials and the next production revolution 27

7. The diffusion of new production technologies: What can governments do? 29

8. Public acceptance and new technologies: Why does this matter and what options are open to government? 33

9. Developing foresight about future production: What should governments do? 35

10. The next production revolution and developing countries 37

11. Cross-cutting policy considerations 40

Notes 43

Bibliography 44

Figures

Figure 1. The confluence of key technologies enabling the industrial digital transformation 14
Figure 2. Enterprises using cloud computing services by employment size class, 2014 15
Figure 3. Leaders in IoT, big data and quantum computing technologies, 2005-07 and 2010-12 17
Figure 4. Global sales of industrial robots, 1993-2013 20

Tables

Table 1. Initial typology of institutions for technology diffusion 31

Boxes

Box 1. How large are the productivity effects? 10
Box 2. Promoting investments in and use of ICT and data 16
Box 3. Supporting the development of skills and competences for the digitalisation of production 17
Box 4. Addressing emerging risks and uncertainties 18
Box 5. What are these technologies? 21
Box 6. Bio-production and industrial biotechnology: main policy considerations 22
Box 7. Nanotechnology: main policy considerations 23
Box 8. Additive manufacturing and sustainability: main policy considerations 26
Box 9. New materials and the next production revolution: main policy considerations 27
Box 10. The diffusion of new production technologies: main policy considerations 31
Box 11. Gene editing in society 33
Box 12. Public acceptance and new technologies: main policy considerations 34

Executive summary

The next production revolution (NPR) entails a confluence of technologies ranging from a variety of digital technologies (e.g. 3D printing, the Internet of Things [IoT] and advanced robotics) to new materials (e.g. bio- or nano-based) to new processes (e.g. data-driven production, artificial intelligence [AI] and synthetic biology). Some of these technologies are already used in production, while others will be available in the near future. As these technologies transform the production and the distribution of goods and services, they will have far-reaching consequences for productivity, skills, income distribution, well-being and the environment. All of these technologies are evolving rapidly. The more that governments understand how production could develop, the better placed they will be to prepare for the risks and reap the benefits.

This report provides specific background to a wider discussion on countries' productivity and economic transformation. It sketches the economic and policy ramifications of a set of technologies likely to be important for production over the near term (to 2030). Many economic and policy trends will of course affect production during the same period, from population ageing to trade policy. This report's focus on technologies affords the opportunity for thinking about technology-related policies, which are many. By concentrating on technological features of future production, the report also permits tractability. Various high-profile studies have recently addressed the digitalisation of industry, which is often referred to as "Industry 4.0".[1] This report has a wider view, examining aspects of production beyond manufacturing, as well as technologies which are not just digital, such as industrial biotechnology.

Key messages

The technologies considered in this report, from information and communication technologies (ICTs) and robots to new materials, have more to contribute to productivity than they currently do. Often, their use is predominantly in larger firms. And even in larger firms, many potential applications are underused. Unexploited opportunities exist throughout manufacturing.

While new technologies will create jobs through many channels, and productivity-raising technologies will benefit firms and the economy overall, the associated adjustments could be significant. Hardship could affect many if rapid labour displacement were to occur in a major sector, or in many sectors simultaneously. Policymakers need to monitor and actively manage the adjustments.

Compared to earlier industrial revolutions, induced by steam and electrification, the creation and international spread of inventions that can transform production will occur quickly. But **it could take considerable time for new technologies, once invented, to diffuse throughout the economy and for their productivity effects to be fully realised**. Moreover, the duration of this period is uncertain. The past has seen unrealistic enthusiasm regarding timelines for the delivery of important production technologies.

D**iffusion of the technologies must include not only the hardware**, but also the complementary intangible investments and know-how needed to fully exploit the technologies, ranging from skills to new forms of business organisation. Here, among other things, the efficient deployment and reallocation of human and financial resources is essential. Aligning framework policies that promote product market competition, reduce rigidities in labour markets, remove disincentives for firm exit and barriers to growth for successful firms is critical. New firms will introduce many of the new production technologies.

Effective institutions dedicated to technology diffusion can help. Especially among small and medium-sized enterprises (SMEs), a major challenge will be the digital transformation of firms which were not born digital. Many entrepreneurs do not fully understand the uses and implications of technologies such as the IoT. Institutions with specific remits to aid diffusion, such as technical extension services (which provide information and outreach, especially for SMEs), tend to receive low priority in innovation policy overall. But such institutions can be effective if properly designed, incentivised and resourced.

Data will be central to 21st-century production. Policy should encourage investments in data that have positive spillovers across industries. Obstacles to the reuse and sharing of data should be examined carefully, and coherent data governance frameworks should be developed. The quality of digital infrastructure, including access to high-powered computing, will be critical for firms in many sectors.

Rapid technological change could challenge **the adequacy of skills and training systems**. Some new production technologies raise the importance of interdisciplinary education and research. Greater interaction between industry and education and training institutions is often required, and this need may grow as the knowledge content of production rises. Effective systems for life-long learning and workplace training are essential, such that skills upgrading can match the pace of technological change and retraining can be accessed when needed. Digital skills, and skills which complement machines, are vital. Also important is to ensure good generic skills – such as literacy, numeracy and problem solving – throughout the population, in part because generic skills are the basis for learning fast-changing specific skills.

Sound science and R&D policies are important. The technologies addressed in this report have arisen because of advances in scientific knowledge and instrumentation emanating from both the public and private sectors. Most firms and countries are technology users. But some will be technology developers. Many of the research challenges critical to the NPR are multidisciplinary. Evaluation metrics for research programmes should properly incentivise multidisciplinary research, research scale-up (such as through test-bed demonstration) and linkages across stakeholders.

Public understanding and acceptance of new production technologies also matter. Policymakers and institutions should voice realistic expectations about technologies. Science advice should be demonstrated to be unbiased and trustworthy. And public deliberation can help to build understanding between scientific communities and the public.

Better anticipating trends through technology foresight could assist policy and the allocation of research funds. **Foresight processes can bring benefits in themselves, such as strengthened stakeholder networks**. They can also encourage policy co-ordination and organisational innovation and help direct policies for science and R&D.

Long-term thinking is essential. Leaders in business, education, unions and government must be ready to frame policies and prepare for developments beyond typical election cycles. Reflection is also required on **how policy priorities might need to evolve**, driven for instance by technological change itself. For example, **major challenges to the intellectual property (IP) system** could soon arise from the emerging ability of machines to create (at least one machine-derived invention has already been patented).

While the NPR will present challenges to developed countries, it could be especially testing for developing countries. New production technologies could erode the low-wage advantage of some developing economies, leading to shifts in global value chains (GVCs). But this scenario might be mitigated by several factors, including rapidly declining costs of some technologies and improved channels of knowledge diffusion. The NPR also creates new exigencies for developing countries aiming to market themselves as attractive investment locations.

In conclusion, the more governments understand how production could develop in the near future, the better placed they will be to prepare for the risks and reap the benefits. The NPR raises multiple complex policy challenges. But through judicious policy, the opportunity exists to influence the NPR now.

Introduction

This paper draws on OECD work on the NPR, as well as material prepared by the United Nations Conference on Trade and Development (UNCTAD) and the United Nations Industrial Development Organisation (UNIDO). Work on the NPR led to a flagship OECD publication launched in May 2017, entitled *The Next Production Revolution: Implications for Governments and Business* (OECD, 2017a). That publication provides more detail on all the issues in this paper.

The NPR project has a technological focus

In different ways, many policy, institutional and broader conditions (or mega-trends) will shape the future of production. These range from environmental conditions, to demographics, to the fact that production will increasingly take place across borders in GVCs (OECD, 2013a). To do analytic justice to all of the above influences on production is barely feasible in a single study. Accordingly, the NPR project aims to explore the economic and policy ramifications of a set of technologies which are likely to be important for production over the near term. This focus on technologies affords the opportunity for thinking about technology-specific policies. A technological focus also permits tractability.

The backdrop to the work on the NPR is one in which major science and technology-driven changes in the production and distribution of goods and services are already occurring. Others – possibly more significant still – are on the horizon. Such changes could have far-reaching impacts on productivity, income distribution, well-being and the environment. These impacts are likely to vary across industries, countries and sections of the workforce. As well as positive impacts, some possible technological developments in production also entail risks (recently, for example, innovation has displaced entire industries, such as chemical-based photography). The more completely governments and firms understand how production might develop, the better placed they will be to prepare for the risks and reap the benefits. Indeed, a number of governments and think-tanks have recently prepared, or are preparing, reports on the future of production, many with a focus on manufacturing.[2]

Many technological changes will affect production and distribution over the next 10 to 15 years

The range of technologies that could significantly affect production and distribution is great. The technological possibilities of production are continuously expanding, with technologies complementing and amplifying each other's possibilities in combinatorial ways. Today, for instance, new software and advances in data science help to develop new materials. And new materials might replace silicon semiconductors with better-performing substrates, allowing more powerful software applications in turn. This combinatorial nature of technology implies that foresight is always tenuous. Indeed, retrospective analysis shows that predictions of technological timelines – when certain milestones will be reached – tend to be particularly inaccurate (Armstrong, Sotala and ÓhĖigeartaigh, 2014). Nevertheless, many potentially disruptive production technologies are on the horizon. A small sampling, examined in recent work, includes:

- powerful data analytics, and large data sets, which increasingly permit machine functionalities that rival human performance in tasks, such as pattern recognition, where humans were long thought to possess a permanent advantage over machines
- robots, which are set to become less costly, smaller, more intelligent, autonomous, and agile
- an increased connectedness of parts, components and machines to the Internet
- synthetic biology, which among other applications could allow petroleum-based products to be manufactured from sugar-based microbes, and bring the life sciences closer to engineering

- 3D printing, which already permits printing of complex objects that embody multiple structures made from different materials (such as electric batteries)
- nanotechnology, through which new properties are being imparted to materials, making them stronger, lighter, more electrically conductive, more sieve-like, etc.

Risks will also attend technological change in production

Risks will arise with technological change in production. The various risks will have higher or lower probabilities, and more or less significance, for different countries and population groups. For instance:

- The effect of technological change on employment and earnings inequality is drawing increased attention from academics, policymakers and the public.
- Policymakers in some countries fear the consequences of unpreparedness in the face of rapid but hard-to-foresee technological change. As this report shows, unpreparedness might take various forms – from skills and infrastructure deficits to regulatory shortcomings – and have numerous consequences.
- As a corollary to the risk of machine-driven labour displacement, automation might undermine labour-cost advantages on which many emerging economies rely.
- As production systems become more complex and ICT-mediated, the risks and consequences of system fragility may increase (Nesse, 2014), while the ability to anticipate failures in technology could diminish (Arbesman, 2016).
- Risks also exist that potentially beneficial technological advances might be held back by a lack of public understanding or social acceptance.
- And innovations could create new hazards that need to be countered. For instance, some nanoparticles might have harmful effects on health. And ICTs allow ever more scientific information to be available to ever larger numbers of people, with some of this information – such as genetic information – being potentially dangerous.

An important issue is the productivity effect of new production technologies. A main message is that much unexploited potential for productivity growth exists. Well-designed policies could help to realise the opportunities for productivity growth and broaden the productive base. A number of other cross-cutting policy considerations are also critical, ranging from issues of technology diffusion, to IP concerns, to the practice of foresight. In addition, technology-specific policy lessons can be learned, including the following:

- Two trends mean that **digital technologies are transformational for production**: (i) their falling cost, which has allowed wider diffusion; and, most importantly, (ii) the combination of different ICTs, and their convergence with other technologies. Data-driven innovation (DDI) is transforming all sectors of the economy and digital technology is also making industry more services-like. Cloud computing and the IoT, among other technologies, will bring radical change. The pervasive nature of digital technology raises many policy challenges. For instance, coherent data governance frameworks are needed, barriers to ICT diffusion, interoperability and standards should be lowered, and complex and sometimes new issues of liability, competition, privacy and consumer protection need well-designed regulations and effective implementing institutions.
- The tools also exist today to begin a **bio-based revolution in production**. Bio-based batteries, artificial photosynthesis and micro-organisms that produce biofuels are just some among recent breakthroughs. Governments can assist the supply of sustainable biomass for bio-based production and help resolve technical and economic questions about production, often through public-private partnerships. Governments can also lower barriers to trade in bio-based products, lower regulatory hurdles that hinder investment, support the necessary interdisciplinary science and education, and develop markets using public procurement.

- **Nanotechnology** can enable many areas of production. Nanotechnology needs international collaboration, as many of the research and engineering tools are hard to gather in a single institute (or even region). Policymakers should develop multidisciplinary networks and support innovation and commercialisation in small companies. Timely and clear guidelines are needed for assessing the risk of nanotechnology-enabled products, as is international harmonisation in this area. Since 2006, the OECD has led international efforts to harmonise regulatory approaches to the safety of nanotechnology-enabled products.

- **3D printing** includes a group of technologies and processes that use a digital file to build a physical three-dimensional object using additive manufacturing. 3D printing could augment manufacturing productivity, although today the technology is most economical for small quantities of complex customised products. 3D printing has potential environmental benefits. To achieve these, policy should encourage low-energy printing processes and low-impact materials. Governments can: (i) target grants or investments to commercialise research in these directions; (ii) remove IP barriers to enable 3D printing of repair parts for legacy products (for instance, washing machines no longer in production); and (iii) support certification of 3D-printer sustainability.

- Recent advances in scientific instrumentation, data science and computation have contributed to a revolution in **materials science**. Industrial materials will have properties not seen before. Increasingly, the desired properties will be deliberately designed into materials. Policies are needed to facilitate open data and open science (for instance for sharing simulations of materials structures). Progress on new materials requires close collaboration between industry, universities, research funding agencies and public laboratories. And, again, steps are needed to foster interdisciplinary research and education.

The remainder of this paper is structured as follows. Section 1 addresses the themes of productivity, work and the NPR. Section 2 examines the role of digital technologies in future production. Section 3 considers bio-production and industrial biotechnology. Section 4 focuses on nanotechnology as an enabler of future production. Section 5 assesses the impacts of 3D printing on manufacturing and the environment. Section 6 considers developments relating to new materials. Section 7 reviews policies to help to foster the diffusion of new production technologies. Section 8 considers the influence of public acceptance on the adoption of new technologies and the options which are open to government. Section 9 examines what governments should do to develop foresight about future production. Section 10 considers how the NPR might affect developing countries, and the implications for policies to attract foreign direct investment (FDI). And Section 11 discusses cross-cutting policy considerations. Where relevant, the sections discuss implications for government policy.

1. Productivity and the technologies of the next production revolution

Productivity and the technologies of the next production revolution

A fundamental relationship exists between innovation and long-term productivity. Today, raising rates of economic growth is a priority for most governments. Over the longer-term, shrinking working-age populations, combined with environmental constraints, mean that the future of growth in a number of economies will increasingly depend on productivity-raising innovation.

Some high-profile commentators claim that faltering productivity growth reflects a general innovation hiatus. These voices come from both academia and industry. Techno-pessimists hold, among other things, that the progress of innovation will slow because the cost of innovation rises as science and technology advance. In contrast, techno-optimists argue, variously, that new digital and other technologies will raise productivity, often in unforeseen ways, and that economic history suggests that technological progress might even accelerate (Mokyr, 2014). Techno-optimists also highlight that official measures of economic growth understate progress. For instance, national statistical offices usually collect no information on the use of mobile apps, or online tax preparation, or business spending on databases (Mandel, 2012), while the consumer surplus created by hundreds of new digital products is absent from official data.

Emerging technologies affect productivity through many channels.

Emerging production technologies will affect productivity through many routes. For instance:

- The combination of new sensors and actuators, data analytics, cloud computing and the IoT is enabling increasingly intelligent and autonomous machines and systems.
- Intelligent systems can almost entirely eliminate errors in some production processes (because sensors allow every item to be monitored, rather than having to test for errors in samples drawn from batches). Machine downtime and repair costs can be greatly reduced when intelligent systems predict maintenance needs. Savings can be had when industrial processes can be simulated before being built. Data-driven supply chains greatly speed the time to deliver orders. And production can be set to meet actual rather than projected demand, reducing the need to hold inventories.
- By being faster, stronger, more precise and consistent than workers, robots have vastly raised productivity on assembly lines in the automotive industry. They will do so again in an expanding range of sectors and processes as industrial robotics advances.
- The mix of industrial biotechnology with state-of-the-art chemistry can increase the efficiency of bioprocesses (most biological processes have low yields).
- By printing already-assembled mechanisms, 3D printing can remove the need for assembly in some stages of production.
- Progress in materials science and computation will permit a simulation-driven approach to developing new materials. This will reduce time and cost as companies perform less repetitive analysis.
- Nanotechnology can make plastics electrically conductive. In the automotive industry this can remove the need for a separate spray painting process for plastics, reducing costs by USD 100 per vehicle.

BOX 1. HOW LARGE ARE THE PRODUCTIVITY EFFECTS?

Evidence on productivity impacts from new production technologies comes mainly from firm and technology-specific studies. A sample of these studies is given here. These studies suggest sizeable potential productivity impacts. However, by way of caveat, the studies follow a variety of methodological approaches, and often report results from just a few, early-adopting technology users:

- In the United States, output and productivity in firms that adopt data-driven decision making are 5% to 6% higher than expected given those firms' other investments in ICTs (Brynjolfsson, Hitt and Kim, 2011).
- Improving data quality and access by 10% – presenting data more concisely and consistently across platforms and allowing them to be more easily manipulated – is associated with a 14% increase in labour productivity on average, but with significant cross-industry variations (Barua, Mani and Mukherjee, 2013).
- The IoT reduces costs among industrial adopters by 18% on average (Vodafone, 2015).
- Autonomous mine haulage trucks could in some cases increase output by 15% to 20%, lower fuel consumption by 10% to 15% and reduce maintenance costs by 8% (Citigroup-Oxford Martin School, 2015).
- Autonomous drill rigs can increase productivity by 30% to 60% (Citigroup-Oxford Martin School, 2015).
- Warehouses equipped with robots made by Kiva Systems can handle four times as many orders as un-automated warehouses (Rotman, 2013).
- Google Datacenters use approximately 0.01% of the world's electricity. In July 2016, DeepMind – a leader in AI – used AI to optimise cooling of data centers, cutting energy consumption by up to 40% and significantly reducing costs.

By raising productivity the new technologies can also improve financial performance among adopters. A case study showed that by developing a significant IoT and data analytics capability, a leading US automaker has saved around USD 2 billion over the past five years (2011-14 and most of 2015). A 1% increase in maintenance efficiency in the aviation industry, brought about by the industrial Internet, could save commercial airlines globally around USD 2 billion per year (Evans and Anninziata, 2012).

But there is much unexploited potential for productivity growth…

The technologies considered in this report have more to contribute to productivity than they currently do. Often, their use is predominantly in larger firms. Even in larger firms, many potential applications are underused. Unexploited opportunities exist throughout industry. For instance, robotics could improve logistics and reduce the price of food and other goods by several percent (CCA/CCR, 2009). Manufacturers see unmet opportunities for automation in skilled and less-skilled fields, from manufacturing parts, to machine loading, packaging, palletisation and assembly (Rigby, 2015).

… and it could take considerable time for the productivity gains from new technologies to be realised

The past has seen unrealistic enthusiasm regarding timescales for the delivery of some industrial technologies. Sometimes, as with nanotechnology, this partly reflected miscalculation of the technical challenges. In terms of adoption, advanced ICTs remain below potential. Cloud computing, for instance, was first commercialised in the 1990s, but has still only been adopted by less than one in four businesses in OECD countries. And the mere availability of a technology is not a sufficient condition for its uptake and successful use. Realising the benefits of a technology often requires that it be bundled with investments in complementary assets such as new skills and organisational forms and that new, better adapted business models are invented that channel income to innovators.

Work, automation and the new technologies of production

Among the general public, senior policy figures and business leaders, growing concerns have recently been voiced regarding the employment implications of digital technologies. For instance, in 2014 the former Secretary of the United States Treasury, Lawrence Summers, argued that a limited availability of jobs will be the defining upcoming economic challenge (Summers, 2014). A recent survey of technology experts in the United States found that 48% were concerned that digital technologies will lead to widespread unemployment (PEW Foundation, 2014). Fears also exist that digital technologies could alter the nature of labour markets – for instance through the growth of a crowd-sourced workforce – to the detriment of some workers.

Progress in computing is leading to novel machine capabilities…

Since the period of manual computing, and depending on the metrics used, the cost of computer calculation has fallen 1.7 trillion to 76 trillion-fold. Most of this decline happened since 1980 (Nordhaus, 2007). Such progress permits the development of some machine functionalities that rival human performance, even in tasks where humans were long thought to possess a permanent cognitive advantage over machines (Elliott, 2014).

… and an increased scope and rate of automation

The routine tasks of most operatives in manufacturing are now automated in OECD countries. Cargo-handling vehicles and forklift trucks are increasingly computerised. Many semi-autonomous warehouses are populated by fast and dexterous robots. Complex aspects of the work of software engineers can be performed by algorithms (Hoos, 2012). Software can generate complex and novel industrial designs. The Quill programme writes business and analytic reports. Computer-based managers are being trialled. Recent softwares can accurately interpret some human emotions, presaging new forms of machine-human interaction (Khatchadourian, 2015). And autonomous vehicles might soon substitute for large numbers of commercial drivers.

Automation has advanced most in tasks more easily defined in computer code, contributing to employment polarisation

In recent decades, the share of employment in high- and low-wage jobs has increased in developed countries' labour markets, while the share of employment in middle-wage jobs has fallen. This polarisation has been linked to the falling share of employment in occupations that involve many routine tasks (i.e. tasks easily described by computer code) (Goos and Manning, 2007; Acemoglu, 2002). Because manual tasks in many services occupations are less susceptible to description in code, automation has also contributed to a shift in employment from middle-income manufacturing to low-income services (Autor and Dorn, 2013).

But new technologies also create jobs through a number of channels

A technology-driven increase in productivity benefits the economy through one or more of the following channels: lower prices of output, higher workers' wages, or higher profits. Lower output prices raise the real incomes of consumers. This increases demand for other goods or services. And higher workers' wages raise demand and job creation in other markets. Higher profits are distributed to shareholders, who spend all or part of this new income, adding to aggregate demand. Even if shareholders and workers save their increased income, the wider economy can still benefit (Miller and Atkinson, 2013). Increases in savings, among shareholders and workers, lowers interest rates and raises investment, eventually creating jobs (if financial institutions efficiently mediate between savings and investment).[3] However, an important consideration is the time period over which such processes occur. General competitive equilibrium can be expected in the long term. But in the shorter term, profits, for example, might not be invested due to a lack of expected demand, and this lack of demand might be due in part to high levels of profit (which dampen consumption).

Productivity-raising technologies benefit the economy

Historical evidence is overwhelmingly positive regarding the overall economic and labour market effects of technological change. To cite just a few country-level studies:

- Investments in ICT are estimated to have raised total labour demand in 19 OECD countries over the period 1990-2007 (but to have reduced it after 2007). ICT investments appear to have no effects on total labour demand in the long run. A permanent decrease in the cost of ICT capital reduces labour demand per unit of output, but increases output by the same proportion. This overall employment neutrality is accompanied, however, by a shift in employment from manufacturing to services (OECD, 2016a).
- In the short-run, employment might decrease following productivity-enhancing technology shocks, but it grows again over the medium-term (Basu, Fernald and Kimball, 2006). Productivity-raising technology shocks reduce unemployment for several years (Trehan, 2003).
- From 1964 to 2013, against a background of accelerating automation, the United States economy created 74 million jobs (Levy and Murnane, 2013).
- In England and Wales, over one and a half centuries, technological change has led to overall job creation (Stewart, Debapratim and Cole, 2014). This period saw a reduction in jobs requiring physical strength: 23.7% of all employment in 1871, to 8.3% in 2011. It also saw a shift to jobs requiring caring and empathy: 1.1% of all employment in 1871 to 12.2% in 2011. Routine jobs suffered most.

In firms and industries, the employment effects of technological change are also generally positive

Evidence at the level of firms and industries mostly shows that productivity-enhancing technology causes job losses in some cases and job gains in others (Miller and Atkinson, 2013). But the number of firms and industries which experience employment growth exceeds the number in which employment contracts. Employment is more likely to grow after technology shocks in firms operating in industries with low inventory costs, elastic demand and flexible prices (Chang, Hornstein and Sarte, 2009).

But adjustment might be painful

The first industrial revolution eventually brought unprecedented improvements in living standards. But for many workers this revolution brought hardship. Indeed, the shift to higher average living standards took many decades, often longer than the typical working lifetime (Mokyr, Vickers and Ziebarth, 2015).

Hardship could affect many if rapid labour displacement were to occur in a major sector, or in a number of sectors simultaneously. The technology of driverless vehicles could present such a case. Taken together, just over 3 million people work as commercial drivers in 15 European Union countries. Suddenly eliminating the need for drivers could create an exceptional labour market shock. However, the likelihood of major simultaneous technological advances in many sectors is low (Miller and Atkinson, 2015). And even in a single sector, projecting the employment effects of new technology is not always straightforward. For instance, driverless cars might not substitute for the work performed by all human drivers. Many delivery drivers must interact with customers in ways that today's machines cannot (Markoff, 2015a).

While new technologies bring jobs, specifying what or where they will be is problematic

The specific types of work brought by new technology have often been hard to predict. For example, after the introduction of the personal computer in the early 1980s, more than 1 500 new job titles appeared in the United States' labour market, from web designers to database administrators. New technologies can also affect employment in very indirect and unexpected ways, hindering foresight. For instance, Toyota has decided to put human workers back into manufacturing after realising that craftsmen also play a role in improving production processes, which robots do not (Markoff, 2015b).

Limits currently exist on the extent of automation

While automation is advancing quickly, machine substitution for workers still has limits. Frey and Osborne (2013) identify three broad categories of ability in which computer-controlled equipment is unlikely to surpass workers in the near term: creative intelligence, social intelligence (as exercised, for instance, in caring professions), and perception and manipulation (as required, for example, in jobs dealing with unstructured or changing environments). Common sense, a hard-to-define attribute which is essential to most work, has also been exceedingly hard to replicate (Davis and Marcus, 2015).

Policymakers need to monitor and prepare for adjustment processes

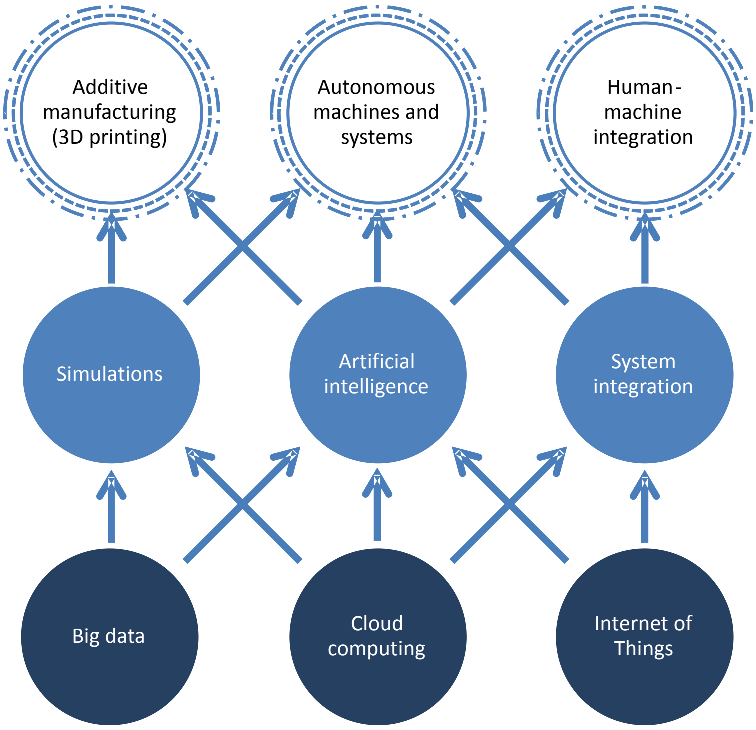
This section has highlighted the historical evidence that productivity-raising technologies lead to labour market adjustments at higher levels of income. It has also underscored that such adjustment might be highly disruptive, while the precise pace and scale of inevitable future adjustments are unknown. It may be that labour will be displaced on a scale and at a speed not seen before, that robots will make income distribution vastly more unequal than today, and that the market wages of the unskilled will fall below socially acceptable levels. Policymakers need to monitor and prepare for such possibilities.

2. Digital technologies and future production

The confluence of different technologies is driving the digital transformation of industrial production

Two trends make digital technologies transformational for production: (i) their falling cost, which has allowed wider diffusion; and, most importantly, (ii) the combination of different ICTs, and their convergence with other technologies (thanks in particular to embedded software and the IoT). In a highly stylised way, Figure 1 depicts the key ICTs which are enabling the digital transformation of industrial processes.

Figure 1. The confluence of key technologies enabling the industrial digital transformation



The technologies at the bottom of Figure 1 enable those on top, as indicated by the arrows. The technologies at the top of Figure 1 – including additive manufacturing (3D printing), autonomous machines and systems, and human-machine integration – are the applications through which the main productivity effects in industry are likely to unfold. The use of the above technologies in industry has been described variously as "Industry 4.0", the "industrial Internet" and "network manufacturing".

Data-driven innovation is transforming all sectors of the economy

The term "big data" refers to data characterised by their volume, velocity (the speed at which they are generated, accessed, processed and analysed) and variety (such as unstructured and structured data). Big data promises to significantly improve products, processes, organisational methods and markets, a phenomenon referred to as DDI. Firm-level studies suggest that using DDI can raise labour productivity by approximately 5% to 10%, relative to non-users (OECD, 2015a). DDI will impact on production and productivity in services, manufacturing and agriculture.

Digital technology is also making industry more services-like

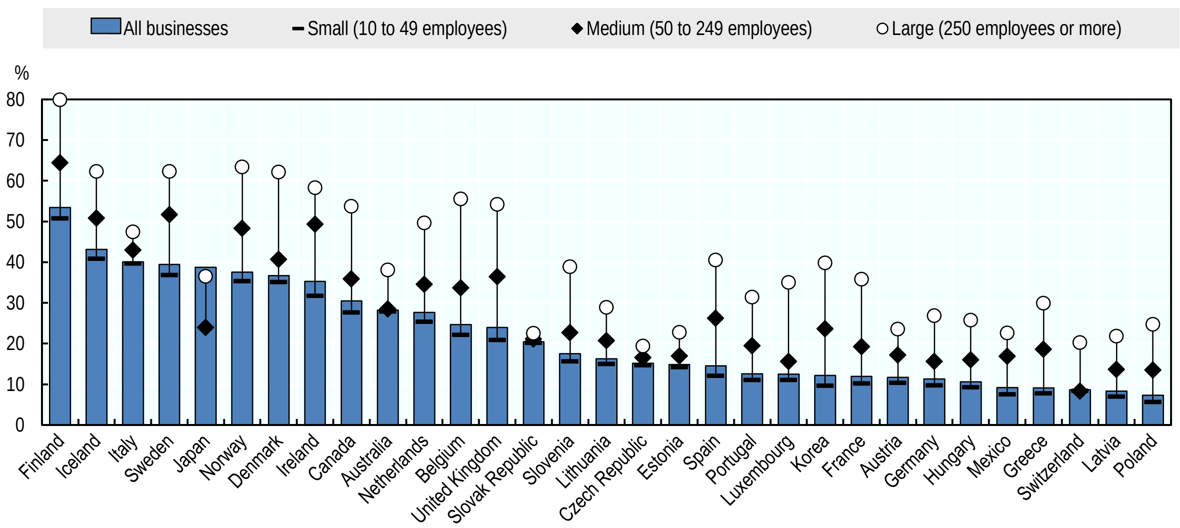
In the 1980s, Rolls Royce began selling "power by the hour", a development made possible by ICTs. Today the IoT allows manufacturing companies to monitor the actual use of their goods and thus provide customised pay-as-you-go services. These services are priced based on real-time operating data. Manufacturers of energy production equipment, for instance, increasingly use sensor data to help customers optimise complex project planning.

Cloud computing enhances agility, scalability and interoperability

Cloud computing allows computing resources to be accessed in a flexible on-demand way with low management effort. Many high-potential industrial applications of ICTs, such as autonomous machines and systems, and complex simulation, are very computationally intensive and require supercomputers. Especially for start-ups and SMEs, cloud computing has increased the availability, capacity and affordability of computing resources. But significant variation exists across countries and firms in the adoption of cloud computing (Figure 2). There is also large variation in use by size of business, with larger enterprises more likely to use cloud computing.

Figure 2. Enterprises using cloud computing services by employment size class, 2014

As a percentage of enterprises in each employment size class



Notes: Data for Belgium, Denmark, Finland, Greece, Hungary, Ireland, Latvia, Lithuania, Norway, Poland, Slovak Republic, Slovenia, and Spain refer to 2014. Data for Canada and Mexico refer to 2012. Data for Canada only include the use of SaaS, a subcategory of cloud computing services.

Source: Based on OECD (2017b), *OECD.Stat*, database, http://dotstat.oecd.org/index.aspx?DatasetCode=ICT_BUS (accessed March 2017).

The IoT will bring radical change

The term "IoT" refers to the connection of devices and objects to the Internet's network of networks. Thanks to new sensors and actuators, and in combination with big data analysis and cloud computing, the IoT enables autonomous machines and intelligent systems. The IoT can bring improved process efficiencies, customer service, speed of decision making, consistency of delivery and transparency/predictability of costs (Vodafone, 2015). The IoT will also bring major economic and social benefits not directly related to production, for instance in health and in vehicle efficiency.

BOX 2. PROMOTING INVESTMENTS IN AND USE OF ICT AND DATA

Governments aiming to promote the supply of key ICTs should consider supporting investments in R&D in enabling technologies such as big data analytics, cloud and high-performance computing, and the IoT, as well as in security- and privacy-enhancing technologies. For example, through its 2014 national digital economy strategy, Canada foresees investment of CAD 15 million over three years to support leading-edge research in, and the commercialisation of, quantum technologies.

Governments should consider using demand-side policies to encourage investments in and adoption of key enabling ICTs, especially by SMEs. This can be done through activities such as awareness raising, training, mentoring and voucher schemes. Demand-side policies should also complement (existing) ICT supply-side policies. In Germany, for example, policies supporting investments in R&D related to industrial ICT applications, IT security research, microelectronics and digital services, are complemented with demand-side policies such as awareness raising and training (for instance through two Big Data Solution Centres established in Berlin and Dresden). The German government has also gathered more than 260 examples of successful "Industry 4.0" projects in an interactive online map.

Governments should encourage investments in data collection, curation, reuse and linkage, with a focus on data that have positive spillovers across industries and higher social than private value. To address the low appropriation of returns to data sharing, governments should consider using a combination of intellectual property rights (IPRs), licences and alternative incentive mechanisms, such as data citations and data donation.

It is important to promote open standards, including in application programming interfaces and data formats. Standards based on pro-competitive and technologically open reference models could boost data interoperability and reuse, and digital services, and reduce technological lock-ins, while enhancing competition among service providers. For example, standards development at the international level is an important part of the United Kingdom's Information Economy Strategy.

Data and digital services are increasingly traded and used across sectors and national borders

Companies increasingly divide their digital processes – hosting, storage and processing – across many countries. Countries are highly interdependent in terms of data flows. Countries which are home to major providers of digital services are likely to also be major destinations for cross-border data flows (from which those digital services are constructed). Conversely, countries which host major users of ICT-related services are often major sources of the data underpinning those services.

Barriers to ICT diffusion, interoperability and standards should be lowered

The digitalisation of production requires the diffusion and use of key ICTs. However, many businesses, and in particular SMEs, lag in adopting ICTs. For instance, the adoption of supply chain management, enterprise resource planning, and radio frequency identification (RFID) applications by firms is still much below that of broadband networks or websites. But it is these advanced ICTs that enable digitalised industrial production.

An important aspect of interoperability for the IoT is identification and numbering policies. An issue that warrants special attention by governments and regulators is the liberalisation of access to international mobile subscriber identity (IMSI) numbers. IMSI numbers allow different sectors of the economy, such as car manufacturers and energy companies, to have access to SIM cards without being obliged to go through mobile operators. This would provide these sectors with more flexibility when selecting a specific mobile network and ease the deployment of the IoT across borders. The Netherlands was the first country to liberalise access to IMSI numbers.

BOX 3. SUPPORTING THE DEVELOPMENT OF SKILLS AND COMPETENCES FOR THE DIGITALISATION OF PRODUCTION

National education systems, in collaboration with business and trade unions, need to support the development of ICT-related skills, starting with basic ICT skills, and including specialist data skills. The educational needs extend beyond ICT to include science, technology, engineering and mathematics (STEM). This calls for measures to: (i) promote digital literacy in schools; (ii) further develop vocational and on-the-job training; and (iii) interlock educational areas, for instance through the establishment of strategic alliances between universities and businesses.

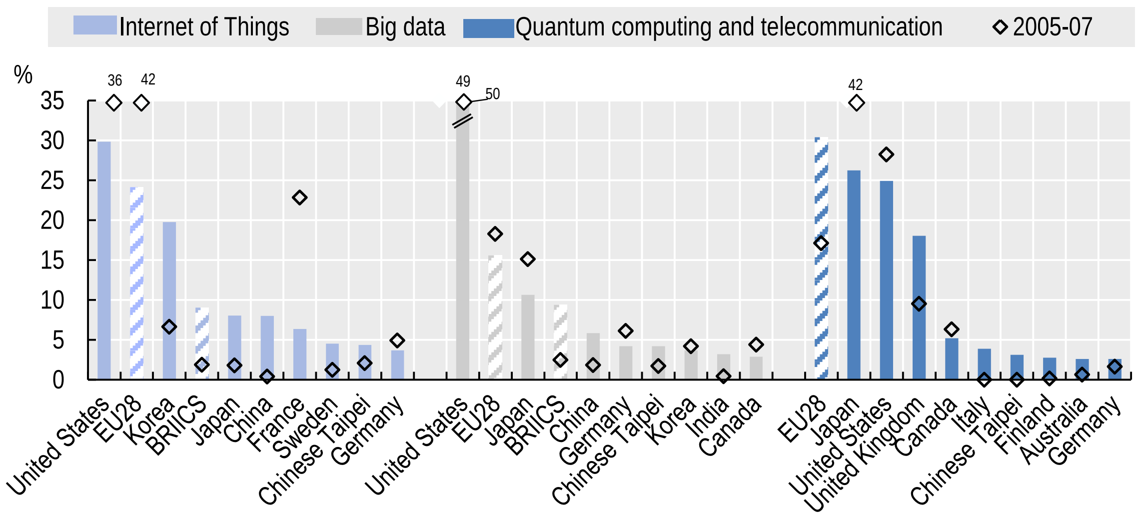
Technical skills are not enough. Technical skills need to be complemented with know-how in domain-specific issues (including knowledge of production processes) as well as "soft skills" such as communication, self-direction, creative thinking and problem solving. Demand for such non-technical skills will continue to grow as the diffusion of digital technologies and new business models changes how work is performed. Especially for low-skill groups, acquiring these skills is particularly important in coping with disruption to existing industries. Businesses and their social partners also have important roles to play, for instance in aligning skills development with real-world need.

The digitalisation of industrial production requires R&D in fields such as the IoT, data analytics and computing

Countries with greater research capabilities in the IoT, data analytics and computing could enjoy first-mover advantages from the digitalisation of industry. Currently, invention of DDI-related technologies is concentrated in only a few economies (Figure 3).

Figure 3. Leaders in IoT, big data and quantum computing technologies, 2005-07 and 2010-12

Share of IP5 patent families filed at USPTO and EPO, selected ICT technologies



Note: USPTO = United States Patent and Trademark Office; EPO = European Patent Office.

Source: OECD (2015c), *OECD Science, Technology and Industry Scoreboard 2015*, http://dx.doi.org/10.1787/sti_scoreboard-2015-en, based on IPO (2014), “Eight great technologies: the patent landscapes”, www.gov.uk/government/uploads/system/uploads/attachment_data/file/360986/Eight_Great_Technologies.pdf (accessed June 2015).

Liability, transparency, and ownership

Data analytics leads to new ways of making decisions. This can raise productivity. But for various reasons, intentional and unintentional, data-driven and AI-enabled decision making can also produce mistakes. For example, unforeseen behaviours in algorithmic trading systems have sometimes led to significant financial losses, such as Knight Capital Group's loss of USD 440 million in 2012. The risk of erroneous decisions raises questions of how to assign liability between decision makers, the providers of data and ICTs (including software).

Privacy, consumer protection, competition law and taxation: New challenges to regulation

New ICTs could raise serious concerns relating to privacy, consumer protection, competition and taxation. Existing regulatory frameworks may be ill-suited for some of the new challenges.

BOX 4. ADDRESSING EMERGING RISKS AND UNCERTAINTIES

Governments may need to act if regulatory uncertainties prevent the adoption of ICTs. This is especially the case if regulations designed for the pre-digital era inadvertently shield incumbents from new forms of competition. For instance, removing regulatory barriers to entry in the mobile market would allow some vehicle manufacturers, whose fleets contain millions of connected devices, to become independent of mobile network operators. This would also strengthen competition.

Governments should support a culture of digital risk management (as promoted by the 2015 OECD Recommendation on *Digital Security Risk Management for Economic and Social Prosperity* [OECD, 2015d]). Traditional security approaches might fail to properly protect assets in the current digital environment, and are likely to stifle innovation (see OECD, 2016b). The usual barriers to a culture of digital risk management in businesses, especially SMEs, are a lack of know-how, and a misunderstanding that digital security is a technical IT management issue (rather than a business management issue). To respond to this challenge, some governments have prioritised awareness raising, training and education on digital risk management. For instance, under the French national digital security strategy, the French State Secretariat in charge of Digital Technology, along with ministries and the National Cybersecurity Agency (ANSSI), will coordinate a cybersecurity awareness programme for professionals.

Barriers to Internet openness, legitimate or otherwise, can limit the effects of digitalisation and may require policy attention. Frequently encountered barriers include technical conditions, such as IP package filtering, one use of which is to optimise data flows, and "data localisation" efforts (either through territorial routing or legal obligations to locate servers in local markets). The limiting effects of barriers to Internet openness are particularly severe in economies where data-driven services are weak due to failures in ICT infrastructure markets. However, openness can present challenges, for instance if it is exploited to conduct malicious activities. Barriers to Internet openness coming from business practices or government policies may thus have legal or security rationales. Governments looking to promote trade in digital services should take the 2011 *OECD Council Recommendation on Principles for Internet Policy Making* (OECD, 2011) into consideration. These principles aim to preserve the fundamental openness of the Internet and the free flow of information.

Obstacles to the reuse, sharing and linkage of data can take many forms and should be examined. Technical barriers can include constraints such as difficult machine readability of data across platforms. Legal barriers can also prevent data reuse and sharing. For example, the "data hostage clauses" found in many terms-of-service agreements can sometimes prevent customers from moving to other providers. Furthermore, non-discriminatory access to data, including through data commons, open data, and data portability, enables users to create value from data in ways that often could not be foreseen when the data were created. Instead of picking winners (users or applications), governments and businesses can instead provide non-discriminatory data access to allow users to discover promising applications.

Coherent data governance frameworks should be developed. Access to data should not necessarily be free or unregulated: a balance is needed between data openness (and the consequent social benefits of greater access and reuse of data), and the legitimate concerns of those whose privacy and IPRs may be negatively affected. This calls for a whole-of-government approach when applying and enforcing data governance and IPR frameworks.

Governments may seek to promote the responsible use of personal data to prevent privacy violations. Governments could promote privacy-enhancing technologies and empower individuals through greater transparency of data processing, and greater data portability (examples of such initiatives include midata in the United Kingdom and MesInfos in France). Governments may need to increase the effectiveness (i.e. resourcing and technical expertise) of privacy enforcement authorities. Data protection regulations should offer a high level of privacy protection and be easily implementable, with the goal of widespread adoption.

Governments may need to assess market concentration and competition barriers using up-to-date definitions of the relevant markets and consideration of the potential consumer detriments of privacy violations. This may also require dialogue between regulatory authorities (particularly in the areas of competition, privacy and consumer protection).

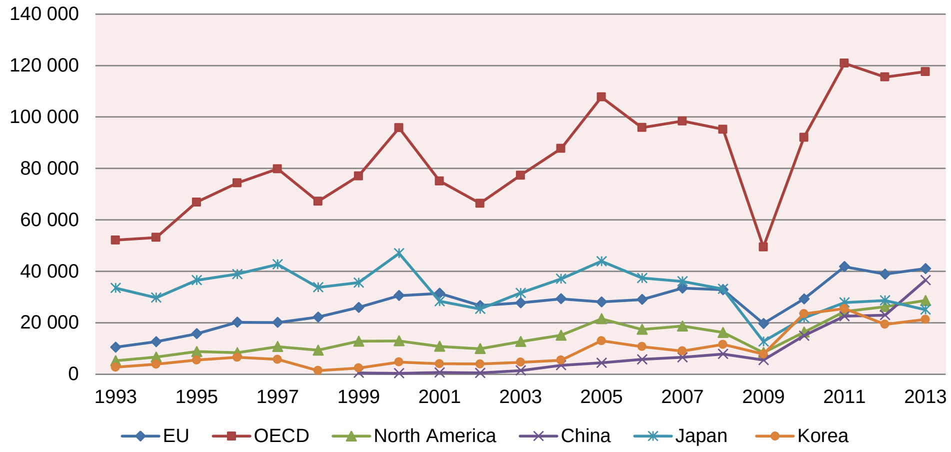
Further thinking is needed on the attribution of responsibility and liability for inappropriate data-driven decisions. Governments may have to assess whether existing regulations and legislation fully address the challenge of attributing responsibility and liability for damaging data-based decisions (as between decision makers and providers of data and data analytics). Multi-stakeholder dialogue at national and international level may help by exchanging best practices. **Careful examination is needed of the appropriateness of fully automated decision making, transparency requirements and required human intervention in areas where the potential harm of automated decisions could be significant.** Transparency requirements may need to extend to the processes and algorithms underlying automated decisions. These transparency requirements may come into tension with existing IPRs and the economic value of the processes and algorithms at the core of some business' operations. More studies are needed to determine how best to assess the appropriateness of algorithms without violating existing IPRs.

Digital technologies also underpin the development of robotics

Robots first entered industry – initially in the automotive sector – in the 1960s. For decades, industrial robots were large, expensive, operated from static positions indoors, and performed one or a small number of repetitive and sometimes hazardous tasks, such as welding and machining. But a convergence of digital and other technologies has yielded a second generation of robots. These are smaller, less expensive, more autonomous, more flexible and cooperative. They can be programmed and used by average workers. Kuka, for instance, makes autonomous robots that collaborate and automatically adjust their actions to fit the next unfinished product (Lorentz et al., 2015). Some robots even perform tasks by imitating workers. Robots also have new roles in services. For instance, using minimally invasive robots, several thousand prostate operations per year are performed in the United States. This allows shorter admission periods, fewer infections and faster recovery (CCC/CRA, 2009).

In 17 OECD countries, from 1993 to 2007, the number of robots in industry increased by over 150%. The market for personal and household service robots is growing by about 20% per year, and prices are expected to decline quickly in the near future (McKinsey Global Institute, 2013).

Figure 4. Global sales of industrial robots, 1993-2013



Note: Data for China spans 1999-2013.

Source: IFR Statistical Department at World Robotics, www.worldrobotics.org.

Robot utilisation varies greatly across countries: 48% of Spanish firms and 44% of Danish firms used at least on industrial robot in 2009, compared to just 23% of firms in the Netherlands (Fraunhofer, 2015).

More intelligent and autonomous robots will come about through improvements currently being seen in computing performance, electromechanical design tools and numerically controlled manufacturing, electrical energy storage and electronics power efficiency, the availability and performance of local wireless digital communications, the scale and performance of the Internet, and global data storage and computational power (Pratt, 2015). Challenges remain, particularly in perception (recognising specific objects in cluttered environments), manipulation and cognition.

The next generation of miniaturised, complex products with short life cycles will require a level of assembly adaptability, precision and reliability which exceeds human capabilities (CCC/CRA, 2009). And as populations age, robots will help to relieve demographic constraints on production. As well as increasing process reliability, robots reduce lead times for finished manufactured goods, allowing greater responsiveness to changes in retail demand. European manufacturers that use robots are more efficient than non-users. And such robot users are less likely to relocate production outside Europe (Fraunhofer, 2015).

Robot use increases strongly with firm size. In Europe, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1 000 or more employees (Fraunhofer, 2015). This size-sensitivity reflects the greater financial resources, experience with advanced production technologies, and economies of scale available to larger firms.

3. Bio-production and industrial biotechnology

Petro-chemistry dramatically changed production in the early twentieth century. Several decades of research in biology have now yielded synthetic biology (see Box 5 for definitions) and gene-editing technologies. When allied to modern genomics – the information base of all modern life sciences – the tools are in place to begin a bio-based revolution. Bio-based batteries, artificial photosynthesis and micro-organisms that produce biofuels are just some among recent breakthroughs.

Everyday chemicals and fuels represent the largest market for bio-based products. In the last few years the technology to produce entirely non-natural chemicals has been proven. This technology is now being commercialised.

BOX 5. WHAT ARE THESE TECHNOLOGIES?

Genomics: is a discipline that applies recombinant deoxyribonucleic acid (DNA), DNA sequencing methods, and bioinformatics to sequence, assemble, and analyse the function and structure of genomes. In many ways it is an information technology: the code is not digital but genetic.

Industrial biotechnology: involves the production of goods from sustainable biomass instead of finite fossil-based reserves. The biomass can be wood, food crops, non-food crops or even domestic waste.

Synthetic biology: aims to design and engineer biologically-based parts, novel devices and systems as well as the redesigning of existing, natural biological systems.

Industrial biotechnology could improve the productivity and competitiveness of the chemicals sector by improving environmental performance. Biotechnology also offers unique solutions to dependence on oil and petrochemicals. For example, a hugely demanding task is to create food crops that make their own fertilizer, through synthetic biology and, in the near future, gene editing (Keasling, 2015). If achieved, this outcome would help to de-link agriculture from the fossil-fuel based fertilizer industry.

Bio-based products are starting to become cost-competitive

Bio-based materials and fuels currently suffer in competition with the fossil-based industry. Over decades, oil and gas supply chains and production processes have been perfected. The production plants are mature and completely amortised, and the economies of scale achieved mean that fossil-based industries produce many products at low cost. Furthermore, fossil-fuel subsidies are vast.

For bio-based products, none of these conditions exist. Investing in bio-based manufacturing – the most potent symbol of which is the integrated bio-refinery – has been a major risk: the early products have not been price-competitive, markets have had to be created by government, and supply chains – particularly the collection of biomass – are far from perfected. However, nascent bio-based manufacturing is bringing new products to market. Indeed, almost one hundred bio-based chemicals are close to commercialisation (E4Tech, 2014).

BOX 6. BIO-PRODUCTION AND INDUSTRIAL BIOTECHNOLOGY: MAIN POLICY CONSIDERATIONS

Governments could help to create sustainable supply chains for bio-based production. Monitoring and controlling the collection of crops and residues is a major task. There are also currently no comprehensive or standard definitions of sustainability (as regards feedstocks), no ideal tools for measuring sustainability, and no international agreement on the indicators to derive the data from which to make measurements (Bosch, van de Pol and Philp, 2015). And currently there are no environmental performance standards for bio-based materials.

Biomass disputes are already occurring and threaten to create international trade barriers. Global sustainable biomass governance is a patchwork of many voluntary standards and regulations. An international dispute settlement facility could help.

Demonstrator bio-refineries are critical for answering technical and economic questions about production before costly investments are made at full-scale. Bio-refineries and demonstrator facilities are high-risk investments, and the technologies are not yet proven. Financing through public-private partnerships is needed to de-risk private investments and demonstrate that governments are committed to long-term coherent policies on energy and industrial production.

One of the greatest challenges in bio-based production is its multidisciplinarity. Research and training will have to create not only the new technologies required, but also a cadre of technical specialists (Delebeque and Philp, 2015). There are some proven ways for governments to tackle this challenge, such as by organising research degrees with a focus on business, not academic, outcomes. To create a non-research workforce, modern apprenticeships would be another mechanism.

A priority in support for research should be synthetic biology and metabolic engineering approaches to reducing the innovation cycle time of industrial biotechnology. It takes about 7.4 years for a synthetic biology company to get a bio-based chemical to market (Lux Research, 2015). Targeted research would help bring products to market on a timescale that can compete with the fossil industry.

Governments should focus on three objectives as regards regulations: to boost the use of instruments, in particular standards, so as to reduce barriers to trade in bio-based products; to address regulatory hurdles that hinder investments; and, to establish a level playing field for bio-based products with biofuels and bioenergy (Philp, 2015). Governments could also ensure that waste regulations are less proscriptive and more flexible, enabling the use of agricultural and forestry residues and domestic wastes in bio-refineries.

Governments could take the lead in market-making through public procurement policies. Bio-based materials are not always amenable to public procurement as they sometimes form only part of a product (such as a bio-based screen on a mobile phone). Public purchasing of biofuels is much easier (for instance for public fleets).

4. Nanotechnology: An enabler to the next production revolution

The term "nano" describes a unit prefix (1 nm = 1 x 10^{-9}m. A sheet of paper is about 100 000 nm thick). The widest definitions of nanotechnology include all phenomena and processes occurring at a length scale of 1 nm to 100 nm. The power and versatility of nanotechnology stem from the ability to control matter on a scale where the shape and size of assemblies of individual atoms determine the properties and functions of all materials and systems, including those of living organisms. The command of materials on the nanometre-scale can enable innovation in all existing industrial sectors. As it develops, nanotechnology will enter a widening range of uses and require complementary technologies and institutions.

In the 1980s, science- and technology-foresight studies envisaged rapid advancements in nanotechnology. Progress in the science and its application, however, has been significantly slower than expected. Progress has been slowed by the high cost of R&D instrumentation, as well as by failures to scale-up from laboratory-scale procedures to industrial manufacture. The difficulty of achieving commercial-scale production was largely due to inadequate understanding of the relevant physical and chemical processes, and the inability to control production parameters at that scale.

However, over the last ten years techniques for large-scale production of nanotechnology-based materials have improved significantly. Nanotechnology is increasingly used in production processes and manufactured products. For instance, nanotechnology can enable the replacement of energy-hungry production processes (such as the fabrication of solar cells in zone-melting processes) with low-cost processes (such as roll-to-roll printing of solar cells in ambient air).

BOX 7. NANOTECHNOLOGY: MAIN POLICY CONSIDERATIONS

Nanotechnology requires increased efforts in institutional and possibly international collaboration. The entirety of research and engineering tools required to set up an all-encompassing R&D infrastructure for nanotechnology might be prohibitively expensive. State-of-the-art equipment costs several million euros and often requires the construction of bespoke buildings. Moreover, some of the most powerful research instruments exist as prototypes only. It is therefore almost impossible to gather an all-encompassing nanotechnology infrastructure within a single institute or even region. Consequently, nanotechnology requires increased efforts in inter-institutional and/or international collaboration to advance to its full potential. Publicly funded R&D programmes should allow the involvement of academia and industry (both large and small companies) from other countries. The creation of networks that involve academia, public research laboratories and large and small companies (including those from other countries) creates an environment in which a research infrastructure can be shared, while simultaneously helping start-ups to establish themselves within a current or potential commercial value chain.

Support is needed for innovation and commercialisation in small companies. The relatively high cost of nanotechnology R&D hampers the involvement and success of small companies in nanotechnology innovation. Nanotechnology R&D is mainly conducted by larger companies. Large companies are better placed to assimilate nanotechnology due to their critical mass in R&D and production, their ability to acquire and operate expensive instrumentation, and their ability to access and use external knowledge. Policy makers could seek to improve SMEs' access to equipment by: (i) increasing the amount of money SMEs get in research grants; (ii) subsidising/waving the service fee; or (iii) providing SMEs with vouchers for equipment use.

Interdisciplinarity must be supported and encouraged. Nanotechnology tends to thrive at the interface of traditional disciplines. This is where discipline-specific research and engineering infrastructures are available – favouring multidisciplinarity – and the expert knowledge in traditional disciplines is pooled. Examples of such conducive environments include virtual networks, such as Germany has created to support biomedical nanotechnology, and research institutes such as the United Kingdom's Interdisciplinary Research Collaborations. As a general purpose technology, nanotechnology has an impact on a wide range of industry sectors. Policy instruments may need to be designed in ways that take into account the multidisciplinary approaches that nanotechnology can require.

Regulatory uncertainties regarding risk assessment and approval of nanotechnology-enabled products must be addressed in internationally collaborative approaches. Regulatory uncertainties severely hamper the commercialisation of nano-technological innovation. This is because products awaiting market entry are sometimes shelved for years before a regulatory decision is made. In some cases, this has caused the closure of promising nanotechnology start-ups, while large companies have terminated R&D projects and innovative products. Policies should also support the development of transparent and timely guidelines for assessing the risk of nanotechnology-enabled products, while also striving for international harmonisation in such guideline.

Policy should support novel business and innovation-funding models, which among other things need to take account of the increasingly collaborative nature of R&D for complex inventions, and the advancing digitalisation of research and production processes. For instance, policy makers need to find models under which pre-competitive data can be openly shared, without compromising the ability of universities to raise income.

5. 3D printing, production and the environment

3D printing is expanding rapidly owing to falling printer and materials prices, the rising quality of completed objects, and innovation. The global 3D printing market is projected to grow at around 20% per year from 2014 to 2020 (MarketsandMarkets, 2014).

Recent innovations permit 3D printing with novel materials – such as glass and metals – as well as printing of multi-material objects – such as batteries and drones. DNA printers and printing of body parts and organs from a person's own cells are under development.

3D printing and the future of manufacturing

3D printing could augment productivity in a number of ways. For instance, 3D printing of already-assembled mechanisms is possible, which could reduce the number of steps in some production processes. And design processes can be shortened, owing to rapid prototyping (Gibson, Rosen and Stucker, 2015). Objects can also be printed which are otherwise impossible to manufacture (such as metal components contained within other closed and seamless metal components). Currently, most 3D printing is used to produce prototypes, models and tools, with only 15% producing parts in sold goods (Beyer, 2014).

In manufacturing, machining is the main method used for prototyping and producing limited amounts of custom parts. 3D printing is already significantly altering the market for machined plastic and metal parts. For instance, Boeing has already replaced machining with 3D printing for over 20 000 units of 300 distinct parts (Davidson, 2012). However, machining is a small industrial niche, comprising no more than a few percent of total manufacturing sales.

Expansion of 3D printing into other industries depends on the technology's near-future evolution in print time, cost, quality, size and choice of materials. The main factor driving or limiting expansion of 3D printing is the cost of switching from mass-manufacturing methods to 3D printing. Costs are expected to decline rapidly in coming years as production volumes grow (McKinsey Global Institute, 2013), although it remains difficult to predict precisely how fast this technology will be deployed. Furthermore, the cost of switching is not linear. 3D printing will rapidly penetrate high-cost, low-volume industries such as prototyping, automotive tooling, aerospace and some medical devices. But 3D printing will more slowly penetrate moderate-cost, moderate-volume industries.

3D printing and the environment

The environmental effects of 3D printing on two important industrial technologies – machining and injection moulding – are particularly interesting to consider. These technologies represent two ends of a spectrum: single-unit prototyping and mass-manufacturing. Even considering these restricted cases, the environmental impacts of 3D printing vary widely. Printer type, frequency of printer utilisation, part orientation, part geometry, energy use and the toxicity of printing materials all play a role. Some experimental systems already have far lower environmental impacts per part than injection moulding – perhaps 70% lower in some circumstances. Industry is not trending towards such systems, but policy could encourage socially desirable choices.

Common misconceptions exist about the environmental effects of 3D printing

Two of the most frequently claimed sustainability benefits of 3D printing – eliminating waste and transportation – fail to take into account the need for high purity materials that often cannot be recycled and the need for feedstock materials to be transported to the printing site. Many printing methods require such a high level of material purity that they discourage recycling.

3D printing's potential for enhancing environmental sustainability is high

Nevertheless, 3D printing can enable more sustainable material use because:

- It permits many materials to be shaped in ways previously possible only with plastics.
- It lowers barriers to switching between materials by reducing economies of scale in some processes.
- It can allow fewer chemical ingredients to yield more variation in material properties by varying printing processes.

3D-printed parts can also lower the environmental impacts of some products because of how the products can be used, even if environmental impacts during manufacturing are high. This can happen in two ways: (i) by printing replacement parts for legacy products that would otherwise be discarded; and (ii) by reducing a product's weight or otherwise improving a product's energy efficiency (General Electric's lighter 3D-printed parts for a jet engine improved fuel efficiency by 15% [Beyer, 2014]).

BOX 8. ADDITIVE MANUFACTURING AND SUSTAINABILITY: MAIN POLICY CONSIDERATIONS

To support sustainability in 3D printing, policy should primarily encourage low-energy printing processes and low-impact materials with useful end-of-life characteristics. Printer design and operation can minimise energy use per printed part by: using chemical processes rather than melting material; using automatic switching to low-power states when idle; and, maximising utilisation (sharing printers among users and, for some printer types, printing more parts simultaneously). Another way in which printers can minimise material impacts is by using compostable biomaterials with high print quality. Printer design and operation can also reduce waste by minimising the use of support material (printers of all kinds often use support materials in addition to the actual modelling material to prevent part warping before they are fully formed). Policy mechanisms to achieve these priorities should include:

- Targeting financial grants or investments (either existing programs or new funds) to commercialising research in these directions.
- Removing IP barriers to enable 3D printing of repair parts for legacy products that lack existing supply chains. For example, a consumer may realise a washing machine is broken and that it only requires a small hinge to be fixed. Theoretically, a consumer with a 3D printer could go to a computer, find the appropriate CAD file and print the new part. But most CADs are proprietary. One solution would be to incentivise rights for third parties to print replacement parts for products, with royalties paid to original product manufacturers as needed.

Creation of a voluntary certification system to label 3D printers with different grades of sustainability across multiple characteristics. Such a voluntary certification system could be combined with preferential purchasing programs by governments and other large institutions.

6. New materials and the next production revolution

Advances in scientific instrumentation, such as atomic-force microscopes and X-ray synchrotrons, have allowed scientists to study materials in more detail than ever before. Developments in computational simulation tools for materials have also been critical. Today, materials are emerging with entirely novel properties, such as solids with densities comparable to that of air. Exotic alloys and super-strong lightweight composites, materials that remember their shape, repair themselves or assemble themselves into components, and materials that respond to light and sound are all now realities (The Economist, 2015).

The era of trial and error in materials development is coming to an end

Progress in computation has allowed modelling and simulation of the structure and properties of materials to inform decisions on how the material might be used in products. Properties such as conductivity, corrosion resistance and elasticity can be intentionally built into new materials. This computation-assisted approach is leading to an increased pace of development of new and improved materials, more rapid insertion of known materials into new products, and the ability to make existing products and processes better (for instance, the possibility exists that silicon in integrated circuits could be replaced by materials with superior electrical properties). In the NPR, engineers will concurrently design the product and its constituent materials (Teresko, 2008).

Among other things, the importance of new materials for manufacturing is reflected in the United States' Materials Genome Initiative (MGI). Introduced by President Obama in June 2011, the MGI aims to halve the time, and lower the cost, to discover, develop, manufacture and deploy advanced materials.

New materials matter for productivity and competitiveness

A simulation-driven approach to materials development will reduce time and cost as companies perform less repetitive analysis. Simulation will also permit better products, such as stronger complex structures. Successful integration of materials modelling and data sciences into decision support for product development can also shorten the time between materials discovery and their commercial use. The Accelerated Insertion of Materials program, run by the United States' Defense Advanced Research Project's Agency (DARPA), has demonstrated such time savings. Large companies, too, will increasingly compete in the development of materials. This is because a proprietary manufacturing process applied to proprietary materials creates long-term competitive differentiation (The Economist, 2015).

BOX 9. NEW MATERIALS AND THE NEXT PRODUCTION REVOLUTION: MAIN POLICY CONSIDERATIONS

Policy making at national and international levels can strongly influence the development of the materials innovation ecosystem, broaden the potential pool of collaborators, and promote adoption of more efficient investment strategies. No single company or organisation will be able to own the entire array of technologies associated with an e-collaborative materials innovation ecosystem. Accordingly, a public-private investment model is warranted, particularly with regard to building cyber-physical infrastructure and developing the future workforce.

New materials will raise new policy issues and give new emphases to long-standing policy concerns. For instance, new cybersecurity risks could arise because, in a medium-term future, a computationally-assisted materials "pipeline" based on computer simulations could be hackable. Progress in new materials also requires effective policy in areas important for pre-existing reasons, often relating to the science-industry interface. For instance, well-designed policies are needed for open data and open science (for sharing simulations of materials structures, or for sharing experimental data in return for access to modelling tools, for example [Nature, 2013]). Advances in new materials also require close collaboration between industry, universities, research funding agencies and government laboratories.

Interdisciplinary research and education are needed. Materials research is inherently interdisciplinary. Beyond traditional materials science and engineering, contributions come from physics, chemistry, chemical engineering, bio-engineering, applied mathematics, computer science, and mechanical engineering, among other fields. In education, students who will become experts in materials synthesis, processing, or manufacture must understand materials modelling and theory, while modellers and theorists must understand the challenges faced in industry.

There is also a need for policy co-ordination across the materials innovation infrastructure at national and international levels. Major efforts are underway to develop the early materials information infrastructure and associated data standards in professional societies (Robinson and McMahon, 2016). A need for international policy co-ordination arises from the necessity of federating elements of the cyber-physical infrastructure across a range of European, North American and Asian investments and capabilities, as it is too costly (and unnecessary) to replicate resources that can be accessed via web services with user support. Ultimately, good policies are required because of the need to change the culture of sharing data and, in particular, to facilitate a pre-competitive culture of e-collaboration.

Deliberation between research bodies, firms, government research laboratories, standards organisations, and professional societies working to develop new and improved materials have predominantly been concerned with the compatibility of data formats. But this needs to evolve towards a focus on how to use these data to support decisions in materials discovery and development, along with many of the foregoing policy issues. Access to high-performance computing and cloud storage is an important element, to which pre-competitive public-private consortia and government policy can contribute. Initiatives such as the Integrated Computational Materials Engineering expert group (ICMEg) in Europe are wrestling with these issues.

7. The diffusion of new production technologies: What can governments do?

A key question is how to ensure that new technologies, ideas and business practices diffuse in OECD economies

A critical issue is how already-developed technologies diffuse. The issue is twofold. First, it is about increasing new-firm entry and the growth of firms which are major carriers of new technology. Secondly, it is about increasing productivity in established firms which face obstacles to implementing technology. In the second case, small firms, in particular, tend to use key technologies less frequently than larger firms (in Europe, for instance, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1 000 or more employees [Fraunhofer, 2015]). The two aspects of technology diffusion – firm entry and growth, and more general absorption – involve different policy instruments.

Several factors shape the diffusion process at national and international levels: (i) global connections via trade, FDI, participation in GVCs and the international mobility of skilled labour; (ii) connections and knowledge exchange within the national economy, such as the interaction between scientific and higher education institutions and businesses; (iii) the scope that exists for experimentation by firms – especially entrants – with new technologies and business models; (iv) the extent of complementary investments in R&D, skills, organisational know-how (i.e. managerial capabilities) and other forms of knowledge-based capital (OECD, 2015b). If firms which could lead the NPR are unable to attract the human and financial resources to grow, the future development of technology and its diffusion will be stunted.

Inefficient resource reallocation can have many causes

The causes of inefficient resource reallocation can be many, including a lack of product competition, rigid labour markets, disincentives for firm exit, barriers to growth for successful firms, and policy conditions such as restrictions on trade. For example, the sensitivity of capital investment to a change in the patent stock is almost double in countries where contract enforcement is less costly (such as Norway), relative to countries where it is more costly (such as Italy) (Andrews, Criscuolo and Menon, 2014).

Learning from the global frontier is a particular challenge for developing and emerging economies

Comin and Mestieri (2013) examined how long it takes technologies to be adopted in developed and developing economies, and how intensely those technologies are used. For 25 technologies, the authors find a convergence in adoption rates across countries, but divergence in the intensity of use. Learning how to use new technologies is still a challenge for companies in many developing economies. Conditions which facilitate such learning include open trade, efficient skills allocation, managerial quality, the volume of business R&D, and the capacity of governments to develop and implement e-government services (OECD, 2015b).

Beyond framework conditions, it is important to design effective institutions for technology diffusion

Institutions for technology diffusion are intermediaries, structures and routines that facilitate the adoption and use of knowledge, methods and technical means. Some of the institutions involved, such as technical extension services, tend to receive low priority in the standard set of innovation support measures. But there is evidence that they can be effective, if well designed.

The conventional rationale for supporting institutions and mechanisms for technology diffusion builds on information deficiency and asymmetry and other market failures. Enterprises (especially SMEs) frequently lack information, expertise and skills, training, resources, strategy, and confidence to adopt new technologies; suppliers and private consultants can experience high transaction costs in trying to diffuse technologies; and finance for scale-up and implementation is not always forthcoming. Support from technology diffusion institutions seeks to guide and support enterprise capabilities, adoption, and justify investment choices in new technology. In the fast moving environment of next generation production technologies, the conventional market failure rationales for institutional intervention are likely to become even more important, to aid potential users to sift through burgeoning amounts of information and to support decision making in the context of rapidly changing technologies and expertise requirements.

Innovation systems invariably contain multiple sources of technology diffusion, such as universities and professional societies. Table 1 offers an initial typology.

New diffusion initiatives are emerging, some of which are still experimental

The need for new strategies to promote institutional change, knowledge exchange, capacity development, and demand-led initiatives for technology diffusion has given rise to new initiatives, some of which are experimental. New production technologies have stimulated partnerships that cross-sectoral boundaries and address problems of scaling up from research to production. Alongside established applied technology centres, such as the Fraunhofer Institutes in Germany, there is an increase in partnership-based approaches. An example is the US National Network for Manufacturing Innovation (NNMI). The NNMI uses private non-profit organisations as the hub of a network of company and university organisations to develop standards and prototypes in areas such as 3D printing and digital manufacturing and design.

Digital information technologies are being deployed to facilitate diffusion

Analogous to the rise of open sharing of research articles and data is the emergence of libraries promoting sharing of technological building blocks. For example, BioBricks is an open source standard developed at MIT to enable shared use of synthetic biology parts through the Registry of Standard Biological Parts. Such open source mechanisms in biotechnology exist against a backdrop of traditional proprietary biotechnology approaches.

Policies to promote diffusion address funding gaps for activities between research and commercialisation, and comparable gaps in the capacity for commercialisation of research

For example, the Innovation Corps (I-Corps) programme was established by the US National Science Foundation (NSF) in 2011 to accelerate commercialisation of science-intensive research. Teams of researchers and budding entrepreneurs receive grants to attend training, which encourages ongoing interaction with customers and partners. The program enhances the knowledge of participants and their capacity to start companies around NSF-funded research (Weilerstein, 2014).

Policies have also placed greater emphasis on demand for new production technologies

Attention to the procurement of innovation by government agencies has grown across many countries, often targeted to SMEs. Incentives such as R&D tax credits, regulations and standards are also being used to encourage pre-commercial R&D activities, such as feasibility studies and prototyping. The effectiveness of technology diffusion institutions depends in part on firms' absorptive capabilities. This suggests the importance of efforts to foster demand through such mechanisms as innovation vouchers, which encourage users to engage with knowledge or technology suppliers. Several countries (including the United Kingdom, Ireland, and the Netherlands) have promoted innovation vouchers.

Table 1. Initial typology of institutions for technology diffusion

Type	Operational mode (primary)	Example
Dedicated field services	Diagnostics, guidance and mentoring	Manufacturing Extension Partnerships (US); German Industrial Collective Research for SMEs
Technology-oriented business services	Advice linked with finance Capacity development	Industrial Research Assistance Program (Canada); I-Corps (US)
Technology transfer offices	IP licensing	University technology transfer organisations (multiple countries)
Applied technology centres	Contract research	Fraunhofer Institutes (Germany), TNO (Netherlands)
Technology information exchange	Technology community networking	Knowledge Transfer Networks (UK)
Demand-based behavioural change	Knowledge transfer incentives	Innovation vouchers (multiple countries)
Technology partnerships	Collaborative applied research Prototyping and standards	NNMI (US)
Open source sharing	Open source sharing Virtual networks	Registry of Standard Biological Parts (US)

BOX 10. THE DIFFUSION OF NEW PRODUCTION TECHNOLOGIES: MAIN POLICY CONSIDERATIONS

Policy making needs to ensure the integration of technology diffusion and its institutions into efforts to implement the NPR. Policy makers tend to acknowledge the critical importance of technology diffusion at a high level, but to overlook technology diffusion in the subsequent allocation of attention and resources. It is important to redress this situation. Major economic and societal value will only occur if the new production technologies are responsibly designed and deployed together with users and other stakeholders, and if these technologies can be scaled up, diffused and improved in use.

Technology diffusion institutions need realistic goals and time horizons. Many new technologies are introduced into existing ecosystems where sunk costs have been invested in old ways of doing things. For example, fully automated factories proposed in the 1980s failed in part due to the difficulty of integrating existing supply chains with newly shortened product life cycles. Introducing new ways to integrate and diffuse technology takes time, patience and experimentation. Yet many governments want visible results quickly, without risk. Evaluation metrics should give more weight to longer-run capability development, rather than short-term incremental outcomes.

Misalignment can exist between the stated aims of technology diffusion institutions and their operational realities. While some new production technologies are promoted for their ability to address societal challenges, funding and evaluation models in many public technology diffusion institutions prioritise revenue generation. Furthermore, there is often a focus on disseminating the latest advanced technology, when many enterprises and users do not use current technologies to their fullest extent and lack absorptive capabilities for sophisticated technologies. In such cases, pragmatic approaches to technology diffusion may be needed, coupled with long-term relationships that build capabilities for more advanced strategies.

Policymaking needs better evidence and a readiness to experiment. A better understanding of effective organisational designs and practices for technology diffusion is vital. There is more to this than redesigning assessment and evaluation, and fostering knowledge about good practices, although these are important. More fundamentally, existing institutions need to be able to discover new approaches, to embed innovative methods in their operations and be well integrated into innovation systems. Concerns over governmental accountability combined with ongoing public austerity in many economies could mean that current institutions will be reluctant to risk change, slowing the emergence of next generation institutions for technology diffusion.

There are also practices that policy makers should seek to avoid. Perhaps the first of these relates to the inclination to concentrate attention and resources on policies to back research breakthroughs and exciting laboratory technologies and to overlook, or at least poorly support, the industrial scale-up and diffusion of new technologies. Furthermore, efforts to diffuse new technologies often target conventional early adopters. These adopters tend to be large multinationals, high technology start-ups, and the small number of companies involved in technology development. Policy attention should not just be placed on these likely early adopters, but should also focus on the much larger number of existing SMEs. Indeed, a substantial part of the success of the NPR will depend on take-up by SMEs. Policies to support institutions for technology diffusion should not be pledged as programmes to restore lost manufacturing jobs. Technology diffusion institutions can help firms today to adjust their business approaches and to adopt new technologies, products, and strategies. Upgrading the ability of manufacturing communities to absorb NPR technologies will take time (five to ten years or more). Accordingly, technology diffusion institutions need to be empowered and resourced to take longer-term perspectives.

8. Public acceptance and new technologies: Why does this matter and what options are open to government?

In the past, public concerns have blocked the development and implementation of some new technologies. This has happened even when a technology's technical and economic feasibility has been demonstrated, where there has been a sound rationale for adoption, and where large investments have been made (EC, 2013). For example, many countries invested in the construction of nuclear reactors in the 1960s and 1970s. Even in the face of expert opinion avowing safety, political protests often halted their use (Winner, 1986).

Public pressure can feed into regulatory choices that condition the adoption of technology. For instance, in the area of biotechnology, public controversies over genetically modified organisms (GMOs) have had a major impact on regulation and approvals of new crops in Europe (Watson and Preedy, 2016).

While public concerns can constrain technology, they can also lead to increased safety and acceptability

Scientific studies and environmental protest in the 1960s and 1970s led to stricter regulation of pesticides and other chemicals (Davis, 2014). Regulation can also enable technology adoption by stipulating the terms of acceptable use: activism in the 1960s about the safety of automobiles led to higher safety requirements and shaped the development of the automobile industry (Packer, 2008).

Biotechnology has been the subject of persistent public conflicts over societal risks

In both developed and developing countries, genetically modified crops have raised concerns around health and safety risks, the capacity to contain and reverse their release, and the effects of IP on concentration in the structure of the agro-food industry (Jasanoff, 2005). Such concerns have been resolved differently in different countries. Stark regulatory approaches growing out of distinct public attitudes to biotechnology have resulted in disruptions to international trade and have even led to dispute settlement at the WTO (Pollack and Shaffer, 2009). Governments will have to anticipate public concerns around the most recent biotechnological advances, especially gene editing (Box 11).

BOX 11. GENE EDITING IN SOCIETY

With so-called "gene-editing" techniques, especially those using the CRISPR-Cas9 system (named as by the journal *Science* as the Breakthrough of 2015), scientists are now able to change a DNA sequence at precise locations on a chromosome. Gene editing will make the design and construction of organisms with desired traits easier and cheaper. It raises the possibility, for example, of new methods for the control of pests and diseases as well as improvements in plant and animal breeding. Recently, CRISPR has been used in China to edit genomes of non-viable human embryos. Similar experiments have been approved in the United Kingdom (Callaway, 2016).

In March 2015, a group of scientists and ethicists, including Nobel laureates David Baltimore of Caltech and Paul Berg of Stanford, proposed a worldwide moratorium on altering the genome to produce changes that could be passed on to future generations. In December 2015, the National Academies of Science in the United States, along with the Chinese Academy of Sciences and the United Kingdom's Royal Society convened an international summit of experts from around the world to discuss the scientific, ethical and governance issues associated with human gene-editing research (Reardon, 2015).

Other technologies addressed in this report have raised public concerns of different kinds

Some concerns have to do with risk, such as how nano-technologies might affect human health (recent work has found significant knowledge gaps with respect to the final disposal of nanoparticles [OECD, 2016c]). Government programs to collect and use big data have also raised significant public concerns and ethical issues. For instance, in the United Kingdom, failure to address privacy and access questions triggered a major public controversy among clinical physicians, disease advocacy groups and the larger public, undermining trust in central health authorities (Kirby 2014). And the NPR could raise societal issues not seen before. For instance, as machine autonomy develops, who will be responsible for the outcomes that machines give rise to, and how will control be exercised?

BOX 12. PUBLIC ACCEPTANCE AND NEW TECHNOLOGIES: MAIN POLICY CONSIDERATIONS

Having realistic expectations about technologies can help maintain trust. In areas of emerging technology, "hype" must be avoided. An emphasis on short-term benefits can lead to disappointment. For example, stem cell research has involved a pattern of inflated predictions by scientific communities, funding agencies and the media (Kamenova and Caulfield, 2015).

Science advice must be trustworthy. There is a close connection between public resistance to novel technologies and the disruption of trust in public scientific and regulatory authorities. In the late 1990s in the United Kingdom a public controversy arose about how government regulators failed to address uncertainties in their risk assessment and management strategies around bovine spongiform encephalopathy, or "mad cow disease". This episode undermined the trust afforded to regulators on the risks of GMOs soon after (Pidgeon, Kasperson and Slovic, 2003). Countries must put resources into making systems of expertise more robust by encouraging more exchange with publics, encouraging clear communication about sources of uncertainty, and making processes of appointment and operation more accountable (Jasanoff, 2003).

Societal assessment of technology can inform science and technology policy. Innovation policy in many OECD countries is now guided by forms of societal technology assessment carried out by a mix of actors, including national ethics committees and other government bodies tasked with taking a broad view of social, health and safety risks. These assessments involve formal risk analysis but can also consider longer-term social implications of technologies not easily reduced to immediate health and safety risks.

Ethical and social issues should be included in major research endeavours. Since the Human Genome Project (HGP), science funders in many countries have sought to integrate attention to ethics, legal and social issues. The planners of the HGP recognised that mapping and sequencing the human genome would have profound implications for individuals, families and society, and so they allocated over 3% of the budget to the ethical, legal and social implications of research. Since this pioneering approach, efforts have been made in many countries to mainstream social science and humanities work into funding streams. The next generation of these approaches integrates social considerations not at the end of technology pipelines, but in the course of their development. This includes Europe's Horizon 2020 programme and the US National Nanotechnology Initiative (NNI).

Public deliberation is important for mutual understanding between scientific communities and the public, and should inform innovation policy. Deliberation can take various forms. Citizen panels and town halls have been pioneered in Denmark and elsewhere for a broad range of emerging technologies relevant to the NPR. Deliberation can take place in the context of national advisory processes and public inquiries, which should include dedicated processes for public engagement and the reception and processing of public concerns, so these might feed into the process.

9. Developing foresight about future production: What should governments do?

Greater foresight in science and technology is sought by most governments. For instance, a goal of the America Competes Act is the identification of emerging and innovative fields. Better anticipation of trends could clearly assist policy development and the allocation of research funds and other resources.

Foresight is a specific type of prospective analysis aimed at thinking about the future and shaping it

Foresight processes aim to systematically and transparently identify and assess social, technological, economic, environmental and policy conditions that shape some aspect of the future. Foresight processes are: (i) action-oriented; (ii) participatory (often involving researchers, business people, policy makers and representatives of citizen groups); and (iii) consider multiple futures.

Prediction is not the primary role of foresight exercises. In developing roadmaps and examining projections, foresight assists preparation for multiple possible futures. In addition, process benefits arise from doing foresight.

Foresight can – and should – take many forms, varying in thematic coverage, geographic scope, focus, methods and time horizons

Several foresight exercises have focused on manufacturing and production, including *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work* (Donofrio and Whitefoot, 2015), *The Future of Manufacturing: A new era of opportunity and challenge for the UK* (Foresight, 2013), and *Manufacturing Visions – integrating diverse perspectives into pan-European foresight* (Arilla et al., 2005).

Foresight can aid thinking about multiple possible futures

Governments can easily be trapped by the need to deal with the short-term. Foresight provides space for longer-term thinking. Foresight also explores different possible futures. In uncertain times, thinking in terms of multiple future states is a pre-condition for devising policies to cope with unexpected developments. Furthermore, in a complex world, many phenomena cannot be understood in isolation. They must be seen in context, from a number of viewpoints. Foresight involving participatory methods can incorporate necessarily diverse perspectives.

Foresight can facilitate the mobilisation and alignment of stakeholders

Most foresight activities not only explore possible futures, they also seek a common understanding of what a desirable future might be. Such visions and – associated to them – operational roadmaps, can be instruments for assembling key players around a shared agenda. By involving participants from different policy domains, policy co-ordination can also be fostered both horizontally (i.e. across policy domains, or between parliament and government) and vertically (i.e. between ministries and executive agencies).

And foresight can help to reframe policy issues and spur organisational innovation

Government bodies tend to be organised along the lines of rigidly demarcated policy domains. Organisational structures can lag fast-changing scientific and technological fields. In such cases, it can be difficult to find a proper place for cross-cutting research or for new ways of directing research (for example, in shifting from S&T-led research to societal challenges-driven research). Government bodies can also be insular, with the same participants sometimes repeatedly involved in decision making. Foresight processes have the potential to enlarge and renew the framing of policy issues. In a connected way, foresight can also induce organisational innovations.

Governments can create conditions which aid effective foresight

Foresight must be appropriately embedded in decision-making processes. Foresight processes should operate close enough to decision making to have influence, but distant enough for intellectual autonomy. Foresight should be orchestrated with policy cycles to ensure that futures intelligence is available at the right time. And some form of institutionalisation – through regular programmes and/or the establishment of dedicated organisations – is needed to create a foresight culture. One-off exercises are unlikely to yield the greatest impacts on policy making. A sustained effort is also required to create the competences for conducting foresight.

10. The next production revolution and developing countries

Just as there are uncertainties in developed countries as to the impacts of new production technologies, so there are with regard to developing economies. Compounding this uncertainty is the fact that developing countries are many and highly economically diverse. Large developing economies, middle-income countries and least developed countries have different absorptive capacities and will not be able to assimilate NPR technologies equally.

Successful absorption of NPR technologies in developing countries could raise productivity, speed structural transformation and stimulate sustainable economic growth. Indeed, some new production technologies are suited to economic conditions frequently found in developing countries. For example, certain state-of-the-art robots are relatively inexpensive and do not require highly skilled operators. And low-cost drone technologies could improve productivity in some agricultural processes. Especially with improved channels of knowledge diffusion, such as the Internet, opportunities for technological 'leapfrogging' could arise, particularly in large developing economies. China, for example, is already the world's largest user of industrial robots, and some 3 000 robot manufacturers report starting operations in China in the past five years (Xinhua, 2016).

However, NPR technologies also raise the possibility of economic disruption in developing countries. As the technologies lead to a realignment of relative costs and the development of new business models, the low-wage advantage of some countries may be off-set, leading to a shift in GVCs. Development models predicated on successive stages of industrialisation could be challenged and the gap between the technologically advanced countries and the rest may grow. Proficiency in NPR technologies may be the only route for many enterprises in developing countries to withstand competition from technologically advanced foreign companies and avoid possible barriers to trade arising from emerging international technical standards.

The next production revolution is likely to affect the future location of production in GVCs, but exactly how is uncertain

Over recent decades, the world has witnessed a growing international integration of markets for capital, intermediate inputs, final goods, services and people. The increased partitioning of production in GVCs has drawn attention to the economic consequences of operating in different parts of a GVC (OECD, 2013a). GVCs are constantly evolving (OECD, 2015c). Recent OECD work finds little evidence at this time of the reshoring of activities from emerging to advanced economies as the result of automation, cost-saving technological change and other conditions (de Backer et al., 2014). However, evidence suggests that European companies which intensively use robots are less likely to locate production abroad. And features of some technologies, such as 3D printing – through which bespoke products or components can be made on the basis of specifications prepared on a computer anywhere in the world - could lead to some production being brought closer to developed-country markets. Developments in China are also likely to play a role. Aside from the fact that China accounted for 20.8% of global manufacturing output in 2013, China's goal of increasing the knowledge content of domestic production will expand the range of markets in which China competes and will also contribute to the development of production technologies in those markets.

Opportunities and risks will vary across types of industry

Labour-intensive industries which predominate in many developing countries, such as garments, shoes and leather, furniture, textiles and food, could be less susceptible to NPR's impact, since many processes in these industries are yet to be fully (or economically) automated. Other developing-country industries such as the electrical and electronics and machinery sectors, particularly those facing growing wages, are likely to be significantly affected by the NPR, given their high potential for automation. In other industries, such as automotive manufacture, adopting NPR technologies is expected to be determined not so much by wages or the potential for automation, but by domestic demand and consumers' growing desire for quality and customisation.

However, technological change could quickly alter the validity of the above observations and threaten capacity in developing countries. For instance, because of dexterity requirements, footwear manufacture has to date been labour-intensive. But a global apparel company recently built a shoe manufacturing facility in Germany which is fully automated and permits significant customisation. The facility consists of machines set in two production lines and anticipated to take up to five hours for a full production cycle (which currently otherwise requires several weeks) (Shotter and Whipp, 2016). Sewbo, a new start-up, is developing automation for garment fabrics where fabrics are woven by machines and cut by computer-controlled cutting machines. And intelligent robots could soon replace service functions, like call centres or accounting operations, which have become growth pillars in many developing countries.

A major challenge will be to upgrade entire interconnected production systems

A challenge for firms in developing countries will be their ability to upgrade machines, factories and business ICT systems, which are required for interconnected production. While 'islands of modernity' exist among firms in many developing countries, the capital stock is often based on older machines and out-of-date or obsolete ICT systems, which are difficult to retrofit with new technologies. NPR technologies operate with tolerances, and with technical standards and protocols, that developing-country firms are often unfamiliar with. And NPR technologies often require a continuous uninterrupted source of power, which is not available in some developing countries. While incremental approaches to adoption will help, the greatest benefits of the NPR accrue when production processes operate as systems.

Financial services may also constrain the NPR in some countries

Many emerging production technologies require large financial outlays, which are generally recoverable over periods above five years. Investments in new technologies are often not limited to specific technologies but require a range of complementary expenditures. Investments in robots, for example, usually entail investments of similar size in peripherals (such as safety barriers and sensors) and system implementation (such as project management, programming, installation and software). Financing NPR investments can thus necessitate: a range of financing institutions, such as venture capital firms and development banks; machinery-related term lending; and, specialized SME and start-up lending. Such a breadth and depth of financial services is only available in a few developing countries.

Upskilling to meet the needs of more advanced industrial sectors will prove challenging

The NPR is expected to shift skills demand from manual dexterity and basic functional skills towards cognitively intensive abilities such as data analytics, problem solving and critical thinking. Developing a workforce with such skills requires well-functioning tertiary-level institutions able to educate students in STEM disciplines, as well as a close integration between production and vocational training institutes. But these are the most resource and investment-intensive areas of education, and as such have not been the traditional priorities of developing countries.

Developing countries will need comprehensive telecommunications infrastructures

Fully benefitting from the NPR requires comprehensive, reliable and secure telecommunications infrastructure, including high bandwidth broadband, wireless networks and mobile and landline telecommunications networks. Providing coverage to remote rural areas, particularly in large countries, will facilitate communication between local producers and consumers and the development of integrated domestic markets. Fast connectivity to facilitate rapid data interchange is likely to be a hallmark of the NPR, and one of its success factors.

Rethinking investment policy for the NPR

The NPR poses challenges for investment policy. Recent decades have seen capacity in many technology-intensive industries move from developed to emerging economies, and labour-intensive industries relocate from emerging economies to less developed countries (particular in Asia, but also in some countries in Africa, such as Ethiopia, Kenya and Rwanda). In other words, independently of their individual level of economic development, most developing countries have been able to count on some form of foreign investment in their development strategies. The NPR could change this and will require careful attention to the design of investment policies.

Some countries are already acting on this challenge. In 2014, India adopted the Make in India and National Manufacturing Policy initiatives. These aim to raise the share of manufacturing in gross domestic product, create 100 million jobs and facilitate innovation, often in high-tech sectors such as aerospace and biotechnology. As part of these initiatives, India plans to open key sectors to FDI, further develop online registration portals and lower corporate tax rates. And in 2015 China adopted Made in China 2025 (subsequently renamed China Manufacturing 2025), which aims to upgrade Chinese industry and develop green and high-tech manufacturing in fields such as biomedicine, digital machinery, energy saving vehicles and IT. In the context of this initiative, China plans to grant foreign investors pre-establishment national treatment rights (subject to exceptions), among other measures.

Developing countries should review their investment-related policy settings

The NPR will change the determinants of some types of FDI, as certain factors once critical for attracting foreign investment (such as low labour costs) may become less important, while others, such as cyber infrastructure and cybersecurity, gain prominence. Governments need to assess and design investment policies in this context, aimed at maintaining and further improving their attractiveness for FDI. All of the policy issues discussed in this paper are relevant, from the quality of the education system, to IP protection in accordance with international standards, such as the WTO-TRIPS Agreement, to regulatory conditions (such as for digital services), to whether host countries are members of international conventions on data protection. Countries also need industry-specific regulations for the post-establishment phase, to avoid that companies operate in a legal vacuum. An example is regulations on biosafety and cell research for the biotechnology industry.

Countries need to consider whether to give foreign investor unrestricted access to specific new industries. For example, China, India and Indonesia have recently explicitly permitted all or part of foreign investment in e-commerce.[4] But not every country has created a policy framework for newly emerging industries. Some impose establishment requirements for foreign investors as a pre-condition for conducting e-commerce. The technology-driven emergence of entirely new industries could also pose challenges for international investment policies. Investment agreements are usually based on a “negative list” approach, meaning that the contracting parties allow foreign investment in all economic activities, except those explicitly excluded. But for new industries, emerging after the agreement, it might be unclear whether they are allowed or not.

Developing countries must also avoid that the NPR remains limited to foreign-controlled companies in their territory, but instead benefits their economies at large. This requires building local absorptive capacities so that domestic firms qualify for co-operation with foreign investors. Lessons learned about policy towards technology diffusion, discussed in Section 7, are directly relevant to this challenge.

11. Cross-cutting policy considerations

The range of relevant policy issues is broad, which highlights the need for policy co-ordination

The range of policy issues relevant to an NPR is extremely broad. Evidently, production is affected by many types of policy, from those on skills and training, to policies affecting domestic and international competition, to tax codes that affect investments in machinery and software, to policies which influence the efficiency of judicial systems and the effectiveness of bankruptcy laws, to policies on infrastructure and financial services. In addition, this paper has pointed to the roles of a "meso" level of policy, such as the design of particular institutions and programmes. The breadth of relevant policy issues underscores that some forms of policy co-ordination may be needed.

Sound science and R&D policies are essential

The technologies covered in this report result from science. Synthetic biology, new materials and nanotechnology, among others, have arisen because of advances in scientific knowledge and instrumentation. Many policy choices determine the strength of science and research systems and their impacts on production. Policymakers need to be attentive to such matters as: the procedures for allocating funds for public research; the balance between support for applied and basic research; a variety of institutional features and incentives which shape open science; the frameworks that provide incentives for firms, public researchers and public research institutes to commercialise research, while protecting the public interest; the development of well-designed public-private partnerships; the implementation of efficient, transparent and simple migration regimes for the highly skilled; the facilitation of linkages and networks among researchers across countries; and, the creation of a judicious evidenced-based mix of support using both supply- and demand-side instruments.

Many of the most important research challenges critical to the next production revolution are multidisciplinary and systemic in nature

Identifying priorities for government-funded manufacturing research programmes and initiatives is increasingly challenging due to the convergence of technologies and the growing complexity of modern manufacturing. To assess the impact of R&D investments – and decide where policy efforts should focus – policy makers need to take account of the increasingly blurred boundaries among manufacturing research domains. Technology R&D programmes can be too "siloed" if mechanisms are not put in place to support multidisciplinary and challenge-led endeavours. Many research challenges will need to draw on traditionally separate manufacturing-related research domains (such as advanced materials, production tools, ICT, operations management). And many government-funded research institutions and programmes have been constrained to only carrying out research, without the freedom to adopt additional relevant innovation activities or connect to other innovation actors. As a result, many government-funded research institutions and programmes are unable to bring together the right combination of capabilities, partners and facilities to address scale-up and convergence challenges.

Issues of scale-up and technology convergence also raise questions about the choice of key performance indicators for manufacturing R&D programmes

Traditional key performance indicators (KPIs) may not adequately incentivise efforts to enhance linkages, interdisciplinarity and research translation. Better evaluation of institutions and programmes may need new indicators, beyond traditional KPIs (such as numbers of publications and patents), including in areas such as: successful pilot line and test-bed demonstration, development of skilled technicians and engineers, repeat consortia membership, SME participation in new supply chains, and contribution to the attraction of FDI. Policy makers should avoid cookie-cutter KPIs that do not account for the systemic nature of the NPR.

Governments must create an environment which fosters business dynamism

OECD research over recent years has highlighted the role of new and young firms in net job creation and in nurturing radical innovation. New firms will introduce many of the new production technologies. But Criscuolo, Gal and Menon. (2014) find declining start-up rates across a wide range of countries since the early 2000s. Governments must attend to a number of conditions which affect this dynamism. These conditions have been treated in detail in other analyses (e.g. Calvino, Criscuolo and Menon [2016] and Andrews, Criscuolo and Menon [2014]).

Technological change is raising new challenges for the IP system – notably the patent system – and raising questions around some of the system's basic assumptions

One major challenge to the IP system comes from the emerging ability of machines to "create", an ability which until now was restricted to humans. For example, KnIT, a machine learning tool developed by IBM, was successfully run to identify kinases with specific properties among a set of known kinases. Those properties were then tested experimentally. In other words, the specific properties of those molecules were discovered by software, and patents were filed for the inventions. A second challenge stems from the ability to digitalise physical objects. 3D printing, for instance, might create complications in connection with patent eligibility. For example, if 3D-printed human tissue improves upon natural human tissue, it may be eligible for patenting, even though naturally-occurring human tissue is not. The future of these technologies could be affected by how IP and patent systems adapt.

Distribution rather than scarcity will be a primary concern

The distributional effects of new production technologies require policies beyond the domains of science and innovation. The possible measures are many, from earned income tax credits to the provision of resources for lifetime learning and job retraining. Tackling an uneven distribution of skills is a key to lowering wage inequality. Among other reasons, this is because work requiring lower educational attainment is more susceptible to automation (Frey and Osborne, 2013).

Education and skills systems will need constant attention

Rapid technological change could challenge the adequacy of skills and training systems to match demand and supply for new skills. For some production technologies, current skills supply is insufficient. Improving the efficiency of skills matching in labour markets supports productivity (OECD, 2015b). It is as yet unknown whether new generations of production technology will significantly alter past norms as regards skills supply and demand balances (although digital technology could of course play a role in augmenting skills supply, for instance through massive open online courses).

Some new production technologies raise the importance of interdisciplinary education and research

Many of the technologies examined in this report require more interdisciplinary education and research. The increasing complexity of some scientific equipment also demands the use of multiple skill types. But some education systems and individual institutions may not be responding as well as is needed.

Achieving interdisciplinarity is not a new challenge. But more needs to be known about the practices adopted across research institutions, teams and departments – private and public – which enable interdisciplinary education and research. Policymakers could seek to replicate, where appropriate, the approaches of institutions successful in fostering interdisciplinary research, such as Stanford's Bio-X.

Greater interaction with industry is needed, and this need may grow as the knowledge content of production rises

Aspects of postgraduate training may need adjustment. In the United States, current life sciences PhD level education is still focused on training for academic careers (American Society for Microbiology, 2013). However, data published in the National Science Board's (NSB's) 2014 *Science and Engineering Indicators* show that just 29% of newly graduated life science PhDs (2010 data) will find a full-time faculty position in the United States.

Developing a high level of generic skills throughout the population will also be important

Generic skills such as literacy, numeracy and problem solving provide a foundation for the acquisition of technology-specific skills (whatever those technology-specific skills turn out to be in future). Good generic skills help to "future proof" human capital.

Many other policy issues that affect skills systems today will continue to be important, but it is not evident that a next production revolution would *raise* their importance. Such issues include: (i) establishing incentives for institutions to provide high-quality teaching; (ii) supporting firm-level training and life-long learning; and (iii) ensuring that any barriers to women's participation in STEM are removed.

NPR may bring changes to labour market policies too

New urgency might be given to employment-related policies and institutions if changing production technologies create large labour market shocks. For instance, a range of labour market policies that aim to re-employ displaced workers in mid-career might also become more prominent. One important issue is whether a new generation of production technologies is likely to change the scale, frequency or character of labour market shocks. Without perfect foresight, governments should plan for scenarios in which future shocks are large and arrive quickly, such as could occur if the remaining technical obstacles to self-driving vehicles were quickly overcome.

Policymakers need to engage in long-term thinking

More public discussion is needed of the policy implications of the new production technologies. Leaders in business, education and government must be ready to examine policy implications and prepare for developments beyond the next ten years (for instance with respect to progress in machine learning). As a possible model, in Germany, the federal Ministry for Economic Affairs and Energy and the federal Ministry of Education and Research have created a coordinating body bringing together stakeholders to assess long-term strategy for Industry 4.0 ("Plattform Industrie 4.0").

A long-term perspective on policy also requires reflection on how policy priorities might evolve

Even best-practice policy today may need to change over time. This could happen because of dynamics inherent to the technologies concerned, or because of wider social or economic trends. Policy makers need to ask: "Are new policy priorities likely to emerge?". For instance, major challenges to the IP system could come from the emerging ability of machines to create, an ability which until now was restricted to humans (at least one machine-derived invention has already been patented). Similarly, 3D printing might also create complications in connection with patent eligibility. For instance, if 3D-printed human tissue improves upon natural human tissue, it may be eligible for patenting, even though naturally-occurring human tissue is not.

Notes

1. Related terms include “the fourth industrial revolution”, “next industrial revolution”, “advanced manufacturing” and “digital manufacturing”.

2. For instance, in the United States, in July 2012, the Advanced Manufacturing Partnership Steering Committee, working within the framework of the President’s Council of Advisors on Science and Technology (PCAST), outlined recommendations for positioning the United States for long-term leadership in advanced manufacturing. Similarly, in 2013 the United Kingdom’s Government Office for Science produced *The Future of Manufacturing: A New Era of Opportunity and Challenge for the UK* (Foresight, 2013).

3. Jobs will also arise in firms that make new forms of production equipment and machinery.

4. See the UNCTAD *Investment Policy Monitor Database*, available at http://investmentpolicyhub.unctad.org/IPM.

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